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Initiator (university):	prof. dr. ir. G. Lodewijks
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Subject: Optimizing the maintenance interval by modeling the state of a conveyor belt regarding splices

Most belt conveyors at Tata Steel are inspected and maintained by internal departments. The department responsible for the maintenance and inspection of the conveyor belts is HTD (Hoofd Techinische Dienst). They have an internal department named vulcaniseer dienst, who is responsible for the maintenance and inspection of the belts. The department is struggling to satisfy the demands of their customers. The predictability of failures of the conveyor belts are too low, causing failures to happen often at random. This causes peak loads which impact quality, disrupt the normal planning and cause's expensive overtime. HTD only works a day shift while the belts are being used 24 hours, 7 days a week. Breakdown outside normal hours causes the on call crew to have to come to fix the belt. This disrupts the daily operations; workers can only work so many hours a day. If they had to come at night for an emergency repair, the scheduled work during the day has to be done another day. Some of critical belts are not allowed to be standing still for longer than 4 hours, otherwise severe cost are involved. Lowering the amount and unpredictability of the disturbances to the conveyor belts, will help with lowering the operation cost. This can be accomplished by improving the quality and efficiency of both the inspections and maintenance. This in turn will lead to an increase of the customer satisfaction and the overall reliability of the system.
Tata Steel location IJmuiden is part of the European branch of Tata steel and focuses on the production of high grade steel. Over 9.000 people are employed and more than 7 million ton of steel is produced each year. The number of belt conveyors at Tata Steel is around 190 with a total length of 72 km. Most belt conveyors are located at the bulk handling area where sometimes up to four different materials in both directions can be transported on a single belt.
HTD at Tata Steel is responsible for the inspections and maintenance for most of the conveyor belts. Since most belt conveyors are used for critical operations, disturbances should be avoided as much as possible. Ideally you would want to know ahead of time when a disturbance is going to happen so you can plan ahead to mitigate this. Furthermore, replacing and repairing the belt of the conveyors can be costly. To improve the performance of HTD towards the customers, the efficiently and reliability of the maintenance and inspections should be improved. A way to accomplish this is by performing preventing maintenance. Since belt conveyors consist of more than only a belt, other parts also have to be included. The parts that have the most influence on the belt are the drive, belt scrappers and idler. The different moving parts of the belt conveyor have a lot of effect on each other; neglecting one can cause problems for the others. To get a good understanding of the problems concerning the reliability of the belt conveyor systems, all important parts should be included. The cost compared with the accomplished effect should also be taken into account.

Supervisor,

Prof. dr. ir. G. Lodewijks

Acknowledgement

Being a student of mechanical engineering at the Delft University of Technology I have written this report as a framework of my final assignment, which is part of the study program of the master transportation engineering and logistics.

The topic of this research has been arisen from the demand of the internal department Hoogovens Technische Dienst at Tata Steel IJmuiden to service their customers more effective.

This report is written for the people at involved with the decision-making involving the planning and maintenance decisions concerning conveyor belt. It is also written for the people at the Delft University of Technology involved in the evaluation of this master thesis. It could also be interesting for people involved in modelling the preventive maintenance interval of a certain installation.

I like to thank Luuk Roggen for the opportunity to perform this thesis in practice in an interesting environment at Tata Steel. It has been a valuable experience. I like to thank Dennis Oudhof for his information, advice and directing me to the correct people. I like to thank Rob Pagter, Jaap van Tilborgh, Pieter van Ammers, Erik Veldt, Cederic Sadee, Machiel IJff and Ruud Boeree for their information and data. I like to thank Jos Oudemast and the crew responsible for the belt maintenance for the opportunity to witness both inspections and belt maintenance in practice and there practical insights provided. I like to thank my colleges at HTD for their educational and pleasant time.

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And last but not least I would like to thank my parents for giving me the opportunity and support to get a university degree.

Summary

Traditionally, maintenance of conveyor belts is performed using corrective maintenance. This means that maintenance to conveyor belts is only performed if the belt fails or severe damage is detected to the belt. Visual inspections to the belt are carried out to detect defects to the belt before the belt fails. Once a belt fails or a defect is detected, maintenance is performed. The amount of maintenance to a system of belts heavily depends on the failures and defects detected. So during a period with little detected defects, the workload is low while the opposite also is true. This leads to a very uneven work load for the department or company performing the maintenance to the belts. Because maintenance is only performed once severe damage is detected or the belt has already failed, the system reliability is lowered. The reliability of the system and the spread of the work load can be improved by using preventive maintenance instead of corrective. Preventive maintenance is performed before severe damage to the belt is present. But how do you know when to perform the preventive maintenance. Performing the maintenance too early will lead to an increase of the number of maintenance actions over time. Performing the maintenance too late and the corrective maintenance has already taken place. Developing a method to determine when the maintenance has to take place, the so called maintenance interval, is the main focus of this research.

To determine the optimum maintenance interval a model has been developed. The model has been designed with conveyor belts into mind but can easily be used on every component that requires preventive maintenance. The model is developed using the Bayesian Belief Network (BBN). Belief networks are graphical representations of models that capture the relationships between the model's variables. The variables that interact directly are identified and are limited to the variables to which they are directly connected. Belief networks may use directed or undirected graphs to represent a dependency model. The directed acyclic graph (DAG) provides a better representation than the undirected graphs. The DAG is also more flexible and is able to represent a wider range of probabilistic independencies. An undirected graph is one where the edges have no direction meaning (A, B) is equal to (B, A). The BBN is a specific type of causal belief network. As for any causal belief network, the nodes represent stochastic variables and the arcs identify direct causal influences between the linked variables. The fundamentals of the Bayesian methodology is too enable prior knowledge of a certain event to calculate the posterior probability of a hypothesis based on the probability of the event.
One of the challenges of the BBN method is incorporating information with a large number of possible values. The thickness of a conveyor belt for example changes of its lifetime because of wear. To take this type of information into account in the model, fuzzy logic is introduced. Fuzzy logic is used to assign a degree of membership to an event. By assigning the thickness of the belt a number of ranges instead of thickness in millimetre, the amount of variations for this node is limited to the number or ranges.

The BBN model is created by using both historical data as the knowledge of experts concerning the part where the model is used for into account. The historical data provide the basic information necessary for the model. The expert opinion can be used to check the information supplied by the historical data as fill in missing data. By introducing reliability of the data and information to the model, the usefulness in practice can be increased. Data for the model determined by a large number of sources and checked by an expert can be considered as reliable. The opposite is also valid and by looking at the reliability of the outcome of the model, the influence of the model on the decision making process can be described. Another factor that is taken into account in the model is the spread in the output. The output of the model will always have an uncertainty that is translated in a spread. This spread can be influenced by the reliability of the model and for example a safety factor for the maintained part in question.

The developed BBN model can provide a boost in both the reliability of the system the part is present in as reducing the fluctuations in the workload for maintenance operations. The workings of the model have been proven with the usage of a test case at the company Tata Steel although the output was not accurate enough to use in practice. Further research is necessary to increase the accuracy of the model to enable the industry to use the method during normal operations.

Samenvatting

Traditioneel, onderhoud aan transportbanden is uitgevoerd volgens de correctieve methode. Dit houdt in dat onderhoud aan een transportband wordt toegepast zodra een transportband kapot gaat of ernstige schaden is gedetecteerd. Visuele inspectie wordt uitgevoerd om schade aan de band te detecteren. Zodra een transportband breekt of schade is vastgespeld, onderhoud aan de band word uitgevoerd. De hoeveelheid onderhoud die moet worden uitgevoerd aan een systeem of transport banden word sterk beïnvloed door het aantal banden die op dat moment stuk zijn of schaden hebben. Dus tijdens een periode met relatief weinig schade gevallen, de hoeveelheid onderhoud dat moet worden uitgevoerd is ook laag. Als er echter veel banden schaden hebben, dan is de hoeveelheid werk voor de onderhoudsploeg hoog. Dit leidt tot een sterk variërend aanbod in de hoeveelheid onderhoud werk. Omdat onderhoud alleen word uitgevoerd zodra er ernstige schade aan de transportband is gedetecteerd of de band kapot gaat, dit lijdt tot een lagere betrouwbaarheid van het systeem. De betrouwbaarheid van het systeem en de spreiding van het onderhoudswerk kan verbeterd worden door preventief in plaats van correctief onderhoud toe te passen. Als preventief onderhoud wordt toegepast, dan vind er onderhoud aan de band plaats voordat er ernstige schade optreed. Maar hoe weet je wanneer je preventief onderhoud moet toepassen. Als het onderhoud aan de band te vroeg word toegepast, dan nemen het aantal onderhoudshandelingen over tijd toe. Als het preventieve onderhoud te laat word toegepast, dan heeft er al correctieve onderhoud plaats gevonden. Het vaststellen van het moment waarop preventief onderhoud moet worden toegepast, het onderhoudsinterval, is het hoofddoel van dit onderzoek.

Om het optimale onderhoudsinterval te bepalen is er een model ontwikkeld. Dit model is ontwikkeld met als uitgangspunt transportbanden, maar kan zonder enige problemen worden toegepast op elk ander onderdeel dat preventief onderhoud nodig heeft. Het model is ontwikkeld met gebruik van het Bayesian Belief Network (BBN). Belief networks zijn grafische weergave van modellen dat de relaties tussen variabelen in het model weergeven. De variabelen die onderling communiceren worden geïdentificeerd en zijn gelimiteerd tot de variabelen met wie zij direct verbinden. De gerichte acyclische graaf, in het Engels directed acyclic graph (DAG), levert een beter beeld dan een ongerichte graaf. De DAG is ook flexibeler en kan een groter assortiment van statische onafhankelijkheden. Een ongerichte graaf heeft kanten met geen richting dus (A,B) is gelijk aan (B,A). De BBN is a specifiek type van causal belief network. Als voor elk causal belief network, de knopen representeren de stochastische variabelen en de kanten representeren de directe causaal verbanden tussen de verbonden variabelen. Het basisprincipe van de Bayesian methodologie is om met behulp van voorkennis of bepaalde gebeurtenissen de posterior probability van een hypothese te bepalen in relatie tot een gebeurtenis.
Een van de uitdagingen wanneer de BBN methode word toegepast is het gebruiken van informatie die een grote hoeveelheid variaties heeft. De dikte van een transportband bijvoorbeeld zal gedurende de levensduur van de band veranderen onder de invloed van slijtage. Om dit type van informatie toe te passen, fuzzy logic kan worden gebruikt. Fuzzy logic word gebruikt om een gewicht toe te wijzen aan waarden. Als bijvoorbeeld aan de dikte van een transportband een aantal waarden toegekend in plaats van in millimeters, het aantal variaties voor dit knooppunt is gelimiteerd tot het aantal toegekende waarden.

Het BBN model is gemaakt met behulp van zowel historische data als de kennis van experts op het gebied van het the moduleren onderdeel. De historische data word gebruikt voor het bepalen van de benodigde informatie voor het model. De kennis van de experts kan worden gebruikt om de juistheid van de informatie verzameld met behulp van de historische data te controleren en missende informatie voor het model in te vullen. Met behulp van het introduceren van betrouwbaarheid van zowel de data als de informatie beschikbaar, de bruikbaarheid van het model in de praktijk kan worden verbeterd. Data verzameld met behulp van een groot aantal bronnen en gecontroleerd aan de hand van de kennis van experts kan worden beschouwd als betrouwbaar. Het tegenovergestelde is ook van toepassing, met behulp van deze betrouwbaarheid kan een niveau van vertrouwen over de uitkomst van het model worden toegevoegde welke tijdens het beslissingsproces kan worden gebruikt. Een andere factor die moet worden bepaald in het model is de spreiding van de uitkomst. De uitkomst van het model zal altijd een zekere mate van onzekerheid bevatten, dit wordt toegepast met behulp van de spreiding. Deze spreiding kan worden beïnvloed door de betrouwbaarheid van het model en het veiligheid niveau van het onderdeel waarop het model word toegepast.

Contents

1. Introduction

A belt conveyor system, in the rest of the report referred to as BCS, is used to transport large quantities of bulk materials between two locations. A basic BCS consist of an endless belt, two pulleys, a drive, idler rolls, one or more scrappers and a frame. Essentially an endless belt moves between two points over a series of supporting rollers, propelled by a drive pulley or “drum” and returning via a second pulley [1]. The supporting rollers are called idler rolls. The scrappers present at the belt prevent material from sticking to the belt. The frame supports the components of the BCS. In Figure 1 an example of a conveyor belt is shown. In this research the main focus will be on the conveyor belt. The reason for only focusing on the conveyor belt is that this research originates from a problem concerning conveyor belt maintenance.

There are a number of types of BCS, for bulk materials a commonly used type is the troughed belt conveyors as is shown in Figure 1. The belts used on this type of BCS can be split in two categories, steel cord belts and fabric belts. Steel cord belts are often stronger so they can be used for long BCS, fabric belt are weaker but cheaper. During this research only fabric belts will be discussed.

Figure 1: Example of a BCS

A BCS consist of a number of components who are all important for operation of the system. The reliability of this system is the sum of the reliability of each individual component. If one component breaks down, either the system may no longer operated or severe damage to other parts or the surroundings may be caused. Since BCS are often used in the normal operations of a plant, disturbances to this system can have a high impact. To prevent breakdowns from occurring, inspections and maintenance has to be carried out to the system. Inspections to monitor the state of the system, maintenance to bring the system back up to standards once a problem has been detected. A method for maintaining a BCS is corrective maintenance. The belt is regally inspected till damage to the belt is so severe that maintenance is required. At this point either emergency maintenance is performed or there is a short interval available to perform the required maintenance. Since the planning of the maintenance only starts once damage to the belt has been detected, the available time for this planning is limited. Waiting too long can lead to extra damage or failure of the system. Because maintenance is postponed to the point where damage to the belt is already severe, the overall reliability of the system will decrease. Combined with the limited flexibility in planning, this can cause disturbances to the normal operations of the BCS. Another negative influence of the corrective maintenance approach is the high variation of maintenance work. Maintenance is only carried out if either a belt fails or severe damage to a belt has been detected. During periods when there are few of such cases, the overall maintenance requirement of the system is low. If on the other hand a lot of damaged belts are detected, the maintenance requirement is high. Performing maintenance to BCS is specialized work, the available maintenance capacity can often be considered as fixed. During the periods with lots of maintenance, there can be a shortage of maintenance capacity. Lack of capacity means that a customer either has to wait longer before his broken belt is repaired or the maintenance has to take place in a less optimal moment.

1.1 Problem definition

There are a number of problems with corrective maintenance mentioned above. For a maintenance department the main problem of corrective maintenance is the highly fluctuation work load. Another problem with corrective maintenance is the short time frame available for the maintenance action. Once a problem has been detected, there is often only a limited amount of time available to plan the maintenance action before the belt completely fails. If the severe damage is not detected on time, the belt can already fail for maintenance can be carried out. The short time frame for maintenance and risk of failed belts leads to a high number of emergency repairs. Emergency repairs can have a huge influence on the maintenance planning. The planned work has to be carried out at another moment and the work time regulations have to be taken into account. The number of emergency repairs can be reduced with a number of adjustments. The first possibility is improving the frequency and quality of the inspections. By detecting the damage earlier, more time is available for planning the maintenance. The chance that a belt fails because damage is not detected on time is also lowered. The improvement of the inspections can for example be accomplished by monitoring the system continuously instead of manual inspections. Another method is changing the maintenance strategy involved with maintaining the conveyor belt. With the use of preventive maintenance the disturbances to the normal operations of the BCS can be limited. When performing preventive maintenance to a conveyor belt, the maintenance is performed before severe damage to the belt is present. Operations of many systems causes stress which results in system degradation and hence an increase in the level of the hazard function with time. Preventive maintenance is assumed to relieve stress temporarily and hence slow the rate of system degradation [2]. One of the challenges when performing preventive maintenance is determining at what point the maintenance has to take place. If the belt is maintained too soon, more maintenance then necessary is carried out to the belt. This will reduce the availability of the belt and increase the maintenance cost. If the maintenance is performed too late, there is a high chance corrective maintenance has already been performed. For parts that operate under relative stable conditions, the part manufacture often provides a preventive maintenance interval. The maintenance interval of conveyor belts is influenced by a large number of factors. Because of this reason, no predefined maintenance interval is available for conveyor belts. The optimum maintenance interval for conveyor belts has to be determined using another method.

So in short: the main cause of the current problems with the maintenance of conveyor belts is corrective maintenance, these problems can be mitigated by using preventive maintenance, to implement preventive maintenance a maintenance interval is required. Determining this maintenance interval is the main problem of this research.

1.2 Research Scope

Before the method for answering the above proposed problem is discussed, first the scope of this research is defined. The scope of this thesis is limited to the maintenance of fabric conveyor belts. For this research, the available maintenance capacity for the maintenance of conveyor belts is considered as fixed. The method for making a model discussed in this thesis can be used on most costly parts that require preventive maintenance, but during this thesis only the method for making a model to determine the optimum preventive maintenance interval for conveyor belts will be discussed. In this thesis a number of improvements to the maintenance process of conveyor belts are discussed. The scope of these improvements is limited to a situation as is present at the company at which this research is carried out. To prove the workings of the method for making a model to determine the optimum maintenance interval a test case has been performed. This test case is based on the available data and situation at Tata Steel. A number of internal departments at Tata Steel own the BCSs; only the data of the department with the highest number of BCSs has been used. During this test case the scope of the model is limited to the splices of fabric conveyor belts transporting cold material between two transfer points. With the scope of the research determined the research question can be defined.

1.3 Research questions

To answer the earlier stated problem, the following main research question is proposed:

How can the state of a conveyor belt be determined using a model, to optimize the maintenance interval for preventive maintenance?

To answer this main research question, a number of sub questions are introduced:

1. What are the causes for maintenance of conveyor belts?
2. How can the current problems regarding maintenance be removed or mitigated?
3. What is the best theory for making a model to determine the state of a conveyor belt?
4. How can the method for making a model made useful for practice?

The above proposed main research question and sub questions are answered during this thesis. The approach and methodology for answering these questions is presented below.

1.4 Approach and Methodology

The approached for answering the research questions used in this thesis is that first some general improvements for the maintenance process are proposed. These improvements are based on the situation as present at Tata Steel. For answering the main research question a method for making a model has to be determined.
Before a method for making a model can be presented, first the type of model used must be chosen. For making the model, three methods will be discussed. The first method that will be discussed is Exploratory Factor Analysis (EFA). EFA is one of the most widely used statistical procedures in psychological research [3]. Although EFA originated from psychometrics it can also be used for applied science that handles large quantities of data. The second type of model is the Fault Tree Analysis (FTA). A fault tree analysis can be simply described as an analytical technique, whereby an undesired state of the system is specified (usually a state that is critical from a safety standpoint), and the system is then analysed in the context of its environment and operation to find all credible ways in which the undesired event can occur [4]. The FTA is mainly used in reliability engineering and safety engineering to deduct how a system can fail. Removing or reducing the cause of failure will increase the reliability of the system. The final type of model discussed is the Bayesian Belief Network (BBN). BBNs can be visualised as "nodes" connected by "links" where the nodes represent chunks of knowledge and the links represent the relation among these bits of knowledge [5]. Belief networks may use directed or undirected graphs to represent a dependency model. The directed acyclic graph (DAG) is a causal network that consists of a set of variables and a set of directed links between variables [6]. The fundamentals of the Bayesian methodology is too enable prior knowledge of a certain event to calculate the posterior probability of a hypothesis based on the probability of the event. This type of method is ideal for the creation of the model. The model can predict the maintenance interval for preventive maintenance based on historical data. Since BCS is expensive equipment with often a long lifetime, historical data is in general available. So the BBN method will form the basis of the method of making a model.

The method for making a model for modelling the state of the belt to determine the maintenance interval follows a number of steps that are briefly explained. The first step when making a model is designing the DAG representing the model. When making this DAG a number of factors should be taken into account. The nodes included in the model should be relevant for the outcome of the model. Including nodes with no or very little impact will only increase the size of the model. It is also recommended to take the available information for the model already into account while designing the DAG. Missing information can be collected using a number of methods but those can be costly and time consuming.

The second step is collecting and processing the data for the model. The data for the model can in general be collected from three different sources. The first source is historical data. Depending on the age of the system, historical data can be available for multiple decades. The second source of data is laboratory tests. Historical data is often based on a combination of different variables. In a laboratory, information of the influence of a single variable on the maintenance interval can be collected. The third source of information is knowledge of experts concerning the part in question. Experts can often provide good indications of the maintenance interval of the modelled part.

Once the data has been collected, the data has to be processed to be useable for the model. The data collected from the different sources have to be combined to determine the necessary information for the model. The first type of information required is the prior probability for each node. The prior probability is required for each range of a node. The number of ranges of each node depends on the type of variable the nodes describes. If the node describes a variable with a fixed number of possibilities, the number of states is equal to the number of possibilities if the number of possibilities is within a reasonable number. For continues variables, a method called fuzzification is used. Fuzzy system theory can be used effectively in cases where exact solutions are not always necessary for example to save computational costs [7]. When using fuzzy logic, a number of ranges are decided for a node either by experience or using the available data. The input for the node is incorporated with the use of memberships for each range. The prior probability is the chance that each range of a node occurs and should be determined for each node of the model.

Once the prior probability for the modes has been finished, the conditional probability can be determined. The conditional probability indicates the result of a combination of nodes with ranges on the model. For each combination the conditional probability has to be determined based on the earlier discussed sources of information. A good method for determining this conditional probability is process the data in such a way that effect of each combination of nodes with ranges on the maintenance interval becomes clear.

Once both the prior probability and conditional probability have been determined the model itself can be created. The output of the model indicates the state of the conveyor belt regarding splices. This state has to be translated to a maintenance interval. Before his maintenance interval provided by the model can be used into practice, it is recommended to add some extra features to the model. The first useful addition to the model is a representation of the reliability of the output. This indicates with what weight the output of the model should be taken into account during the decision making process. The reliability of the output can be determined by taking two factors into account. The first factor is the reliability of the input of the model. Is the input based on hard data like sensors or on subjective information? The second factor is the reliability of the conditional probability. Having sufficient data for each combination of ranges with states is unlikely so often some of these conditional probabilities are based on trends or expert opinion. These types of conditional probabilities could be assigned a lower reliability.

Another type of output provided by the model that is necessary for usage in practice is the spread. The output of the model will always contain some uncertainty what is represented as spread. The size of this spread can even be combined with the reliability. Another method of determining the spread is simply looking at the size of the maintenance interval or by taking the safety factor of the part in question into count.

The method for making a model described in this thesis has been tested in practice at the company Tata Steel IJmuiden. Tata Steel has an internal department carrying out most of the maintenance to the around 375 conveyor belts present. For testing the model into practice a limited number of those conveyor belts have been used. From the conveyor belts that fitted the earlier discussed scope a selection has been made based on the amount of maintenance to the belt performed and the importance of the belt on the overall system. Information concerning these belts have been collect, both of the department who carries out the maintenance as the department who owns the BCS.

The output of the model for the preventive maintenance interval for the maintenance interval of conveyor belts has been compared with the real data available from corrective maintenance. Because of the difference in maintenance strategy, validating the model was not possible. The model how ever has been verified and the correlation between the real data and the modelled data is promising. It should be noted however that the data available for making the model was limited. The way data is handled is based on daily operations; a lot of detailed information is transferred orally or by mail and is not archived properly. Because of this the model created as test case cannot be used in practice with the limited amount of data available.

The conclusion concerning this research is that the BBN combined with fuzzification is a good method for making the model. The test case showed correlation even with the limited amount of information availbe. More research could be performed on extracting detailed information form sources that vary highly in quality. Develop methods to transfer the expert knowledge to useful data is another point of interest. Finally, the model is currently created fully manually, by automating both the data processing and the determination of the prior probabilities and conditional probabilities for the model; more detailed models can be created. Some methods for making a learning Bayesian belief network are proposed by J. Cheng and R. Greiner [8].With a self-learning model the current labour extensive process of making the model can be largely avoided.

1.5 Thesis outline

This thesis consists of two parts. The first part consists of the introduction to both the situation and the problem followed by the process of making a method to determine the maintenance interval for preventive maintenance. The second part consists of a test case where the method created in the first part is tested in practice, followed by the conclusion and recommendations. The structure of this thesis is as follows:

Chapter 2 provides a short introduction to both belt conveyor systems as the company at which this research is carried out. The entire process involved with the maintenance of conveyor belts is then presented. Finally the problem definition and the scope of this research are shown.

Chapter 3 presents some general improvements that could be carried out to the maintenance process of conveyor belts. After the general improvements are shown, the process of deciding the type of model used for making a method to build a model is presented. The advantages and disadvantages of each method are given after which a multi criteria analysis is performed to determine the best type of model for this research. The last part of this chapter gives more information on the Bayesian Belief Network and shows an example of this method.

Chapter 4 introduces the method for making a model to determine the maintenance interval for preventive maintenance. The complete process of building the model is discussed, from designing the model to collecting data and finally implementing the model. The first phase of the model creation process based on a test case in practice is shown next.

Chapter 5 starts with describing the process of collecting and processing data. Once the data has been collected and processed, the creation process of the model in practice is shown. The process of verifying and validating the model is also discussed in this chapter. Finally some recommendations are given on how the model can be improved in this test case.

Chapter 6 concludes the work by presenting the conclusion and provides recommendations for future research.

2. Belt conveyors and maintenance

In the first part of this chapter, BCSs are introduced. Then some general information on the company and the department where this research is carried out is presented. Some details on how the maintenance department operates in combination with the departments who own the BCS is also given. Once the BCS and the department who carries out the maintenance are introduced, the complete process of performing maintenance to a conveyor belt is presented. Finally some problems with the current method of maintenance are shown.

2.1 Belt conveyor system

A BCS consists of a number of parts that together perform the task the system was designed and build for. The main parts of the BCS consist of an endless belt, idler rolls, pulleys to support the belt, drives to power the system and a frame where the different parts are attached to. The most costly part of the BCS is the belt. The length of a BCS can vary from a couple of meters to a length of multiple kilometers. A BCS between India and Bangladesh for example has a length of 17 km [9]. There are a number of different types of belt conveyors. In this thesis only troughed belt conveyors will be discussed. This type of belt conveyor is often used for the transportation of bulk materials.

Most troughed belts consist of three distinguished layers. The top layer is used to transport the material, depending on the type and temperature of the material, the thickness can vary from 3 to 12 mm. The middle layer is called the carcass. This layer is responsible for the strength of the belt. The carcass can consist of layers of fabric or steel cords both encased in rubber. In Figure 2 an example of the steel cord present in the carcass of a steel cord belt and some fabric layer in the carcass of a fabric belt are shown.

Figure 2: on the left: making of splice in steel cord belt, right: different layers of fabric in fabric belt

The material used for the carcass depends on the strength required of the belt. This research will only discuss fabric belts. A fabric is built up of yarns that are twined bundles of fibers [10]. In general three types of materials are used for the fabrics in the belt: Polyamide (Nylon), Polyester and Aramid [11]. The fabric present in the belt used for the test case is a combination of Polyamide and Polyester. The bottom layer of the conveyor belt has a thickness between 1,5 to 4 mm and is used for carrying the conveyor belt. A profile of a fabric conveyor belt is given in Figure 3.

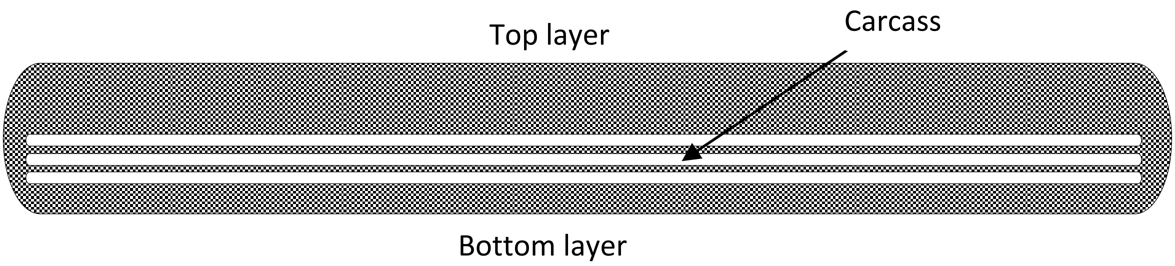


Figure 3: Profile of a fabric conveyor belt

The top and bottom layer protect the fabric against the material transported and the environment. The belt is supported along the length by idler rolls and has pulleys at either end. Some idler rolls and pulleys are used to guide the belt. Only in theory it is possible to have a conveyor belt run in a predetermined track without any kind of tools whatsoever [12]. At least one of the pulleys at a BCS is powered to rotate the belt. Depending on the design of the BCS the belt rotates either only in one or in both directions. The movement of the belt transports the material from the take-up location to the transfer point. To limit belt sag and provide sufficient friction between the powered pulley and the belt, the belt is pre-tensioned. To tension the belt a so called take-up device is used. The belt can be stop during operations utilizing the motor or using brakes if they are present at the BCS.

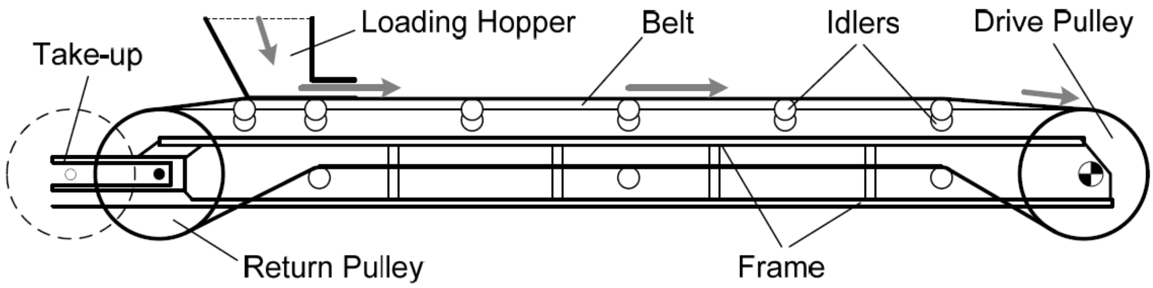


Figure 4: Conveyor belt Assembly (Pang 2010)

In Figure 4 an assembly of a conveyor belt is presented. This assembly is one of the most basic designs of a BCS. Depending on the requirements of the BCS the design is changed. The bulk material is place on the belt at the loading hopper and leaves the belt at the drive pulley. Near the location where the material leaves the belt a scrapper is often present. This scrapper removes most of the material that sticks to the belt. Material that is not removed from the belt can fall from the surface of the belt during the return journey of the belt. The material can also stick to the return idler rolls that are in direct contact with the material transporting side of the belt.
While looking at the reliability of the BCS, one must look of the combined reliability of all parts. The different parts of the BCS work together to perform the designated task. If one part of the system breaks down there is a possibility that the BCS does not longer operate or damage is inflicted to the rest of the system. By increasing the reliability of each individual component, the reliability of the overall system can be improved. By improving the overall reliability the amount of downtime can be minimized and costly disturbances to the normal operations avoided. The reliability of the parts can decrease over time because of damage occurring during normal operations and wear. Inspecting and replacing these parts before critical failure occurs prevents the system from reaching a low level of reliability.

2.2 Tata Steel

Tata Steel Europe Ltd. is a subsidiary of Tata Steel since 2007 and is the second largest steel maker of Europe. The main production location is Tata Steel IJmuiden. Founded in 1918 as koninklijke hoogovens, became Corus in 1999 and kept operating under that name till 2010. The terrain of Tata Steel IJmuiden is the largest continues company terrain of the Netherlands. One of the main benefits of the location is the direct sea connection; ship with large draught can dock without the delay of locks or long cannels.
Every year Tata Steel uses around 4,5 million tons of coal and around 9 million tons of iron ore to produce high quality steel. Of the production of around 7 million tons of steel, 4 million tons is transported by ship or barged, the other 3 million tons reaches the customer by train or road [13].
The creation of raw iron from ore is performed in three processes. The first process is the creation of cokes from coal. This process is performed in airless furnaces under high temperatures. Some of the coal is grinded for direct injection in the blast furnaces. The second process is creation of sinters and pellets from the iron ore. This is also performed by heat treatment of the iron ore. The final process is the creation of the raw iron in the blast furnace. The pellets, sinter and cokes are put in the blast furnace and form raw iron that is extracted at a temperature of around 1500 degree. The raw iron still has to undergo a large number of processes to reach the necessary quality of steel that can be ship to the customer. Since nearly all belt conveyors are located in the production process before the blast furnace, this is the most interesting part of the company for this research. In Figure 5 you can see on the foreground the bulk material storage piles. Left of the bulk storage piles the different plants used for the production of iron can be seen.

Figure 5: The bulk handling side of Tata Steel

This research is carried out at the internal department Hoogovens Technische Dienst, in the rest of the report referred to as HTD. HTD is responsible for most of the inspections and maintenance to the belts of the belt conveyors located at Tata Steel. The BCS are owned by the department who mainly operate the belt conveyor. These departments also carry out the maintenance to the drives, idler rolls and other parts except the belt of the BCS. The only part of the BCS that is not primarily maintained by Tata Steel are the scrappers present on the BCS.

2.3 HTD

HTD is responsible for the inspections and maintenance for most of the conveyor belts. HTD is a department with around 800 employees that is specialized in the maintenance of most equipment present on the terrain of Tata Steel. For the production of steel a large number of large and complex machines are used. Because of this, HTD has a lot of internal departments that each has their own specialization. There is for example a department specialized in hydraulics but also one for the replacement of heat resistance tiles in train carriages. The internal department relevant for this research is part of the department montage. Internally it is often called: “vulkaniseer dienst” since they vulcanize some of the belts. The number of people working in the vulkaniseer dienst is 20. During the rest of this research the internal department “vulkaniseer dienst” who is part of montage is simply mentioned as HTD. The internal department structure inside HTD is not really relevant for this research, the relationships between HTD and the production departments do influence the problem definition of this research. Production departments have a production planning they have to deliver. In case of problems they want HTD to come and fix the problem as soon as possible to minimize the disturbance on their production. Scheduled maintenance is planned in consideration with both the production department and HTD since HTD has only a limited capacity. Another factor that has to be taken into account is that all the production process at Tata Steel is a line. If one plant stops, the next plant can continue producing till the buffers are empty and then has to stop. An unscheduled stop of a blast furnace is very expensive and should be avoided at all cost.

2.4 Departments

At Tata Steel a lot of different departments are present. Each department has its own specialty or factory. There are for example two departments who are responsible for the creation of cokes but each has their own cokes plant. The belt conveyors on the terrain of Tata Steel belong to the department who is responsible for the raw material at that point of the production chain. In general GrondStoffen Logistiek (GSL) is responsible for transporting the bulk material from the quay side to the different plants and the transportation between the plants. Before and after each production process a buffer is present. GSL mostly transports the material based on the amount of material present in the buffers. If a buffer gets below a certain level, GSL uses their conveyor belt network to fill the buffer back to full capacity. The conveyor belts between the buffer with the bulk material used for the production process and the buffer with the product created in this plant are owned by the department who runs the production plant. Taking this into account, the BCSs at Tata Steel have 7 main owners. To complicate matters some departments have their belt conveyor split over different divisions inside the department. GSL for example has two divisions who own BCSs. One division focuses on transporting the material from the quayside to the storage piles. The second division is responsible for the transportation from the storage piles to the plants and the transportation of bulk material between the plants. Some decisions concerning the BCS they share while others are separated between the two internal departments.

So in short, there are 7 departments that own BCSs and an 8th department, HTD, who is responsible for the maintenance of the conveyor belts. Each department has its own planning and financial responsibility. The 7 departments are shown in Table 1 together with the amount of BCSs they own and the total length of the conveyor belts. The 7 owners of the BCS all have their own planning and want the maintenance to the belts performed at their own optimal time. The current method of preforming maintenance to the conveyor belt has a low flexibility concerning planning. Combined with a high number of disturbances introduced by emergency maintenance the maintenance performed to the belt is often at a suboptimal time for the owners of the belt. Increasing the amount of flexibility in the planning and decreasing the number of emergency maintenance actions will improve the amount of maintenance actions performed at the optimal time for the conveyor belt owners. Since the owners of the BCS can be considered as internal customers of HTD, this will increase the customer satisfaction. How the current maintenance is performed and how this can lead to the high number of emergency maintenance actions and low flexibility in planning will be discussed in the next part of this chapter.

Table 1: Departments with BCS

Department	Full name	Number of BCS	Total length belts (km)
GSL	Grondstoffen Logistiek	150	40.9
KGF1	Kooks en Gas Fabriek 1	36	4.8
KGF 2	Kooks en Gas Fabriek 1	35	6.5
PEFA	Pelletfabriek	76	3.8
SIFA	Sinterfabriek	49	4.6
HO 6	Hoogoven 6	12	1
HO 7	Hoogoven 7	18	1.9

The scope of the test case was defined as using only data into account from a single internal department. This department is GSL since this department owns the most BCSs.
In Figure 6 an overview is given of part of the belt conveyors owned by GSL at Tata Steel. This section contains the quay side where bulk carriers can be unloaded, two ore storage areas and an ore blending pile. The lines with a number above them are all BCS. The belt conveyors form a complex network that is used to transport material between two locations. If possible redundancies are built in to minimize disturbances.

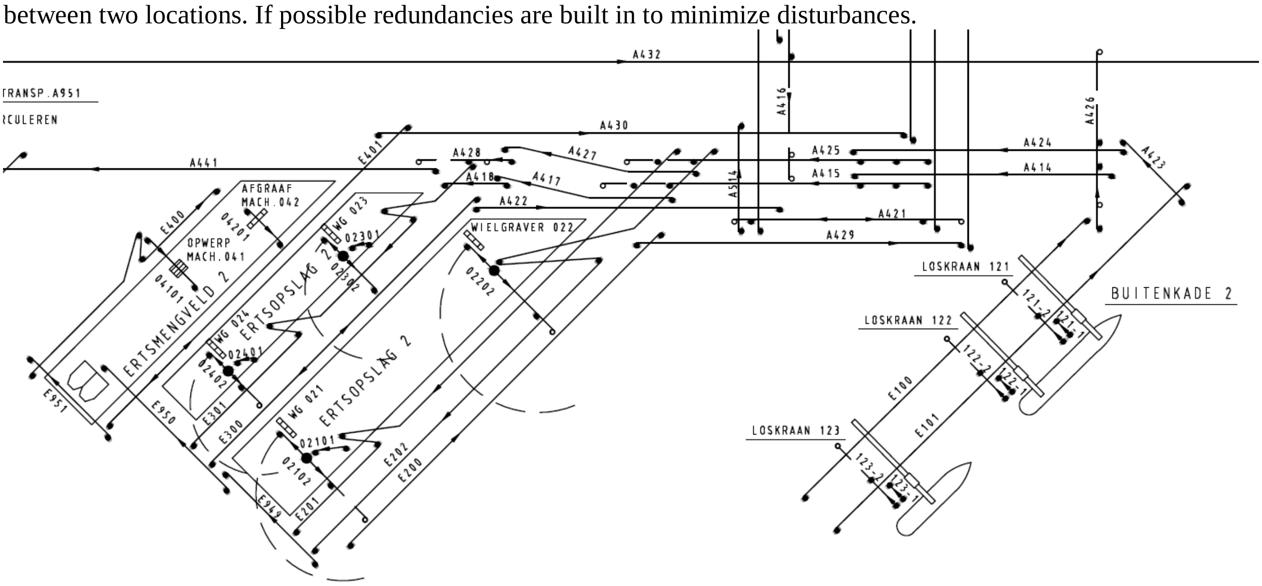


Figure 6: Small number of the BCS present at Tata Steel

2.5 Most common types of damage to belt

Before the entire process of performing maintenance to a conveyor belt is explained, first the most common types of damage to a belt are discussed. Damage to the belt is often limited to a number of types. The first type of damage to the belt is caused by external influences. This damage is mainly caused by a foreign object transported in the bulk material. There are sometimes fillers present in the network of BCS´s to remove these objects. These filters have to be designed in such a way that they are not blocked by the bulk material during normal operations. Because of this, the size of the openings in these filters is rather large allowing some of the foreign objects to pass unobstructed. An example of a foreign object is a crowbar used for maintenance somewhere along the path the bulk material takes from the mine to the plant. If this crowbar falls with the wrong orientation at the takeover point, the crowbar can puncture the belt. The crowbar can then get stuck at an idler roll tearing the belt in half in the longitude direction. An example of some holes in a conveyor belt is shown in Figure 7.

Figure 7: example of some holes in a conveyor belt

Not only foreign objects can cause damage to the belt. Another external cause for damage to the belt are the other parts of the BCS. A worn out idler roll can cut the belt in halve. A badly attached scrapper can scrap of the protective cover of a conveyor belt at an alarming rate or tear a splice open. Damage caused by external influences is generally hard to predict since they happen at random.

The second type of damage to the belt is to the protective surface. Bulk materials can damage the protective cover at impact at the transfer point. Even with scrapper's present some bulk material will still stick to the surface of the belt of the return side of the conveyor belt. Some of this material will drop during the return trip, causing bulk material to collect under the BCS. If this is not removed in time, the amount of material present can get so large that it connects with the conveyor belt. The friction between this bulk material and the moving belt will cause severe wear to the belt and can damage the belt surface. In Figure 8 an example of bulk material touching the belt surface is presented.

Figure 8: bulk material touching the belt surface

At transfer points dust seals are often used to prevent material from falling next to the belt. In theory these dust seals have to be made from a softer material than the protective cover of the conveyor belt. These dust seals are in direct contact with the conveyor belts and when two surfaces of which one is moving are in contact, the softest one will wear the most. In practice the dust seals are often made from old conveyor belts causing them to be harder than the actual belts themselves. For belt that have a lot of contact with the dust seals or where the contact pressure is high, this can causes severe wear to the belt surface. Stuck idler rolls or other objects touching the belt can also cause damage to the conveyor belt surface. In Figure 9 an example of longitude damage to the belt surface is shown. The final damage to the belt surface is caused by heat. The source of this damage can in general originate from two sources. The first source is the transportation from warm material. Belts that transport warm material often use special protective covers that can handle higher temperatures than normal belts. But even when using special belts, the warm material sometimes causes damage to the belt surface. The second cause for damage to the belt is fire. Bearings of the pulleys are sometimes not lubricated enough causing a bearing to catch fire.

Figure 9: Damage to the belt surface in longitude direction

Another cause for maintenance to a conveyor belt is damage to the moulded edge. Damage to the moulded edge is mostly caused by unaligned running of the belt. A belt running unaligned can be caused by a great number of factors. Some of the more common reasons are incorrect loading of the belt, stuck idler rolls, incorrect positioned idler rolls or pulleys and buckled support frame. This is only an example of some of the causes for the unaligned running of the belt. For fabric belts the moulded edge often serves only as a buffer before damage to the carcass is caused by the unaligned running. Maintenance to the moulded edge often consists of cutting of the damaged parts in trying to locate the cause of the unaligned running of the belt.

The last type of damage to the belt is damage to the splice. This type of damage is by far the most common type. Damage to the splice can occur because of a number of reasons. The first reason is operating the belt. When the belt is running the splice will be subjected to chances in the amount of tension present on the splice. Near the drive pulley the tension on the splice will be relative high while right behind the drive pulley the tension will be low. The splice is also subjected to internal tension while the splice moves around a pulley. During this process the inside of the belt is compressed while the outside is stretched. To minimize the effect of this internal tension, pulleys have a minimum diameter depending on the belt type. Even so, during the lifetime of a splice the splice is gradually weakened because of these tensions. The second reason is tearing of a fabric layer inside the splice. Inside a splice the tension on the fabric has to be transferred trough a lower number of fabric layers then in the rest of the belt. Because of this the tension on each layer is higher than in the rest of the belt. This tension is the highest directly at a step so the tear in this layer will often form there. Another reason for a tear at a step location is damage to the fabric layer during the splice creation. During the creation of the splice, the protective cover and depending on the step number, some fabric layers have to be cut trough. This cutting is performed manually and if the cut is a bit too deep, the next fabric layer is damaged. If a tear in a fabric layer occurs it is often at the weakened location. In Figure 10 an example is shown of a splice that requires maintenance.

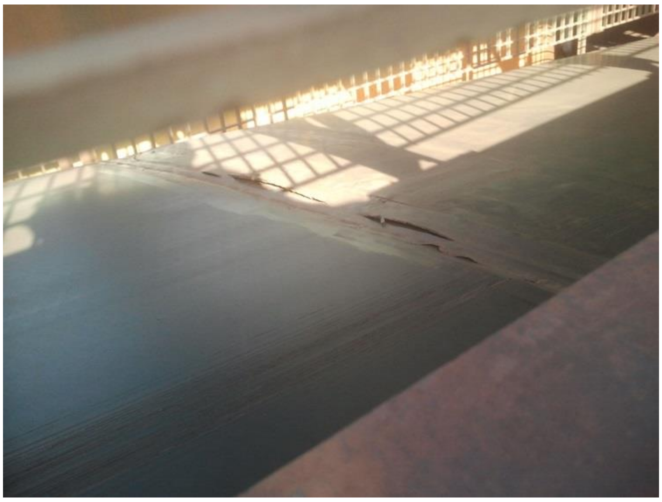


Figure 10: Example of a damaged splice

Another cause of maintenance of the belt is an air bubble inside the belt. This air bubble can be introduced during the production of the belt, during maintenance or by damage to the belt. The location of this air bubble is often between the carcass and the protective cover. When this air bubble passes a pulley, the bubble is pushed back. In time the bubble can form a tunnel through the belt where the carcass and protective cover are no longer connected to each other. A Dutch term that perfectly describes this phenomenon is “mollengang” (mole tunnel). The air pocket inside the belt often escapes at the splice. The final cause of damage to the splice is caused by overloading of the splice. This is either because of using the incorrect belt type, starting or stopping of the belt or incorrect operating of the belt. An example of incorrect operating of the belt is starting the belt if the transfer point is filled with material. The correct way is removing this material by hand using a shovel. Starting the belt a couple of times till the overheat protection of the drive kicks in is a much easier method. The splice in this case is put under much more tension then the belt was designed for. With the main sources for maintenance actions presented, the first sub question is answered.

2.6 Maintenance approaches

Every object and machine that requires maintenance like a conveyor belt, can be maintained following a number of different approaches. According to Smith, maintenance can be approached from a number of different directions [14]. The first approach is corrective maintenance which is the most basic one. When using a corrective maintenance approach, you wait till a machine breaks down; you then replace the broken part and wait till the next time a part breaks. Using this approach on a belt conveyor leads to very low reliability and possibly extra wear from broken parts.

The second approach is based on decision making. You look at every component of for example a car and decide how important for functioning they are. A spare wheel in the Netherlands is not extremely important for the functioning of the car. Good road services and a high density of garages have reduced the need for the spare wheel. The result is that having a spare wheel is nice but you do not have to replace it often to keep it in prime condition.

Preventive maintenance is the third approach. When using preventive maintenance you keep track of how long or often a certain part is used. Based on experience or factory specifications you know how long that part is likely going to last. Before the end of its lifetime you replace the part with a new one. You thus replace the part before it breaks down. When using this approach a good balance has to be made between the replace time and the required reliability. The closer to the expected breakdown point a part is replaced, the higher the change it breaks. Replacing a part to early, on the other hand, will lead to extra cost since you use more parts over the lifetime of the machine and have extra labor costs. There basically two methods to measure the moment when preventive maintenance is required. The first method is time; after a certain period maintenance is performed. This method is mostly useful for parts that always operate for the same period and conditions. The second method is by measuring the usage of the part. After a part has been in operations for a certain time period or traveled a predetermined distance, preventive maintenance has to be performed.

Another approach is condition based maintenance. Condition-based maintenance (CBM) is a maintenance program that recommends maintenance decisions based on the information collected through condition monitoring [15]. For idler rollers for example you can measure the temperature or the sound produced by the bearings. When large differences between earlier measurements are detected you know that they are at the end of their lifetime. It is recommended to replace the part at this time to prevent failure. The advantage of this approach over preventive maintenance is that, depending on the measurement interval, the replace point is much closer to breakdown point. One has to take the extra cost involved with collecting and processing the measurements into account. The interval between the measurements have to be short enough too accurate determine the end of the lifetime of a part. But also long enough to keep the cost involved with the measurements in check. Ideally you want real time measurement of the different components by sensors. The data collected should be analyzed by a computer who determines when maintenance or replacement is needed.

A fived approach that is certainly valid for BCS that are nearly continually in use is random maintenance [16]. Maintenance at BCS can often only take place on specific times, for example when no bulk carrier is being unloaded or the plant the BCS supplies is closed for maintenance. The maintenance to a BCS cannot be performed at the optimal time but when the opportunity arises. If an opportunity approaches, an inspection can be carried out to see what parts are close to breaking down so they can be replaced. Sometimes parts are replaced to early because there might be no possibility to replace them on a later time before they expected to break down.

When looking at the five described maintenance approaches above, you notice that the current maintenance approach performed at Tata is a combination of two. Both corrective and random maintenance are currently preformed, depending on the operation conditions of the belt. How this works in practice will now be discussed.

2.7 The entire maintenance process of a conveyor belt

The general process for maintaining a conveyor belt will now be presented. The first step in this process is the inspection of a belt. The data collected by the inspections has to be processed to determine the state of the belt. Once sufficient damage has been detected to a belt, a maintenance action has to be planned. Finally the maintenance is carried out. Only maintenance to fabric conveyor belts will be discussed here.

2.7.1 Inspection of a conveyor belt

Inspections to a conveyor belt can in general be split in three types. The first type is the daily inspection of the entire BCS. This inspection is used to detected large, easily detectable problems to the BCS and is not specifying targeting the belt. Large defects also get often noticed by people working near the belt. An example of damage to a belt that is easily spotted is show in Figure 11.

Figure 11: Easily detectible damage to a splice

The second type of inspections to conveyor belts are performed by an inspector only looking at the belt. This inspector is often specialized in inspecting conveyor belts. The frequency of these inspections is much lower than the general inspections. The interval of these inspections can be once every four weeks.
The inspections depended heavily on the surroundings according to an inspector himself; the inspections are a bit of a “lottery”. The belts he needs to inspect are often in use so the only location he can inspect the entire belt is at the return pulley. Most of the time this is located very close to the transfer point for the material so you only have a fraction of time to insect the splice and detect damage on the belt. Belts also can be standing still, only the part in view can be inspected at that time. Another problem is that during the design of the conveyor belts, inspection and maintenance have sometimes not been taken into account. Belts also can be surrounded by machinery or other obstacles making inspection hard to impossible.

The inspection of the conveyor belt can be split in two parts. The first part of the inspection is determining the expected lifetime of the belt. This can often be determent by looking at the remaining belt thickness. This is not true for belts that transport warm material because of the influence of the heat on the rubber, but this is outside the scope of this research. A belt has to be replaced once the carcass is no longer protected by rubber. The fabric in the carcass will wear fast once in contact with the material. This will cause the strength and reliability of the belt to decrease. Ideally you want to replace a belt as close to the end of its lifetime as possible to reduce cost. Because a new belt has to be ordered and the replace action has to be planed, you want to know the replace date ahead of time. Currently the remaining lifetime of a belt is determined by looking if the carcass is visible or if color difference can be detected. A lighter color of the rubber reveals that the carcass is very close below the top layer. The final indication of a low belt thickness is a so called “kattenrug”. A “kattenrug” is sometimes formed near the pulley when the middle part of the belt is much thinner than the outer parts. The middle part of the belt in this case, is too weak to push the side parts from the belt outwards. This will make the middle part bulge between the pulley and the first idler rolls. A measurement device to detect the remaining thickness of the belt has been successfully tested during the creation of this thesis. The usage of this device for inspections is currently being implemented.

The second attention point during inspections is to detect damage to both the belt and the splices. This inspection is carried out by visually looking if damage is visible. If damage is detected, the severity has to be determined. This gives an indication of the available time left before maintenance is needed. If the damage to the belt or splice is extensive, instant maintenance can be necessary. Light damage can be maintained during a scheduled standstill. Damage to the splice inside the belt, can sometimes be visible through color differences of the rubber. If the carcass is damaged and stretched out, lighter rubber is sometimes visible on the surface. This is caused by stretching of the rubber. Most of the inspections are carried out on a moving belt so determining the exact extend of the damage can be a challenge. The speed of a belt can be more than 4 m/s.

After the inspector walks his rounds past the different belts, he makes a report of the attention points he has noticed. This can be of a belt that is nearing the end of its lifetime or damage to a belt or splice. In Figure 12 an example of a photo that is sent alongside the report is shown. This report is then presented to the people responsible for determining of maintenance is necessary or not.

Figure 12 Example of a picture sent together with a report

The third type of inspections to the belt is continues inspections, either by cameras or sensors. A better term for continues inspections is monitoring of the belt. A camera installed at a belt can continues look at the surface of the belt to detect defects. Another method to detect damage to the belt is the use of conductive monitoring. For this method a metal wire has to be inserted in the fabric. If this wire is broken because of damage to the belt, this is detected by the conductive sensors. This method cannot be used for the splices of a belt while these often require the most attention during inspections. While manual inspections often provide an output that is directly useful for determining if maintenance is required. Cameras and sensors provide raw data that first has to be processed.

2.7.2 Processing inspection data

Once an inspection has been carried out, either by a person or a sensor or camera, the data collected has to be processed. Inspections performed by a person often provide data that can be used directly. The data provided is often a report where the type of damage to the belt is described sometimes accompanied by photo's detailing the problem. Depending on the knowledge and skill of the inspector, a recommendation for maintenance can also be present. Based on the information the inspector provides a maintenance decision has to be made. Data provided by a camera and sensors is raw data. Before this data can be used to make a decision this data first has to be processed in usable data. Data from a sensor can for example be compared with historical data. If the data provided by a sensor shows a sharp deviation of the historical data, a problem with the belt can be present. Data provided by a camera can be hard to process. Either someone has to view the output of the camera manually or image recognition software has to be used. Once the data has been processed, it can be used to determine if maintenance to the belt is required. Determining if and when the maintenance is carried out is determined by the owners of the belt based on the information they have available and the future planning for the belt.

2.7.3 Planning of the maintenance action

Once the decision has been made that maintenance is required to a belt, this action has to be planned. If the maintenance action either requires an entire new belt or only part of the belt is being replaced the first action is to check if this belt is available. Because of the delivery time of a new belt, the replacement belt has to be ordered well ahead of the maintenance action. If no new belt is available either the maintenance has to be delayed or an alternative belt has to be used. Once this requirement has been fulfilled the maintenance action can be planned.

In general the operating conditions for BCS operating in plants can be described as two types. It should be noted that it is assumed that the BCS are located in a plant that is operating 24 hours a day. The first type is a BCS that operates under continues operating conditions. This type of belt conveyor is often used to supply or is operating within a plant. Some of the most crucial belt conveyors can often only be maintained if the entire plant shuts down for maintenance. Belts of this type often can only be maintained without disturbing the normal operations when an opportunity arises. A maintenance shutdown of a plant is often known long before this happens. The main challenge for the planning during this shutdown is often the sheer number of belts that require maintenance.

The second type of BCS is often located near the quay side. When a bulk carrier docks at the quay, it has to be emptied as soon as possible. A ship lying in port is not earning any money and companies that are responsible for loading or unloading the bulk carrier are often finned if it takes too long. Delays in the unloading process can be extremely expensive because of these fines. During the unloading process all BCS involved should be operating at full capacity. Maintenance to the belts during this time should be avoided if possible. Once no bulk carrier is present at the quay, the belt can be maintained. The main challenge for planning of these maintenance actions is that the exact data of the arrival of the bulk carriers is often only known a limited time ahead. The arrival data is often influenced by a number of factors like the weather. Because of this, planning the maintenance a long time ahead is often not possible. At Tata Steel for example the length of the planning is because of this factor limited to a week.

Taking the above circumstances into account the maintenance action can be planned. In this planning both the capacity of the people carrying out the maintenance as the availability of the belt has to be taken into account. During a maintenance standstill of a plant for example, a lot of belts are available for maintenance. The limiting factor during this time is the capacity of the people carrying out the maintenance. If there is both a ship at the quay side and all plants are in full operation, no belts can be available for maintenance while there is sufficient capacity available for carrying out maintenance actions. The result of these limitations is that the planning of the maintenance is often sub-optimal.

2.7.4 Performing the maintenance

Once the maintenance is planned, it can be carried out by the maintenance crew. For conveyor belts the maintenance actions can be split in three different types. The first is the replacement of either the entire belt or part of the conveyor belt. Once a belt is worn out or damaged beyond repair, the belt has to be replaced. The second type is maintenance to the splice. This maintenance can be that either part of or the entire splice is loose. Another common maintenance action to the splice is the repair or replacement of the sticker on the inside of the belt who protects the splice against the scrapper. The last type of maintenance is to the rest of the belt. Damage to the rest of the belt can be caused by a foreign object damaging the belt or for example the scrapper. Compared to the first two types of maintenance actions, damage to the rest of the belts is at Tata relative uncommon. The cause of this damage is also a lot more random and situational then maintenance to the splices. Because of this, the main focus will be on maintenance concerning the splices.

For explaining the maintenance process, the replacement of a belt is discussed in more detail. Before the maintenance can take place, the properties of the area surrounding the BCS have to be taken into account. If the belt is elevated or not easily accessible for another reason, a scaffold has to be erected. If rain is expected or the weather conditions are insufficient for the creation of a splice in the outside, a tent has to be constructed to protect the splice. For the replacement of the belt itself, a crane is sometimes required because of the weight of the belt and the limited accessibility of the BCS. In Figure 13 a crane is used to remove the old conveyor belt.

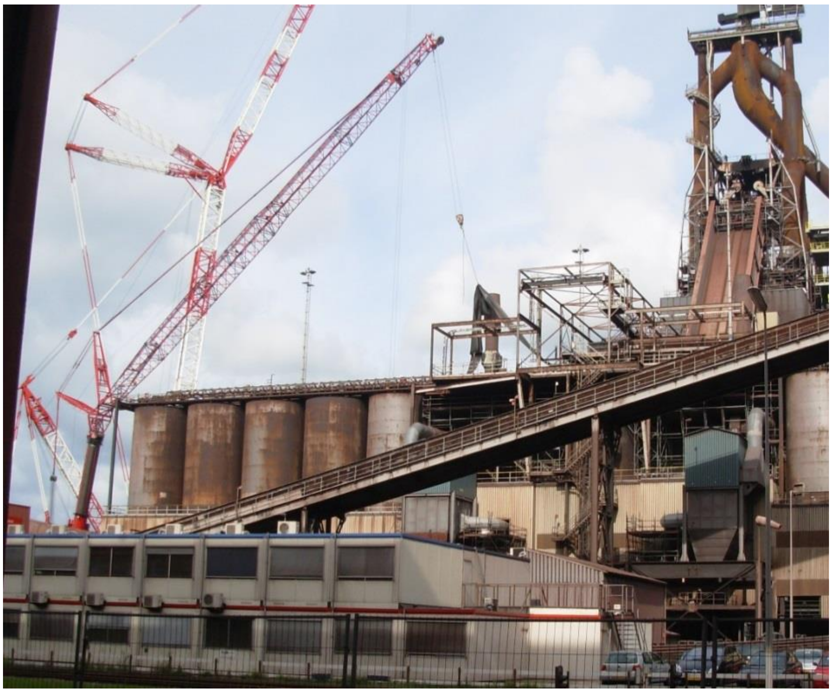


Figure 13: A crane is required to replace the belt

The replacement of the old belt with the new belt is performed using the following procedure. First the old endless belt is cut and the new belt is attached to one of the sides of the old belt. The old belt with the new belt is then pulled through the BCS. Because the old and new belt are attached to each other, no mistakes about the path the belt take trough he idlers and pulleys can be made. Once the new belt completely replaces the old belt, the new belt can be made endless. This is done by making a splice utilizing the two ends of the belt. Depending on the length of the BCS, the belt can consist of multiple parts. For the transportation from the factory to the customer a size and weight limit is present. If a belt is too long, it will surpass this limitation meaning it has to be transported in two parts. The belt can also get so large and heavy that it becomes unwieldy.

The creation of a splice for a fabric conveyor belt is performed using the following process. From both ends of the belt the protective rubber layer is removed for the splice length. This means that the fabric inside the carcass of the belt is now visible. In Figure 14 the rubber protective cover of the conveyor belt is removed to repair the splice.

Figure 14: Removing the protective rubber cover

Once the protective cover has been removed, the carcass can be prepared for the splice creation. Depending on the number of fabric layers present in the belt, a number of so called steps are created. These steps have a fixed length depending on the properties off the belt. In Figure 15 a graphical representation of the two sides of the endless belt with a splice in the middle is presented. The belt in this figure has a carcass consisting of three layers so for the creation of the splice, two steps had to be created. For a belt that only rotates in a single direction the way the splice is created is of great importance. The direction of the splice has to be in such a way that the scrapper has to lowest chance to damage the splice.

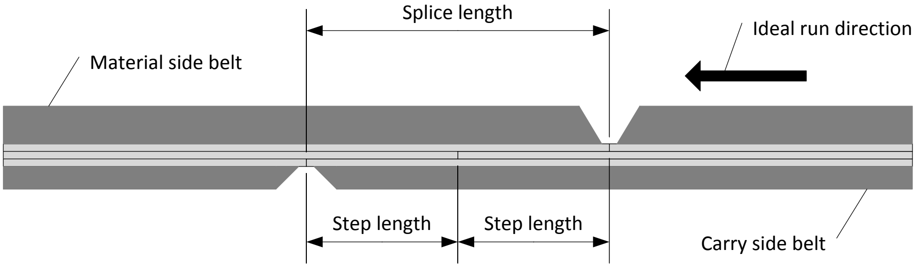


Figure 15: A conveyor belt with 3 plies: two steps

After the belt has been prepared for the splice creation, cement is spread over both surfaces that will be attached to each other. In Figure 16 the cement is been spread over the prepared area. This cement first has to dry for a bit, the dry time is currently purely based on experience and circumstance. The time between the first coat and the second one often depends on how long the lunch or coffee break takes. After the second coat of cement has been spread over the splice area, the two sides of the belt are attached to each other. When the two parts of the belt are attached, it is crucial that they are more or less in line. If the two parts of the belt are unaligned problems could arise during the running of the belt. After the splice has been created a certain dry time has to be taken into account before the belt can be used for normal operations.

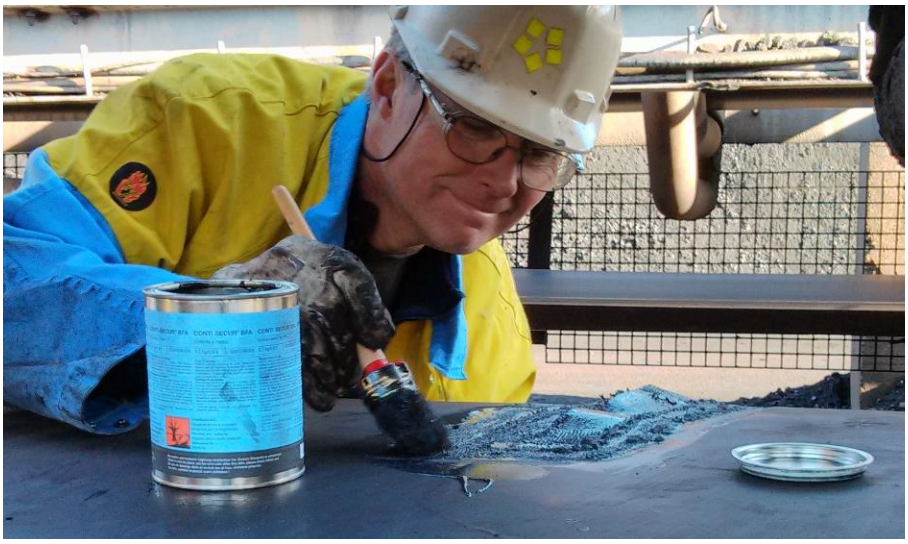


Figure 16: Cementing the fabric before a repair

The process described was the creation of a so called cold splice. This is one of the two types of splices created by HTD for fabric belts. The other type is a hot splice. A hot splice is based on vulcanization. The first part of process of making a splice is the same only this time no cement is used. Instead of cement, rubber is inserted between the two fabric layers that have to be attached to each other. Under the influence of heat and pressure, the rubber is molted and the two parts are attached to each other. The two parts of the belts are put between two heated plates. These plates are also used to press the two part of the belt with high force against each other. The time required for this process depends on the properties of the belt. The thicker the belt, the longer the belt has to be heated. In Figure 17 the creation of a hot splice is shown. After the splice creation, the belt has to cool down for a certain period of time before it can be used in normal operations.


Figure 17: Hot splice creation

One of the main differences between a cold and a hot splice is that for a hot splice more equipment and room is required than for a cold splice. Because of the limited space available at some locations only cold splices can be performed on those belts. The main rule to decide if a cold or hot splice is used is: normally always a cold splice is created unless material warmer than 80 degrees is transported or the customer specifically wants a hot splice.
One of the main challenges during the creation of the splice is cutting in the belt exactly to each fabric layer. The cutting is purely done on feeling, from the resistance of the knife the workers know in what part of the belt they are cutting. Tools that fix the cutting depth can only be used on a brand new belt. For a new belt you know the thickness of the protective cover and each layer of the carcass. If a belt has been used a wear pattern is introduced in the cover. A typical pattern is presented in Figure 18. In this case there are three worn out areas in the belt. The large middle one is caused by the material transported by the belt. The two smaller ones are created through the friction with the dust seals. A complex tool that takes the wear of the belt into account would be

required to fix the cutting depth on a used belt. The tool should also be small enough to use in tight areas, resistant against dust and sturdy enough to withstand heavy operating conditions.

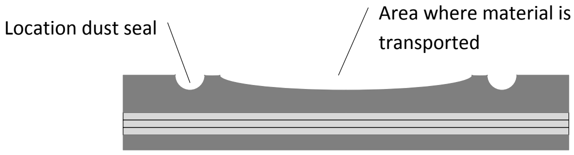


Figure 18: Typical profile of a used conveyor belt

2.8 Problems involved with the current maintenance process

The original question that led to this research was the following. How can HTD improve their customer satisfaction? Since HTD is a department of Tata Steel, their customers are only the earlier discussed 7 internal departments.

Customer satisfaction is a wide concept; it can be the cost of the provided service, the quality and so forth. For HTD one of the most important aspects of customer satisfaction is the moment they perform the maintenance. All their customers have their own production planning that allows only limited access to the conveyor belts for maintenance. For the customers the optimal maintenance moments are at such a time that no or very little disturbances to their daily operations are created. For HTD the main challenge is to plan the available maintenance capacity in such a way that the maintenance they perform is at the optimal moment for their customers while also taking their own maintenance capacity into account. Unfortunately the current method of performing maintenance to the conveyor belt combined with emergency repairs leads to a short term planning with lots of disturbances. This has as effect that maintenance actions are sometimes performed on suboptimal times. Other times the maintenance has to be postponed because of no available capacity leading to a lower system reliability of that particular BCS. Furthermore, because of the limited planning time available for maintenance actions; the amount of maintenance required fluctuates heavily over time.

To improve the customer satisfaction a number of options are available. One can look at the quality of the work performed; improving the quality could reduce the number of emergency maintenance actions. Another method is optimizing the available maintenance capacity. By analyze the maintenance requirement over time the optimum maintenance capacity for the department performing the maintenance can be calculated. This can be accomplished by taking the cost and befits of the different maintenance capacities into account. Both discussed methods are not targeting the source of the problem but try to minimize the effect. The source of the problem is the short interval available for planning combined with emergency maintenance actions that are caused by corrective maintenance. In section 2.6 a number of maintenance approaches have been discussed. One of the maintenance approaches discussed is preventive maintenance; this approach can improve both the flexibility in the planning as the system reliability.

The main challenge when performing preventive maintenance is to determine the interval for the maintenance. Too determine the optimum maintenance interval for a conveyor belt; the different influences on this maintenance interval have to be taken into account. A method for incorporating these influences in the maintenance interval is by looking at the state of the conveyor belt. The resulting main research question and sub questions have already been presented in chapter 1.3.

3. Improvements to the maintenance of conveyor belts

In this chapter, first general improvements to the maintenance process for conveyor belts are presented. Then a number of types of models are presented to be used for making the model for answering the main research question. From these models, the best model for answering the problem is selected; this model is then explained in more detail. Finally an example of the usage of this model is given.

3.1 Possible improvements

When looking at the current process of performing maintenance a number of improvements are possible. These improvements are based on the situation as at Tata Steel but can easily be used at other companies maintaining equipment under the same conditions. The process of maintenance where for these improvements are proposed has been discussed in the previous chapter.

3.1.1 Inspections for BCS

The current practice for inspections for conveyor belts is that an inspector walks past the belt and visually checks for defects. As state before, the current quality of the inspections heavily depends on the current operation conditions of the belt. The most important part of the belt for inspections is the splice. If the belt is in operation these splice move often so fast that the inspector only has a fraction of time to inspect the splice. If the belt is standing still, the splice is located at a random location so it is based on luck if the splice can be inspected or not. An improvement of this process could be made by inserting a RFID or other traceable object in the spice. This can then be used in combination with a sensor to stop the belt at a designated location. This way the splice would stop at a visible location. For a belt that is moving during inspections a camera could be used. By playing the video of the belt, screen by screen, a detailed visual inspection of the splice can be made. Another option is monitoring the conveyor belt continuously. This potentially saves labor cost caused by the manual inspections and could increase the reliability of the system. Yusong Pang describes in his doctoral thesis a method to automate the monitoring of a BCS [17]. To use the collected data in a system with a lot of BCS the method proposed by Stefaniak, et al. can be used [18].

Implementation of a complete monitoring process for each BCS is for existing systems expensive. A easier option is the usage of measuring devices during the manual inspections. Currently the entire inspection is performed visually; introducing measurements could increase the quality of these inspections. One of these measurements that could be performed is the remaining belt thickness. By measuring the remaining thickness of the protective layer on the belt a better estimation of the remaining lifetime of the belt can be made. Melinda Hodkiewicz, et al. discusses methods to determine the expected life time of conveyor belts other than looking at historical data [19]. One disadvantage of using a measurements device is safety. For a visual inspection no contact with the belt or other moving parts of the BCS have to be made. Before measurements to the belt can be made, the BCS first has to be secured so it cannot suddenly start moving. This can require an extensive protocol which the inspector himself is not allowed to perform.

3.1.2 Performing the maintenance action

One of the current problems with the maintenance of conveyor belts is emergency maintenance actions. If the company is operating full time and the maintenance department is only operating using a single shift schedule, maintenance outside of operating hours of the maintenance department sometimes have to be performed. Workers are limited in how much time they are allowed to work. In the Netherlands for example, a lot of restrictions are present to prevent a worker from working too long. If a worker has to perform maintenance during the night, he has to be given leave during the next day. Maintenance planned for this worker during the day has to be shifted to another moment. There are three methods to mitigate the effects of these emergency maintenance actions. The first way is to improve the quality of the inspections. Increasing the quality of the inspections will lower the amount of undetected defects. Because more defects are detected before they can lead to severe damage to the belt, less emergency and more planned maintenance actions can be performed.

Another cause for emergency maintenance actions outside the normal operation hours of the maintenance department are emergency maintenance actions decided by the operators of the BCS's. Not every defect requires emergency maintenance; basic guidelines for under what conditions emergency maintenance should be performed and when not should be present. The personnel responsible for deciding if the emergency maintenance is required often do not know the full effect on the maintenance department of their decision. For them it is easiest if the belt is repaired in the middle of the night so they do not have to take measures to operate without using that particular belt. The final method to decrease the amount of emergency maintenance is the usage of another maintenance strategy, this has already been discussed.

If the emergency maintenance is really needed, an alternative way for making splices could be used. Currently the only options for connecting two parts of a belt are either a hot or cold splice. For maintenances that has to be carried out quickly or is performed outside normal operating hours, alternatives could be used. An example of such an alternative is the Super-Screw® [20]. This is a flexible rubber splice that can be screwed on a belt. The main advantage of this method is that it requires a lot less specific knowledge than making a hot or cold splice. There is also no dry time, so it is a lot quicker. When this method is performed during the night, no specialized workers are required. If skilled workers are needed, this number can be limited to one or two workers instead of an entire crew. The main disadvantage is that you lose some length of the belt. For using the Super-Screw®, the entire thickness of the belt is required. You have to cut of the old splice to get sufficient thickness.

The creation of the splices during normal maintenance actions also deserves some attention. Often these splices are created based on the experience of the crew. The time for the first cementing layer of the splice to dry for example is based on experience and time required for the coffee break and not facts. One must mention that the dry time provided by the glue manufacture is in general on the safe side. A dry time could be determined using a number of factors like the temperature of the surroundings.

The impact of the environment on the splices is currently largely unknown. If rain is expected or it is already raining, a tent is build. Measures against dust are currently not preformed. The impact of dust on the splice can be reasoned as negative but how much effect dust really has on a splice is currently largely unknown. Some splices are created under very dusty conditions, performing more research to the effect of this dust on the splice is recommended.

3.1.3 Planning of the maintenance

In chapter 2 the current method for planning is discussed. The short time span of the planning combined with disturbances caused by emergency maintenance creates a highly fluctuating work load for the maintenance crew. Increasing the time span of the planning is currently not feasible, the time frame is determined by the arrival of bulk carriers who have a large impact on the schedule. One could mitigating this by making a schedule with a longer time frame and reserve spot for maintenance to conveyor belts once there are no bulk carriers present. This will lead to a complex schedule where in the end, the real schedule will still be week based. A better approach is reducing the amount of emergency maintenance with the use of the above described methods. The flexibility of the maintenance performed should also be increased. Currently maintenance is only performed once damage to the belt has been detected, leaving a short timeframe. By following a different maintenance strategy the maintenance can be performed before damage to the belt is reaching dangerous levels. Because the maintenance is performed preventive, there is more space in the planning to shift the maintenance actions around a bit. This leads to a planning with a more constant work load and a higher reliability of the conveyor belts present.

Part of the planning process is also making the decision to replace a conveyor belt. Some important belts are replaced based on a preventive approach. The belt is replaced before the end of its lifetime since the belt is rarely available for maintenance. Unfortunately the quality of the predicted lifetime is often low and not based on the state of the BCS. As a result, some belts need an emergency replacement since they are scheduled to late. Others are replaced far too soon. The prediction is currently purely based on the previous lifetimes of the belts located at that BCS. The result is that when you are replacing a conveyor belt too soon, you keep doing it because the historical data says so. Another problem is that the other parts that have influence on the conveyor belt are completely ignored. This can lead to nasty surprises when a belt has to be replaced far sooner than expected. This process can be improved by taking the information from the inspections into account before determining the replacement date.

3.1.4 Maintenance strategy

As discussed in chapter 2 the current common practice for maintain a conveyor belt is a combination of both corrective as random maintenance, depending on the operating conditions of the BCS. In the previous chapter it is also reasoned that implementing a preventive maintenance strategy is the best methods to improve the customer satisfaction in this case. The reason the current maintenance strategy is based on corrective maintenance is very simple. Waiting for something to break down before you repair it seems an extremely logical approach. Why would you repair something will it is still doing its job. To indicate the current thinking process at Tata the following example is provided. The replacement of idler rolls is currently often base on an idler roll being broken. Broken consist of: impossible to rotate or the roll is broken into halve. The result is that if you are a bit too late, catastrophic damage can be caused to the conveyor belt. In Figure 19 an example is given from an idler roll that was replaced too late. The second reason to replace an idler roll is the sound production. Worn out idler rolls can produce noise which can surpass the allowed sound levels by regulations. Another approach would be to replace an idler roll once the bearings are worn out. Once the bearings of the idler roll are worn out, the friction of the idler rolls increases leading to a higher energy consumption of the BCS. The wear and chance of damage occurring to the belt will also increase once the bearings are worn. One of the problems is detecting when a bearing is worn out. The number of idler rolls present is often large so intensive inspection is not feasible. Some methods like ultrasonic or temperature measurements are often hard to perform. A better option is to replace the idler roll after a certain number of rotations. The manufacture often presents a number of rotations the bearings are likely to last. Using the bearings longer increases the chance of failure. This last option is preventive maintenance; replace the idler rolls before they fail.

Figure 19: Example of idler rolls that where replaced to late

For idle rolls a manufacture presents a number of rotations the bearings are likely to last. For conveyor belts this type of information is not supplied by the belt manufacturer. The maintenance interval for a conveyor belt depends on a large number of factors. For a belt manufacturer is nearly impossible to provide an accurate maintenance interval because of the high influence of these factors. In chapter 2.8 the state of a conveyor belt was introduced to determine the optimum maintenance interval. Performing the preventive maintenance too earlier leads to a larger number of maintenance actions over time and an increase of cost. Performing the maintenance to late and corrective maintenance has already taken place. Determining the optimum maintenance interval is of high importance when performing preventive maintenance. To determine the state of the conveyor belt, a number of options are available. One could simply look at historical data. The average maintenance interval for a new belt was 150 days, so the optimum interval is just before these 150 days. This method is inaccurate since only a very limited amount of information is taken into account when determining the interval. Another method is making a simulation of the conveyor belt and use this to determine the optimum interval. The basic properties and operating conditions of the different BCSs can vary widely; making a simulation that can take all these different factors into account will be very complicated. After this simulation is been made, it is questionable how useful it is in practice. The process of determining the state of the belt should accomplished in a reasonable amount of time to be useful. Tweaking a complex simulation to determine the state of the belt for each case is not practical. The final method is making a model. The model should take the different factors influencing the maintenance interval into account and use those influences to determine the state of the conveyor belt. This state can then be used to optimize the maintenance interval for preventive maintenance.

3.2 Model selection

Before a model can be made first a method for making this model has to be decided. The first step in determining the correct model for the problem is listing the requirements for the model.

3.2.1 Model requirements

The goal of the model is to determine the state of the belt to determine to optimum preventive maintenance interval. Because of the complex type of operation that is being modeled, providing an interval without a spread is unrealistic. So the model has to take the influence of the different variables into account and use that to determine the state of the belt and the spread for the maintenance interval of a conveyor belt.

The input variables for the model will differ in type. Some input variables are constants like the length of a belt. This is a fixed value for every particular belt conveyor. Other variables can differ between scenarios; weather for example can differ greatly during different maintenance actions. Finally there are variable that describe a group of items. For bulk material one could say, the BCS is transporting iron ore. The ore itself can differ significant from where its origin is. Even ore from the same origin is not a uniform material; every particle has its own size and shape. The model potentially has to manage a variable like iron ore on such a level that it is relevant for the model. A belt conveyor has a capacity of tons per hour, modeling every individual ore particle is far from realistic. The model has to be able to utilize all the different types of variable to determine the output.

The last requirement of the model is that the model is usable in practice. At companies there is often a large number of BCS present. The model should be designed in such a way that it can be used for more than only the belt conveyors discussed in this thesis. This requires that the input variables are in such a way that they can be entered in a timely fashion by someone that does not require extensive knowledge in the working of the model.
Looking at the above described requirements for the model, the three models discussed below have been selected as possible methods.

3.2.2 Bayesian Belief Networks

The first type of model discussed is the BBN. The BBN is one of the methods for modeling systems that includes causal relationships among variables. A BBN is an acyclic directed graph that represents a factorization of the joint probability over a set of random variables. The graphical structure of the network is the qualitative part of a BBN and embodies a set of nodes representing the random variables and a set or arrows representing direct dependencies between connected variables. Absence of an arrow between variables indicates that these variables are conditionally independent. The parents of a variable are the variables connected with an arrow with its direction going into this variable. The joint probability is the quantitative part of a BBN and embodies the conditional probability defined with each variable. This probability characterizes the influence of the valuated parents on the probabilistic values of the variable itself. A probability is the prior probability when a variable has no parents. The uncertainties in the parent nodes, represented by marginal probability, produce uncertainties in the child nodes that are based on conditional probabilities and physical cause-and-effect relationship. The directed graphs of BBN provides representation of the set of variables that are related to each other in providing knowledge about the state of the system.

The foundation of the BBN is the Bayes theorem which can be described as for any events E and H,

$$P(H|E) = \frac{P(E|H) \times P(H)}{P(E)} \tag{3-1}$$

This formula denotes the conditional probability that H occurs, given that E is known to occur. In the conveyor belt inspection process, if H refers to a inspected variable and E represents the new observed data, then P(H) is the prior probability that H occurs; P(H | E) is the posterior probability of H occurs, given E ; and P(E | H) is the conditional probability that E occurs, given H . This formula enables us to use the prior knowledge of an event to calculate the probability of the other event(s). [21]

The Bayesian Theory is actively used on multiple fields in the industry. An example of the usage of the Bayesian Theory is to estimate the failure probabilities of safety systems and end-states in chemical plants [22]. The Bayesian Theory can also be used to process the data collected through continues monitoring of a device for condition based maintenance [23].

3.2.3 Exploratory Factor analysis

The second type of model discussed is EFA. EFA originated from psychometrics and can also be used for applied science that handles large quantities of data [24]. Factor analysis work with the principle that a number of observed variables can be used to determine the variation in a smaller number of unobserved variables. The observed variables are referred to as surface variables; the unobserved variables are referred to as factors or latent variables. A set of surface variables are referred to as a battery. In a model multiple groups of variables can be present, in other words, multiple batteries of variables can be used. Between the factors two types can be distinguished, common factors that influence more than one surface variable and specific factors who only influence a single surface variable. The third influence on the surface variables is the errors of measurement. These errors originate from observing each service attribute. The error of measurement are represented in the factor theory as additional factors, higher reliability of measurements of the surface variables will lower these factors. In Figure 20 a basic schema of common factor theory is shown.

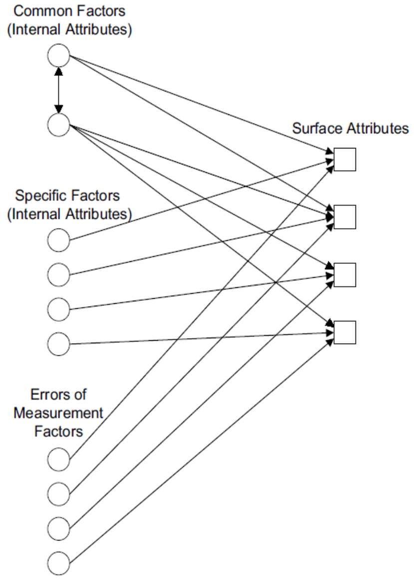


Figure 20: Basic schema for common factor theory

In the figure above a surface attribute could for example be lifetime of a conveyor belt and the lifetime of the gearbox of the belt conveyor. A common factor in this case would be the amount of material transported per hour and the belt speed. The belt speed and the capacity of the conveyor belt have influence on each other. That is why these two factors are a common factor. A specific factor could be the height of the takeover point. This factor is completely separate of the other factors. The errors of measurements factor could be the exact amount of material transported per time unit. EFA can provide a good basis to use confirmatory factor analysis. Confirmatory factor analysis uses the same principle but with more constrains. The goal of confirmatory factor analysis is to check of the data fits a hypothesized measurement model.

3.2.4 Fault Tree Analysis

A FTA is a top down, deductive failure analysis where an unwanted state of a system is analysed. Fault trees are mainly used in reliability engineering and safety engineering to deduct how a particular system can fail. This in term can be used to reduce or remove the cause for the failure to happen. It can also be used to determine the rate of events to happen. An example of a fault tree is given in Figure 21.

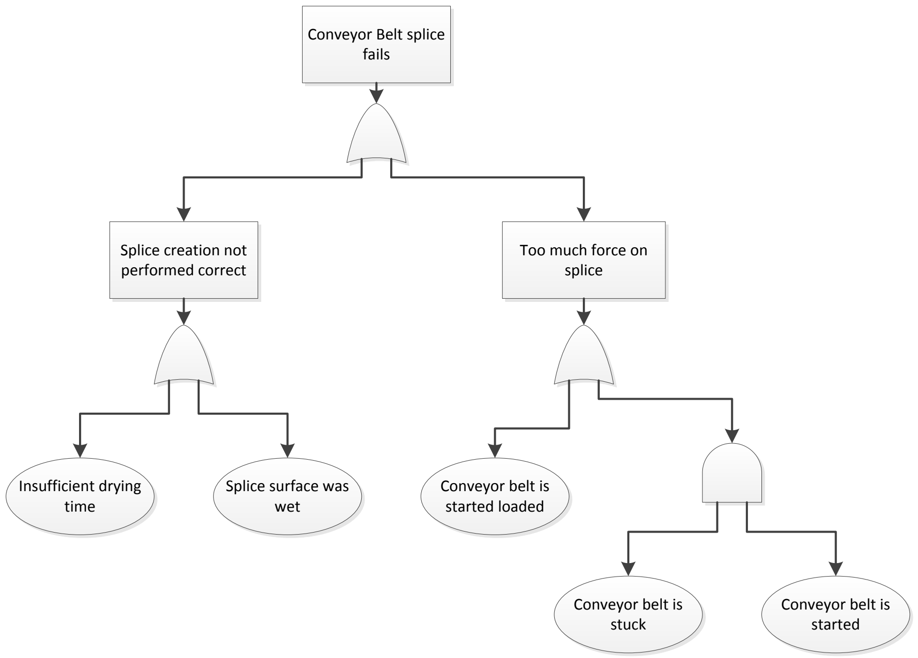


Figure 21: Fault tree for the failure of a splice in a belt conveyor

In the fault tree above both the OR and AND statement is being used. In Figure 21 the splice of a belt conveyor can fail because of two reasons, either the splice creation is not performed correctly or there is too much force on the splice. The splice creation not being correct can be caused by either insufficient drying time or the splice surface was wet during creation. So far only OR statements have been used. Too much force on splice is caused by either the conveyor belt is started loaded or both the conveyor belt is stuck and is started. The conveyor belt is stuck and the conveyor belt is started must both be true at the same time to have an effect on the too much force on splice. This is an example of a AND statement.

3.3 Model selection

To select the correct model, the three models stated above have to be compared to the requirements. To do this, the advantages and disadvantages of the models are mentioned first, after this some remarks about the fit towards the requirements are given. The first model discussed is the Bayesian Belief Network.

Bayesian Belief Network

The main advantage of BBN is the fact that it also works with not all information available. You can start modelling and update the model when more information is available. Once the model is made, so called “What-if” analysis are easy preformed. The main disadvantage of the BBN method is the quantification of the conditional probability tables. For a node with N parents, each having 2 states, the amount of entries is 2N. If a node has K possible states the conditional probability table has K4 entries. As you can see, the amount of entries can spin easy out of control once a lot of nodes with multiple states are involved.
According to P. Weber et al. [25] a trend is noticeable that BBN are recently more often represented in literature for dependability, risk analysis and maintenance areas. This trend is due to the benefits that Bayesian networks provide in contrast with other classical methods of dependability analysis such as Markov Chains, Fault Trees and Petri Nets.

BBN can manage variables with more than two states. With the use of fuzzy logic one can also implement harder to define variables like state of a mechanism in de model. The main challenge of this model will be to create all the conditional probability tables necessary to determine the outputs. The size of the conditional probability tables can be limited with the use of divorcing. Divorcing is a technique whereby some of the parents of a variable are removed or divorced from that variable by introducing a mediating variable and making it a child of the divorced parents and a parent of the original child.

Exploratory Factor Analysis

EFA mainly used as a tool to discover its factor structure. Once a factor structure has been determined, confirmatory factor analysis can be used. The main advantage of the EFA is that you do not have to know exactly what a variable represents. This is the reason this method is very often used in psychometrics. If you have a number of results from different behaviour test, the EFA helps to find correlations between different variables. Another use of factor analysis is to reduce the number of variables present.

Looking at properties of the variables used in the model compared to EFA analysis one could state that they are not a good fit. Both the variable and the correlations between the different variables of the BCS are known, so it is not necessary to make a model to discover them. Using the EFA to reduce the number of variables could be useful, but the variables are selected in such a way that they represent useful aspects of the BCS. Variable that describe the same part twice can be avoided and since the different variables are clear, accidental duplication of a variable can be neglected.

Fault Tree Analysis

Preformed correctly, FTA often identifies problems with a system other design and analytical methods may have overlooked [26]. FTA can be a great tool to analyse complex problems for inappropriate behaviour. The method can often lead to so called "Eureka" moments, "I did not know the system could do that". The cause of these "Eureka" moments is often the discovery of a common cross-link or single failure point that could fail two reluctant or seemly independent systems.

One of the largest pitfalls of FTA is how deep the analysis has to be performed. It is possible to go to subatomic levels with the analysis. When doing a FTA one must always keep in mind how deep the analysis should go. It is also very easy to create a FTA so big that working with it becomes extremely troublesome. While making the analysis one must also take all aspects of the interactions into account. So when making a FTA not only mechanical or electrical parts have to be included but both.

FTA can be very interesting to perform on the lifetime and maintenance frequency of BCS. The main problem concerning the method is the size of the model. Using FTA it is very easy to create a huge model with countless variables that are in some way connected. Defining a model of that size will be a large amount of work and once finished the question arises, is it useful. Some very interested conclusions might be drawn about the relationships between certain factors but the number of variables required might be too large to use in practice. The model is created to use on a large number of BCS. The amount of variables needed to define for the model has to be kept at such a level that the result is reliable, but the time required to use the model limited.

Multi criteria analysis

In the previous section the advantages and disadvantages of each of the three methods has been discussed. To make an educated decision on which of the three methods is most suitable to be used in this case a multi criteria analysis is being used. In this multi criteria analysis a number of factors that are important for the model will be listed. Each factor gets its own weight factor, depending on how important it is in the overall model. In Table 2 the weight factors and the scores of the three methods are shown.

Table 2: Multi criteria analysis for the three different methods

	Weight	BBN	EFA	FTA
Different inputs	5	5	4	1
Output	4	4	1	5
Not all inputs present	2	5	1	1
Easy usage	3	3	1	5
Fast usage	3	5	3	1
Total		**75**	**38**	**45**

The first criteria is how well the method can handle different inputs. The input of the model will not only consist of Booleans or integers but of different types of variables. A model that can only handle a single input type will severely limit the inputs for the model. Because the different types of inputs are crucial for the model, this criteria deserves the highest weight factor.

The criteria output indicates what type of output the model provides. The criteria does not only takes the output itself into account but also how easy it is to trace back the steps that leads to this output. A black box where you put some inputs in and get a output out can be very useful if you are only interested in that output. Getting more information on what leads to this particular output and what are the most interesting inputs to improve is much more interesting in this case. Since this model is going to be used for the determination of a maintenance interval, extra information on what leads to this interval is very useful. For this reason this criteria is valued as the second important. FTA receives the highest score here because of the easily understandable output. BBN also provides a output with a high volume of useful information. EFA provide an output that is not really relevant for this research, that why it receives a low value.

The criteria not all inputs present indicates if the model also works when not all inputs are supplied. The reason that not all inputs are supplied to the model is either that some are for the current question unknown or determining all the inputs takes too much time. For the model to operate under the above described conditions is more of a kind of feature. It is very useful to have but often not totally necessary for the model to operate. Because of this reason the weight factor for this criteria is the second lowest. BBN has methods to incorporate missing information in the model that is why it receives the maximum score.

Easy usage is a criteria that indicates how easy some can use the model without extensive knowledge about the working of the model. The model should clearly indicate how to use the basic functions, in this case, where the input and output is located. It should also be clear in what format the variables in the input should be provided. A user should be able to use the model without reading the report or dig through the model to discover the basic working principle. Since this criteria indicates how well the model can be used in practice the weight attached to it is 3. It is important but other criteria have a higher importance. Because of the structure of the FTA for most users this method is easy to use. BBN can provide a clear input and output but it can be harder for users to understand what exactly happened in between. EFA can be used to detect relationships between variables but what those relationships mean is for the user to determine. Because of this EFA receives the lowest score.
The criteria fast usage indicates how quick the model can be used in the daily operations. If the model is only used rarely the amount of time required for using the model is of less importance than when the model is used often. Because of the amount of belt present and the impact the model could have on the planning, the model will be designed to be used often. This brings the requirement that the model is fast to use. If filling in the model takes too much time, the model will likely be ignored. The weight of this criteria is the same as the criteria easy usage. It is important but other criteria have a higher importance. BBN receives the highest score for this criteria. It should be noted that this score is based on a finished model that is used in practice. Once the BBN model has been made it can be used within a short time span. FTA receives the lowest score because of the effort and time required to provide every input for each situation. Because of this, FTA is less useful for quickly determining the maintenance interval.

The conclusion from the multi criteria analysis is that the BBN method is the most suitable for the creation of the model.

3.4 The BBN in more detail

Using the multi criteria analysis performed above the BBN network was determined to be the most suitable method for making the model. Before the workings of the BBN network are discussed in more detail first Fuzzy logic in introduced. Considering the variables and information used by the model including Fuzzy logic can provide great benefits. Parameters concerning a BCS are often continues, the length of a conveyor belt is often represented by meters. With the usage of Fuzzy logic, continues variables and discrete variables with a large number of possibilities can be included in the model. Fuzzy logic can also be used to combine different information sources, obtain consistent information from different data sources and helps with the interpretation of information.

3.4.1 Fuzzy logic

Fuzzy logic was introduced by Zadeh in 1965 [27] as a methodology of representing and manipulating data that was not precise, but rather fuzzy. Classical logic allows a proposition only to be true or false. If you look at a conveyor belt, one could ask the question: is it moving? The answer to this question is either yes or no. The question: at what speed, is a bit trickier to answer. You either have to measure the speed and then represent it in X m/s or give a general description. The belt for example can move according to your observation fast. Fuzzy logic introduces values of truth to continues variables. The value of truth is between [0,1], 0 for untrue and 1 for true. If we look at the previous example of speed, let us assume a belt moves fast at 3 m/s and slow at 1 m/s. If you measure the belt and it moves 3 m/s the statement the belt moves fast is true so equal to 1. If the belt moves 2.5 m/s both slow and fast are true although for a different degree. In this situation fast is true for 0.75 and slow for 0.25. The value of truths is also called the membership. The example given above gives an indication what the fuzzy logic can do but this is not the only method of using it.

The data and information used for making the model consists of both continues and discrete variables. An example of a continues variable is the earlier discussed belt speed. The process of how these types of variables can be included in the model will now be explained. Let us assume that the speed of a belt can be anything between V(m/s) = [0,3]. To use this variable in the model a fuzzy membership function is used. To represent the speed of the belt 4 fuzzy ranges are introduced. Each range has an evidence, for the belt speed the range in V(m/s) and the evidence is shown:

Range:	0	1	2	3
Evidence:	Still	Slow	Medium	Fast

For each area of range (r_i) boundaries, if the value $x \in [r_i, r_i + 1)$ is considered with its evidence (e_i) description, we construct the membership function as [28]

$$g_{e_i}(x) = \frac{1}{r_i - r_{i+1}} x - \frac{r_{i+1}}{r_i - r_{i+1}} \tag{3-2}$$

$$g_{e_{i+1}}(x) = \frac{-1}{r_i - r_{i+1}} x + \frac{r_i}{r_i - r_{i+1}} \tag{3-3}$$

Where we have

$$g_{e_i}(x) + g_{e_{i+1}}(x) = 1 \tag{3-4}$$

The ranges can be determined by analyzing the available information and data. Another method that can be used to establish the ranges is the usage of expert opinions. This is mainly useful if insufficient data or information is available. By deriving fuzzy values from the membership function, each value covers a range of the observed parameter. The size of the range is

$$S_{e_i} = r_{i+1} - r_i \tag{3-5}$$

3.4.2 Likelihood Estimation and posterior probability

The BBN in equation 3-1 represents a hypothesis H with a single event E. The following equation represents equation 3-1 for more than one event.

$$P(H|e_i) = \frac{P(e_i|H) \times P(H)}{P(e_i)} \tag{3-6}$$

Using fuzzy values of evidence and the likelihood density when hypothesis H happens, given the evidence e_i, the posterior probability is calculated. Given the value x of evidence e_i, by using the membership function and conditional probabilities, the likelihood sampling distribution is estimated as

$$f'(e_i|H) = \sum_i g_{e_i}(x)\, P(e_i|H) \tag{3-7}$$

After defining a fuzzy set of prior probability which assigns each value of *x* for the evidences with rang [0,1] the likelihood is computed. The estimated likelihood density for fuzzy valued evidence is computed as the weighted likelihood according to the following formula

$$f^*(e_i|H) = w_{e_i}(x)f'(e_i|H) \quad (3\text{-}8)$$

Where $w_{e_i}(x)$ is the weight coefficient defined as

$$w_{e_i}(x) = \frac{S_{e_i}}{S_{e_i} + S_{e_{i+1}}} \quad (3\text{-}9)$$

The weight coefficient is used to define the two ranges of the fuzzy values of each evidence. The weight coefficient is used to evaluate the proportion to the corresponding size of the interval of the fuzzy values.

Once the likelihood probability has been determined using the above described method, the posterior probability can be calculated. The formula for calculating the posterior probability is as [29]

$$P(H|e_i) = \frac{f^*(e_i|H) \times P(H)}{\sum_j f^*(e_i|H_j) \times P(H_j)} \quad (3\text{-}10)$$

3.5 Example of Bayesian network

To demonstrate the working of the Bayesian network, an example is presented. For this example we look at the starting process of a conveyor belt. When a conveyor belt is started, a higher tension than the normal tension can influence the splices in the belt. This higher tension can cause splice degradation. The higher the number of starts of a conveyor belt, the more impact this higher tension can have on the splice degradation.

For this example first two hypotheses are presented: Low splice degradation (SD_L) is caused by starting a belt rarely with a low tension during the start. High splice degradation (SD_H) is caused by starting the belt often while it is subjected to a high tension during the starting process. The number of starts of the belt is described as the average number of starts per hour (NS). A variable of 0.2 for NS means that the belt is only started 0.2 times per hour or once every 5 hour. The maximum tension on belt during the starting process is described as the maximum tension (MT). The MT is the relationship of the peak tension (PT) during the start compared to the designed tension (DT) of the splice. The PT is then divided by the DT to indicate the factor of the PT compared with the DT. The higher this factor is, the higher the splice degradation caused by the peak tension during the starting of the belt.

Since this is an example of the method only two ranges for the two causes for splice degradation are used. The ranges are number of starts few (NS_F), number of starts many (NS_M), maximum tension low (MT_L) and maximum tension high (MT_H).

Range: (starts/hour)	0.2	1	Range: (PT/DT)	0.75	1.5
Evidence:	NS_F	NS_M	Evidence:	MT_L	MT_H

With the ranges of the two membership functions known, we now look at how these ranges can be used to fuzzify the input for the model. Let us assume that in a certain situation the number of starts of a conveyor belt is 0.4 per hour and the maximum tension is 105%. Using equation 3-2 to 3-5 and this information the membership function fuzzy values in each fuzzy range are calculated as

$$\begin{aligned} g_{NS_F}(0.4) &= \frac{1}{0,2-1}0,4 - \frac{1}{0,2-1} = 0.75 \qquad & g_{MT_L}(1.2) &= \frac{1}{0.75-1.5}1.05 - \frac{1.5}{0.75-1.5} = 0.6 \\ g_{NS_M}(0.4) &= \frac{-1}{0.2-1}0.4 + \frac{0.2}{0.2-1} = 0.25 \qquad & g_{MT_H}(1.2) &= \frac{-1}{0.75-1.5}1.05 + \frac{0.75}{0.75-1.5} = 0.4 \end{aligned} \quad (3\text{-}11)$$

With the fuzzified inputs ready for the nodes, the next step is determining the prior probability of the splice degradation. The prior probability of the splice degradation caused by the starting of the belt can be determined by observing the historical data. In

Table 3 an example is shown of five data points with the SD at that instance.

Table 3: Historical data points for the splice degradation caused by the starting of the belt

Data point	SD
1	Low
2	High
3	Low
4	Low
5	High

With the usage of

Table 3 the prior probability of SD can be determined. $P(SD_L)$ is equal to 0.6 because 3 of the 5 data points have a SD low. $P(SD_H)$ is 0.4 since 2 of the 5 data points are high. The sum of $P(SD_L)$ and $P(SD_H)$ is always equal to 1.

$$P(SD_L) = 0.6 \qquad P(SD_H) = 0.4 \tag{3-12}$$

Finally the conditional probability is required; Table 4 contains an example of this conditional probability. The conditional probability table is based on the data or expert opinion available for the causal relationships.

Table 4: conditional probability of the splice degradation example

	NS	NS_F	NS_F	NS_M	NS_M
	MT	MT_L	MT_H	MT_L	MT_H
SD	SD_L	0,81	0,41	0,53	0,12
	SD_H	0,19	0,59	0,47	0,88

All the information needed for carrying out the BBN method is now available. The first step for determining the posterior probability of the SD for the situation in this example is calculating the estimated likelihood density. The estimated likelihood density can be calculated using equation 3-8. The weight coefficient in this example is equal to one since only two ranges for the membership functions have been set.

$$\begin{aligned} & f^*(NS_F, MT_L|SD_L) \\ & = g_{NS_F}(x) \times g_{MT_L}(x) \times P(NS_F, MT_L|SD_L) + g_{NS_F}(x) \times g_{MT_H}(x) \times P(NS_F, MT_H|SD_L) \\ & + g_{NS_M}(x) \times g_{MT_L}(x) \times P(NS_M, MT_L|SD_L) + g_{NS_M}(x) \times g_{MT_H}(x) \times P(NS_M, MT_H|SD_L) \\ & = 0.365 + 0 + 0 + 0 = 0.365 \end{aligned} \tag{3-13}$$

$$\begin{aligned} & f^*(NS_F, MT_H|SD_L) = 0.123 \\ & f^*(NS_M, MT_L|SD_L) = 0.078 \\ & f^*(NS_M, MT_H|SD_L) = 0.012 \end{aligned} \tag{3-14}$$

Similarly we have

$$\begin{aligned} & f^*(NS_F, MT_L|SD_H) \\ & = g_{NS_F}(x) \times g_{MT_L}(x) \times P(NS_F, MT_L|SD_H) + g_{NS_F}(x) \times g_{MT_H}(x) \times P(NS_F, MT_H|SD_H) \\ & + g_{NS_M}(x) \times g_{MT_L}(x) \times P(NS_M, MT_L|SD_H) + g_{NS_M}(x) \times g_{MT_H}(x) \times P(NS_M, MT_H|SD_H) \\ & = 0.057 + 0 + 0 + 0 = 0.086 \end{aligned} \tag{3-15}$$

$$\begin{aligned} & f^*(NS_F, MT_H|SD_H) = 0.177 \\ & f^*(NS_M, MT_L|SD_H) = 0.071 \\ & f^*(NS_M, MT_H|SD_H) = 0.088 \end{aligned} \tag{3-16}$$

With the estimated likelihood densities calculated the main question is, what does this indicate? For the SD_L the largest value is present when the NS_F and the MT_L. This means that in the current situation a low splice degradation caused by the starting of the belt is most likely if there are few starts with a low maximum tension. This outcome matches our intuition.

For the SD_H the largest value is present when the NS_F and the MT_H meaning that the highest likelihood of high splice degradation is present with few starts and high tension. At first this outcome sounds a bit strange. You would expect the highest splice degradation during many starts under high tension, so why is it during few starts in this situation. The reason for the highest splice degradation during few starts is the value of NS. The fuzzified value NS_F is three times higher than NS_M, so because NS_M only has a limited influence on the estimated likelihood density, in this situation the highest splice degradation is present with NS_F and the MT_H.

With the estimated likelihood densities calculated the posterior probability can be determined. The equation used for this calculation is 3-10. The estimated likelihood densities are combined with the prior probability to calculate the posterior probability.

$$P(SD_L|NS,MT) = \frac{f^*(NS,MT|SD_L) \times P(SD_L)}{f^*(NS,MT|SD_L) \times P(SD_L) + f^*(NS,MT|SD_H) \times P(SD_H)} = \frac{0.578 \times 0.6}{0.578 \times 0.6 + 0.422 \times 0.4} = 0.67 \quad (3\text{-}17)$$

$$P(SD_H|NS,MT) = \frac{f^*(NS,MT|SD_H) \times P(SD_H)}{f^*(NS,MT|SD_L) \times P(SD_L) + f^*(NS,MT|SD_H) \times P(SD_H)} = \frac{0.422 \times 0.4}{0.578 \times 0.6 + 0.422 \times 0.4} = 0.33 \quad (3\text{-}18)$$

So we have now calculated the posterior probabilities, but what does it tell us. From equation 3-17 follows that the chance that splice degradation is low is 0.67. Equation 3-18 tells us that the posterior probability of splice degradation high is 0.33. This means that in the current situation the chance of low splice degradation is about twice the size then of high splice degradation. This posterior probability can be defuzzified to indicate a maintenance interval for example. The process of defuzzification this value is discussed in section 5-5.

4. Making a model

In chapter 3 the process of determining the method used for the model has been discussed. The theory behind this method is also explained in more detail. In this chapter the way this method can be used in practice to make the model will be presented. The first step in making the model is designing the model itself. Then the data necessary for the model has to be collected and processed. Using this data the necessary information for the model can be determined. Using this information the model itself can be made. Finally some methods are discussed that can be used to improve the model.

4.1 Designing the model

The first step in making the model is determining the shape of the model. With the shape of the model the different nodes and the relationships between the different nodes is intended. The shape of a model that is used to determine the preventive maintenance interval for a certain part will converge to a single node. This node is used to translate the output from the model to a value useful in practice. The model is represented as a DAG; an example of a DAG is given in Figure 22.

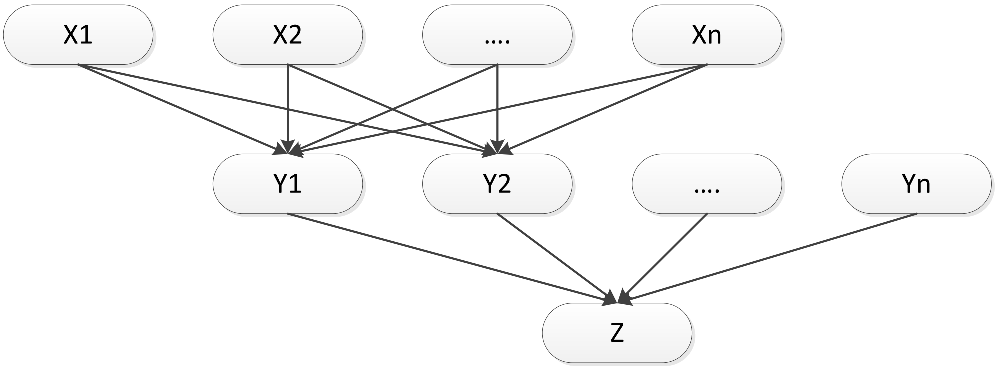


Figure 22: Example of a directed acyclic graph (DAG)

When making the DAG representation of the model, one must take great care to avoid cycles. An example of such a cycle would be: X1→Y1→X2→Y2→X1. While making the representation of the model a number of factors should be taken into account. The first and most important factor is: Does the node have a direct influence on the final node Z or in this case of the intended model, the maintenance interval. Including nodes that have no influence on the maintenance interval will only bloat the model while not improving it. The second factor that has to be taken into account is: is there sufficient information or data available to provide the necessary data for the model. The type of information and data necessary for the model will be discussed later. Taking the available information into account during this stage can greatly benefit the making of the model. Data or information that is not available can be obtained by other means like laboratory tests or installing new sensors, but this can be a long and expensive process. If during the design process of the model this is already taken into account, delays or missing information in the resulting model can be avoided. The final factor that has to be taken into account is: The influence of each node on the output of the model. Collecting, processing and finally incorporating the data in the model can be a very labour intensive process. By limiting the model to the nodes that have the most influence on the output, the amount of labour involved with the model can be reduced. Selecting the nodes that have the most influence on the model should be performed with great care. Some nodes could potentially have a large influence on the output while at first glance this is not visible. Scraping too many nodes could reduce the quality of the output of the model.

The design process of the model is one of the most important phases of the model making process. Small errors or oversights during this process can have a large influence on the output of the model. Excluding important nodes could lead to a model with a low accuracy and reliability. Before one starts with the next phase of the model making process, one should double check if design fulfils all the above described factors. The next step in the making of the model is data and information gathering and processing.

4.2 Data and information gathering and processing

Data and information can in general be gathered from three different sources. The first source is historical data. Data concerning the BCS is often documented over its lifetime. This source of data is of course not available for a new BCS. The historical data should be collected over a long period of time since work performed to BCS is often infrequent. The historical data can span a period of multiple decades leading to some extra challenges in processing the data. Over time the operating conditions and methods of maintenance can changes, this changes has to be taken into account when processing the data. When gathering the historical data for the model one should focus on data describing a relationship between variables and the maintenance interval. These variables relate to the nodes determined during the model design phase. The main challenge during this process is determining the dependencies of the maintenance interval for the different nodes. The maintenance interval rarely depends on a single node but often on a large combination of nodes. Determining from the data what exactly the effect from each state of each node is can be extremely hard. There are two methods to mitigate the effect on the maintenance interval from the different nodes.

The first method is collecting sufficient data so that trends are visible. If the number of data points are sufficiently large a trend can be determined if there is one present. If the data is completely random this method will not work since no trend is present to discover. The second method is also the second source of information. Using laboratory test one can more accurate determine the effect of the different nodes. Using laboratory test to collect the data for the different nodes can be extremely costly. Specialized setups often have to be created to determine the effect of the different nodes on the maintenance interval. Even using the specialized setups, the data collected can greatly differ from the real operation conditions. Some results are only noticeable after long periods of operation time or under certain conditions. An example from practice of this is the so called FN-foil. This foil was used during the splice creation to increase the strength of the splice. In the laboratory the results of this foil on the strength of the splice were severe. A field test with the foil lead to all the belts containing this foil failing after around eight months since the foil turned into small balls. Because of the movement inside the splice caused by going around the pulleys, the foil disintegrated and weakened the belt instead of strengthening it after a certain amount of time. So when possible, the laboratory results should be compared with information from practice.

The final source of information is knowledge or the so called expert opinion. The people responsible for the maintenance of the BCS often can provide indications about the maintenance interval based on their experience. The hard part is translating their experience to useful data for the model. They can often provide a good indication of the maintenance interval in a certain situation, but translating this data to the different nodes can be tricky. Extreme situations are often remembered bests since they deviate from the day to day operations. The maintenance interval an expert predicts during normal operations is often also based on a lot less variables than used in the model since it is nearly impossible for a human to keep track of each and every variable involved. The expert opinion is a good way to check the information collected from the historical data or use if no historical data is available.

Once all the data and information is collected, it should be processed to be usable for the model. The first step in processing the data is determining the fuzzy intervals for the different nodes. These intervals can be determined using two methods.

The first method is based on experience. An inspector for example might describe a tear in the belt of 5 cm as small, 10 cm as average and 15 cm as large. The node in this case has 3 fuzzy ranges to describe the size of a tear. The second method is using the data. If one looks at the data available for tears in a belt and three groups of lengths are detectible, it is logical to split the data in 3 fuzzy ranges.

One property of the BBN method that has to be taking into account during the determination of the fuzzy ranges is the amount of ranges used for each node. A large number of ranges for each node can improve the accuracy of the model but also increases the work involved with the making of the model.

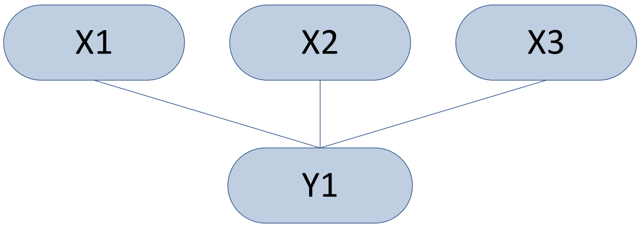


Figure 23: Small section of a DAG

If we look at the example presented in Figure 23 which represents the relationship between (X1,X2,X3) to Y1. The range of each node is R, the formula for the number of combinations (N_c) is $N_c = R^{X_n}$ so X1,X2,X3 with each 3 ranges leads to a number of combinations of $3^3 = 27$. Increasing the number of ranges can lead to a large number of combinations fast. For each combination the conditional probability has to be determined so a high number of ranges combined with a lot of nodes can lead to a very large conditional probability table.

After the ranges for each node has been determined the prior probability has to be defined. The prior probability is based on the historical data. By analyzing the historical data, one can determine how often a certain state of the node is true. Transforming the number of times true compared with the total number of actions gives the prior probability. The sum of the prior portability for each node is always equal to one.

The next step is determining the conditional probability for the model. The first step in making the conditional probability for the model is making tables containing all possible combinations from the nodes and ranges. The combinations of the nodes are determined while designing the model. Combining these combinations with the earlier determined fuzzy ranges of the nodes leads to tables containing all possible combinations. Once these tables are made, the conditional probability for each combination has to be determined. The data required for this process has to be collected from the three earlier discussed sources.

A good method for determining each conditional probability for the table is determining this value from the historical data or laboratory test. Once this value has been determined, it can be checked using an expert opinion. During the data collection process, the main focus was to determine the maintenance interval depending on the variables included in the nodes. For the conditional probability this interval has to be translated to a value between [0,1] so it can be used in the model. The nodes X1,X2 and X3 influences the node Y1 through its state. If the node Y1 has two hypotheses, for example: the belt is either in perfect condition so maintenance is not needed for a long time or destroyed so maintenance is needed now, the maintenance interval can be translated to a value. The first step is determining the maximum maintenance interval, for example 365 days. So if the combination of states of the three nodes gives a maintenance interval for 365 days or longer, the range of node Y1 of perfect condition is 1. If the range of node Y1 of destroyed is equal to 1, the maintenance interval is equal to 0 so the belt requires maintenance at that moment. Using this method every value for the conditional probability can be determined.

One of the challenges for this process can be the amount of combinations that require input. Another problem is that some combinations either have no data available or too little to provide an educated value. This value has to be determined with the usage of an expert opinion or by looking at the trend of the other values. Let us look at the example of the tear in the belt again. If the average values for a small tear is 0.5 and for an average tear 0.6, the trend for a large tear is 0.7. A larger number of ranges would help with determining this trend.

4.3 Implementing the model

Once the conditional probability tables are constructed, the model itself can be made. The first part of the model consists of fuzzification process of the inputs of the model. The ranges for the nodes have already been determined during data processing. For input with a fixed number of possibilities this process is easy, type of splice used for example can only be two types. Values with a large range of possibilities like the length of the belt have to be fuzzified. How this fuzzification process works is already discussed in chapter 3. The end result of the fuzzification process is that each range of the different nodes receives a membership between [0,1].

The part of the model consists of implementing the BBN method. The first step for determining the output is calculating the estimated likelihood density functions. For the calculation of the estimated likelihood density functions, equation 3-7 can be used. With the estimated likelihood density the posterior probabilities can be calculated. With this process done, the output of the model can be calculated.

In Figure 24 a graphical representation is show of the last part of the model.

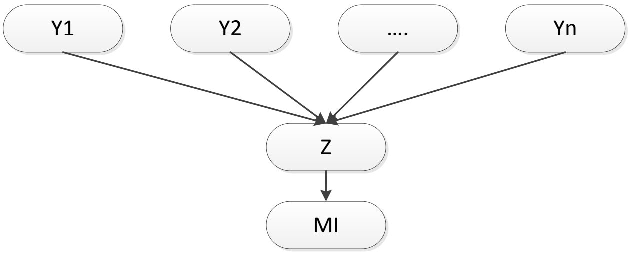


Figure 24: The state of node Z is used to determine the Maintenance Interval (MI)

The node Z represents the state of the system. Let us assume that in this example the node Z is the state of the conveyor belt. The better the state of the belt is, the longer the maintenance interval (MI). The state of the belt has to be transformed to a maintenance interval that can be used in practice. The easiest method is simply multiplying the state with a certain value, for example 365 days. In this case you assume that the maximum maintenance interval is 365 days if the state of the belt is perfect and that there is a linear relationship between the state of the belt and the maintenance interval. This method can only be used if there is a linear relationship between the state of the belt and the maintenance interval. In other situation a formula must be created to capture the relationship between the state and the maintenance interval. This formula can for example be based on the historical data. One fact should however be taken into account. The inputs for the model has been fuzzified, the output could also be determined by defuzzifying the state of the belt. In this case a defuzzifying graph or table can be used to transform the state of the belt to a maintenance interval. The defuzzifying process can for example be based on historical data or expert opinions.

4.4 Fine-tuning and preparing the model for practice

The framework for the model has now been made but some fine-tuning and additions for improving the quality of the model for practice could be performed. Each node in the current model is equally important. During the design of the model all the unimportant nodes should already have been removed. But even with only the important nodes left some nodes will have more influence on the maintenance interval than others. By assigning a weight factor (WF) to the different nodes, this difference can be taken into account. A node that represents a part that is crucial for the normal operations of the BCS can have for example a WF of 10. A part that could potentially damage other parts but only under certain circumstance would receive a WF of 1. With the usage of this WF, the accuracy of the model can be improved.

For the model to be used in practice an important piece of information from the output is still lacking. The output is composed of a single value for the maintenance interval. For a model to be useful in practice a spread for the maintenance interval is also required. This interval can be used for the planning of the preventive maintenance. Another source of information lacking is the reliability of the prediction. This can either be incorporated in the spread of the maintenance interval or presented separately.

The reliability of the output can be determined using a number of methods. The first method is assigning each value of the prior probability and the conditional probability a reliability factor (RF). The value of the RF depends on how sure you are, this value is correct. So a value that has been determined using a large number of data points and is check using an expert opinion can receive a value of 1. Values that have very little to no information available receive a RF closer to 0. By combining the RF from all the prior probabilities and conditional probabilities used during the process of determining the output, the overall RF can be represented as a value between [0,1]. This overall RF can be fuzzyfied to indicate the reliability of the system. This will give a good indication in how the maintenance interval determined by the model should be incorporated in the decision making process.
Another method to take the RF into account could be combined with the earlier discussed process. In this case a RF is assigned to the inputs for the model. Some of the inputs for the model could either be an subjective value or lacking in some cases. By assigning a RF to the input, a separation can be made between values that are collected by sensors, determined with estimations or subjective values. One could even go further and use the RF to take the accuracy and quality of the sensors present into account. Combining the RF for both the prior

probability and conditional probability with the RF for the input will give a good indication on the reliable the output is for use in practice. The formula for combining the two RF to a RF_{tot} is:

$$RF_{tot} = \sqrt{\left(RF_{input}\right)^2 + (RF_{data})^2}. \quad (4\text{-}1)$$

The spread of the output can be determined using a number of methods. The first method is using the earlier discussed RF to determine the spread. A higher reliability of the model will lead to a smaller spread of the output. First one must determine the spread of the output during a number of high and low reliability cases. Using this data a formula can be made to translate the RF to a spread.

The second method is a more basic method of providing the spread. One only looks at the maintenance interval and uses that value to determine the spread. By fuzzifying the maintenance interval, the spread can be determined. So a maintenance interval of shorter than a month has a spread of 3 days, between 1 and 3 months a week and so forth. This method is extremely basic and does not take any extra information of the model into account. Because of this, the spread provided is often incorrect.

The third method is taking the safety factor for the belt into account. Different belts often have a different importance for the normal operations. Some belts are allowed to be broken for a extend period of time will others are nearly always needed. For determining the safety factor for a belt a number of methods are available like FMEA. Once a safety factor has been determined, it can be incorporated in the model. If the spread of the maintenance interval is assumed as a normal distribution, also called Gaussian distribution, this distribution can be used for taking the safety factor into account. In the case of this model the μ or mean life expectancy is the maintenance interval. The σ or standard deviation is the spread for a normal maintenance action. This means that 68.3% of the maintenance actions are inside the domain of σ^2. If for the highest level of safety an accuracy of 95.5% is required, 2σ should be taken into account. So if the normal spread is ±10 days, the spread for the highest level of safety is ±20 days. Other levels of safety can be determined using the Gaussian distribution.
The different methods for obtaining the spread can of course also be combined to improve the quality of the spread.

4.5 Model in practice

Now that the process of making a model has been explained, this theory is tested in practice. Before a test case can be performed, first a design of a model for determining the state of a conveyor belt has to be made. The first design of this model gives an indication what factors will influence the state of the conveyor belt for the maintenance interval. Based on the available data and the situation at Tata Steel, the scope of the model is then limited to the state of the splices. For the conveyor belts used in the test case, the splices of the conveyor belts where by far the main source of maintenance actions. First a model is designed for the state of the splices based on the earlier described criteria. This model will take the most important factors for determining the state of the belt concerning splices into account. The second simplified model only takes a limited number of factors into account. The factors for this model have been chosen based on available data at Tata Steel and their impact on the state of the belt in the situation present.

4.6 Complete model for conveyor belt

When looking at what can cause maintenance to a conveyor belt, four main sources can be identified. An overview of these four sources is given in Figure 25. The belt surface can require maintenance once it is for example damaged by a foreign object in the transported bulk material. Another reason for carrying out maintenance is that repairs to the carcass are required. The moulded edge can be another source of maintenance actions; this is mainly caused by unaligned running of the conveyor belt. The final source of maintenance is the splices present in the belt.

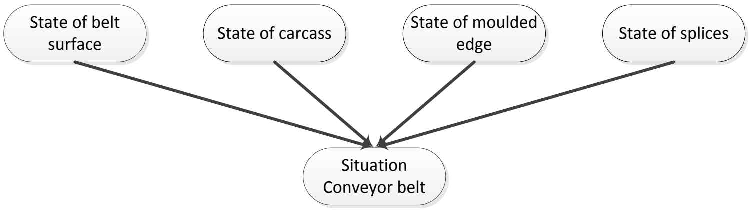


Figure 25: The four main sources that determine the state of a conveyor belt

When looking at the reason and frequency for the maintenance requirement of the four maintenance sources mentioned in Figure 25 some conclusions can be drawn. Based on the data available at Tata Steel, maintenance to the carcass rarely happens. If there is maintenance performed to the carcass it is nearly always at the location of a splice. Maintenance actions to the moulded edge are mostly caused by unaligned running of the belt. There are a large number of causes why a belt is running unaligned; most of these causes are hard to predict making the optimization of a maintenance interval hard. For the fabric belts used in the test case, the moulded edge is also not required for the normal operations of the belt. The maintenance actions to the moulded edge themselves is often limited to cutting of the lose rubber parts to prevent these loose parts getting stuck in the frame or at an idler roll. The maintenance actions to the belt surface are often caused by foreign objects in the bulk material or other external influences. As a result these types of maintenance actions are relative random. The final sources of maintenance actions to the belt are the splices. During the data analysis of the data at Tata Steel it was concluded that for the belts used in this research, 95% of the maintenance involved the splices in some way. Either a new splice had to be created during the maintenance action or a repair to the splice was performed. Because of this reason, only the state of the splices is modeled to be used for determining the optimal maintenance interval.

4.7 Complete model for conveyor belt splices

In the complete model al inputs that fulfill the discussed criteria in section 4.1 are included. Using the inputs the model will determine an output in the shape of: situation belt regarding splices. This output can be used to determine the optimum maintenance interval for the belt regarding the splices. The factors that have an influence on the situation of the belt regarding splices are determined as four main factors. In Figure 26 an overview is given of these factors that influence the situation of the belt regarding splices.

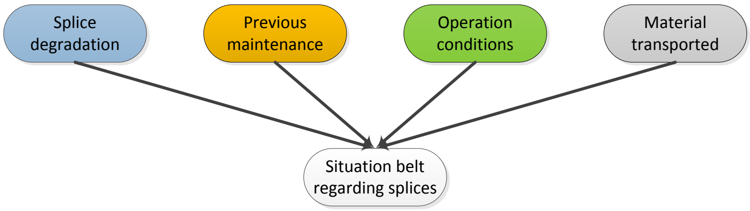


Figure 26: Complete model

The first factor is splice degradation either caused by usage or by starting and stopping of the belt. The second factor is previous maintenance. The quality of the previous maintenance action performed has an influence on the state of the current splice. The third factor is operation conditions. This indicates the properties of the belt and the surroundings. The final factor is the material that is transported by the belt. This has mainly an influence on the expected lifetime of the belt, but can also impact the state of the splices. The four factors that determine the situation of the belt regarding splices will now be discussed in more detail.

4.7.1 Splice degradation

The splice degradation can be traced back to four main causes. Two causes are present during the starting and stopping process of the belt. The other two are present during the operation of the BCS. First the two types of degradation present during the normal operation conditions will be discussed. After that the two peak tension degradations will receive a closer look.

Splice normal tension degradation

Splice normal tension degradation is caused by a number of factors. The main factors influencing the splice normal tension degradation are presented in Figure 27.

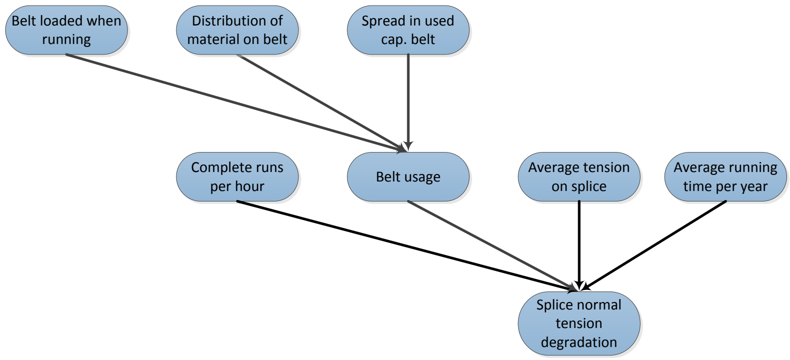


Figure 27: Splice normal tension degradation

Average tension splice
The average tension on the splice is the tension on the belt originates mainly from the tensioner and the force introduced to move the system. The tension in the belt will increase towards the drive pulley.

Complete runs per hour
A complete run of the BCS is defined as a single point on the conveyor belt passing the same point alongside the belt for the second time. One could count the amount of times a single point passes a location along a belt during an hour to determine the number of complete runs per hour. An easier method would be to calculate the number of runs the BCS could make based on the length and the speed of the belt. The number of runs per hour is L/(v*3600) with L in meter and v in m/s. This is used to distinguish a slow/long and a fast/short BCS. The splice is mainly subjected to degradation during a change of tension or direction. By taking the amount of complete runs of the belt conveyor into account, the amount of tension and direction changes are modelled.

Average running time per year
The average running time per year indicates how much percent of the time the belt is running. This percentage indicates the running time over a complete year. The more a belt is running, the longer a BCS is subjected too belt degradation during a certain time frame. One can assume that the amount of degradation during standstill is negligible. One thing that should be taken into account is that a belt is not always running fully loaded. The BCS used at GSL are mostly part of a larger network. They often operate following order to transport a certain amount of material from point A to point B. If the order is finish, the belt has to be emptied before the next order can be performed. Depending on the location in the BCS network, a BCS can run most of the time empty.

Loaded belt usage
The loaded belt usage indicates how often and in what distribution the belt is loaded while running. Belt loaded when running represents the percentage of the running time, the belt is actually transporting material. A belt on the beginning and end of a BCS network can both transport the same amount of material, but have completely different running times. The distribution on the belt indicates how the material is distributed over the belt. Material that is deposed by a silo on a belt often has relative even distribution. In other words, the amount of material on the belt on each section is around the same. If a BCS is supplied by for example a quay crane or bucket wheel excavator, the material is often supplied in sections. Because of the operations the loading equipment performed, the supplied material stream is not constant. The belt is loaded for a section, the next section is empty and the section after that is loaded again. This can lead to larger differences in stress than an even loaded belt. The final factor that influences the loaded belt usage is the spread in transported material. If a belt is always transporting the around the same amount of material, the tension on the belt during loaded running would also be around the same each time. If on the other hand a large spread is present in the amount of material transported, the difference in tension would also be present. The tension on the belt would be lower than average if the belt is transporting little material while higher when lots of material is transported. Using this factor, the spread in transported material can be taken into account.

Splice bending degradation

When a splice is moving around a pulley, splice degradation can take place. The rate of this splice degradation is influence by a number of factors. The most important factors are presented in Figure 28. Some factors are the same as discussed in splice normal tension degradation; this is why they are not mentioned again.

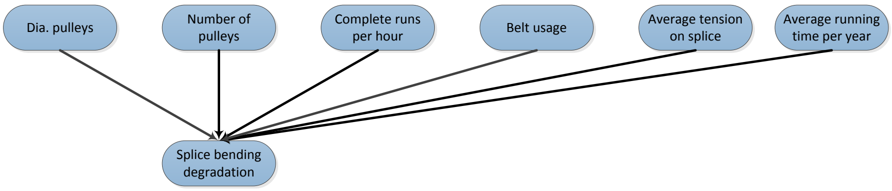


Figure 28: Splice bending degradation

Number of pulleys
The number of pulleys indicates the amount of pulleys present in the BCS used for guiding the belt. No difference is made considering drive or tail pulleys. The number of pulleys present in a BCS is at least 2 and can increase in number depending on the design of the BCS. Extra pulleys can for example be installed for the tension mechanism or a second drive.

Diameter pulleys
The diameter of the pulleys is of importance for the magnitude of the direction change of the conveyor belt. The pulleys can be separated in three different types: drive pulleys, tail pulleys and snub pulleys. Drive pulleys often have the largest diameter while snub pulleys have the smallest. The minimum required diameter of the different types of pulleys can be determined with the use of norms or from the specifications of the belt manufacturers. One could argue that as long as the diameter of the pulleys satisfies the minimum requirements of the norms/belt manufacturers. They are large enough and the influence on the severity of the splice degradation because of bending is limited. On the other hand, if the pulley is larger, the bending stress will be lower. So the larger the pulley is, the lower the bending degradation of the splice.

Splice start tension degradation

When the belt is started, a larger tension than during normal operations can be present on the belt. The influence of this peak tension is influenced by the factors given in Figure 29.

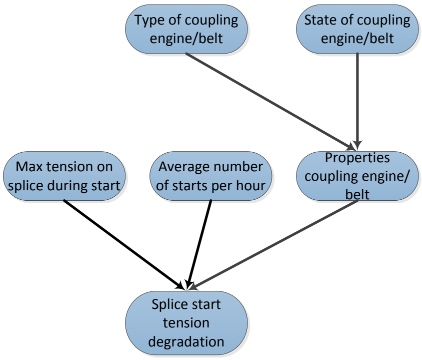


Figure 29: Splice start tension degradation

Maximum tension on the splice
The maximum tension on the splice will either take place during the starting or stopping of the belt. Whether the maximum tension is present during the starting or stopping of the belt depends on the BCS properties. During start-up the maximum tension depends on the power provide by the engine and the type of coupling present. A direct coupling between the engine/gearbox and the drive pulley can lead to a peak torque on the belt of a factor 2 to 3 higher than normal. With the usage of a fluid coupling or soft starter this peak torque can be limit. The tension during breaking depends on how much mass have to be stopped in what time frame. Stopping a long, fully loaded belt going downhill in a short time using only one pulley with brakes would lead to a high break tension in the belt. If multiple brakes are present, this tension could be limited.

Average number of starts/stops per hour
The more a belt is stopped and started again, the oftener the peak tension on the splices is present. This peak tension only originates during starting and stopping of the belt. As long as the belt is running, this peak tension will not take place. The degradation of the splice because of the peak tension during starting and stopping of the belt depends both of the height of the tension and the frequency.

Properties coupling engine/belt
This node indicates how the engine/gearbox is connected to the drive pulley of the belt. In general you could designate three different types: fixed, fluid coupling or soft starter. The soft starter is not really a connection between the propulsion and the belt but a regulator for the start-up of the engine. A fixed coupling transmits the power straight from the engine/gearbox to the drive pulley. The peak torque from the engine during start-up is transmitted fully to the belt. A fluid coupling is used to lower the amount of peak torque transmit from the propulsion to the belt. The peak torque on the belt caused by the start-up is between a factor of 2 to 3 on a fixed coupling, a fluid coupling can limit this, depending on the type of fluid coupling used, to around 1.5. A soft starter does nothing to reduce the amount of peak torque supplied to the belt from the propulsion to the belt. It does reduce the amount of peak torque created by the engine itself. Depending on the type of soft starter the peak torque can be limited to a factor of around 1.2. The lower the peak torque during start-up, the lower the maximum tension on the splice during the starting of the belt.

Splice stop tension degradation
Not only during the starting process of a BCS a peak tension on the belt can present, during the stopping of a belt a peak tension can also exist. The most important factors are given in Figure 30, most are already discussed for the splice start tension degradation.

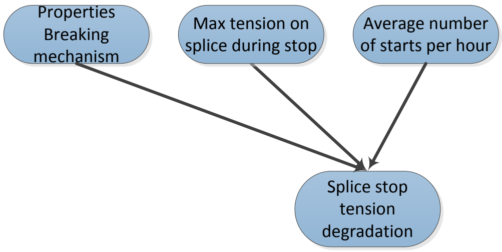


Figure 30: Splice stop tension degradation

Properties breaking mechanism
As discussed earlier under maximum tension on the splice, the properties of the breaking mechanism influence the maximum tension on the splice. The distribution and how the breaks are used will influence the splice stopping tension degradation. If the brake time is kept constant, the more brakes along the BCS are present, the lower the brake tension peak. The brakes should be spread along the length of the BCS and not placed all on the same location. The way for example a pulley is used for braking also influence the splice stopping tension degradation. If the pulley in question is locked in an instance to slow down the belt, a large tension spike will arise.

4.7.2 Previous maintenance
Previous maintenance carried out to a conveyor belt has an influence on the state of the splice. The node previous maintenance can be traced back to a number of factors. These factors are listed in Figure 31.

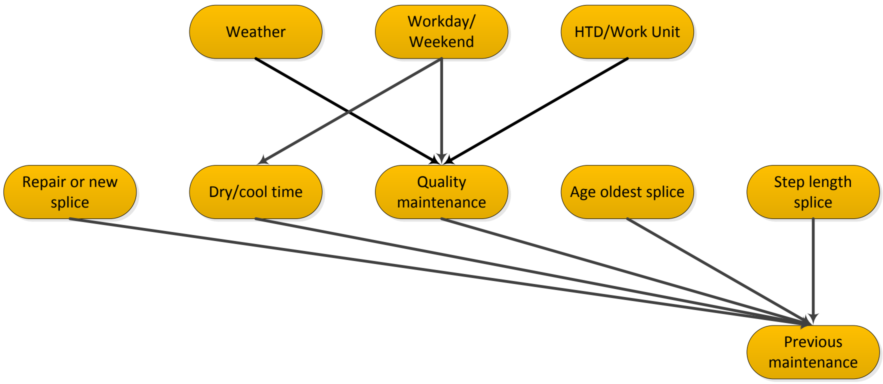


Figure 31: Previous maintenance

The age of oldest splice
The age of the oldest splice influences the maintenance interval. The older a splice is, the higher the chance maintenance is required. Splice degradation through normal operations or starting/stopping has more time to influence the quality of the spice. By looking at the oldest splice present in a BCS, the maximum effect of the ages of the slice is taken into account.

Quality of maintenance
The quality of the maintenance performed has an impact on the maintenance interval of the splices. The maintenance is performed by humans so the quality of the work will vary. The amount of factors that influence the quality of the work performed by humans is nearly unlimited. For the sake of this research the factors are limited to three: HTD or work units, workday or weekend and finally the type of weather. HTD or work unit determines the experience of the worker performing the maintenance. The workers of HTD all have extensive experience performing the maintenance. Most performing the same job for a lot of years already and perform nothing else than belt maintenance each work day. Work units on the other hand do in general little maintenance to the BCS. If they do maintenance it is a small repair or they have to perform maintenance because HTD has no time.

The node workday or weekend indicates if the work is performed during work time or overtime. The reason that this node is represented as workdays and weekend is because not sufficient data was available to determine of each maintenance action when it exactly happened. Since Tata is a 24 hours a day company and HTD works only a single shift of 8 hours, overtime during weekdays can take place. Emergency repairs can happen outside the normal work hours of HTD, repairs can also take longer than planned. Repairs performed in overtime, can be considered of less quality than those during working hours. In general, maintenance during working hours is planned so preparations can be made. Sufficient personnel are scheduled to perform the task at hand. Outside work hours, workers are extra expensive and the allowed work hours should be taken into account. The amount of workers that perform a task will be limited as much as possible. Less people must perform the same work, can lead to loss of quality. If maintenance is performed outside working hours, it is mostly emergency repair. This has as result that there is extra pressure on the workers to complete the maintenance as fast as possible to minimize the disturbance to the normal operating process.

The final factor taken into account is the weather during the maintenance of the belt. This has only an impact if the maintenance is performed outside, belts inside are protected against the elements so are not influenced by the weather. Since the exact time of each maintenance action is unknown, the average weather during the entire day on which the maintenance takes place is used. To determine the influence of the weather, two variables are taken into account. The amount of rainfall and the average wind chill temperature during the day of the maintenance action.

Dry/cool time after repair
Another factor that influences the previous repair is in the case of a hot splice, the cool time and for a cold splice, the dry time. If a belt is used to soon after maintenance, the splice might be damaged. The required dry/cool time depends on multiple factors; the most important once are the temperature of the environment, humidity and width and thickness of the belt. The dry/cool time is currently determined based on experience. Once a repair is finished, a worker from HTD tells the department who owns the belt, when they can use the belt again. This time is based on observed conditions by the worker, not on measurements or hard data.

Repair or new splice
The type of maintenance is used to determine if the last maintenance action was the creation of a new splice or a repair too an old splice. A repaired splice has in general a shorter maintenance interval than a new splice. A repair is nearly always weaker than a new splice. A repair is used to fix a damaged area of a splice, but it is nearly impossible to repair all the damage to the old state.

Step length of the splice
A splice in a fabric belt is created by attaching two layers of the two ends of the belt together. The length used for making such a connection is called a step. The longer a splice step is, the more area of a fabric layer is present to transmit the tension from the fabric of one end of the belt to the other end. The belt manufacture normally indicates this required step length. At some locations the area available for the splice creation is so small, that the step length has to be reduced.

4.7.3 Operation conditions

The conditions in which the BCS is operating can have an influence on the maintenance interval of the splices. The most important factors that have an influence on the maintenance interval have been given in Figure 32.

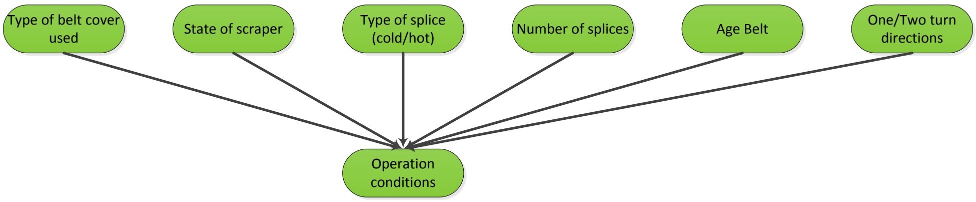


Figure 32: Operation conditions

One/two turn directions

Belts can have one or two turning directions. A single direction is used if a belt has to transport material from a take-up location to a transfer point or buffer. Two directions can be used if the take-up location is near the center of the belt while on both sides silos are present. For the splice, the main difference between one or two directions is the interaction with the scrapper. If the belt is running in a single direction, the direction of the splice is in such a way, that it is impossible for the scraper to get stuck on the splice. If the belt is running in both directions, only one turning direction is safe. The other turning direction could possibly destroy the splice if the scraper gets stuck. The state of the scrapper is mainly important for a belt that runs in both directions. If the scrapper is not positioned correctly or is not operation according to its specifications, the risk is present it destroys the splice.

Type of splice (cold/hot)

The splice can be created using two types of splicing methods. Either by cementing (cold splice) or vulcanizing (hot splice). The main reason for using the hot splice method is the temperature of the material transported on the conveyor belt. If the temperature of the material is warmer than 85 degree, a hot splice has to be performed. The cement used during the creation of a cold splice would melt at this temperature. Another reason to use a hot splice is if the department owning the belt specifically asks for a hot splice. A hot splice is in general more reliable than a cold splice. The main disadvantage of a hot splice is the equipment needed to create the splice. Because of this equipment, a larger work space is required than for a cold splice. The equipment also has to be transported to the work location. There is only a certain amount of equipment available for the creation of hot splices, this leads to a limit on the amount of hot splices that can be created at the same time.

Number of splices

The number of splices present in a particular conveyor belt is important to determine the maintenance interval concerning the splices. Short belt often only have a single splice. If a part of the belt is damaged to such extend that this has to be replaces, it is easier to replace the entire belt instead of only a part. For longer belts it is often cost effective to only replace the bad part of the belt. The result is that the number of splices can increase over the life time of a belt. Another factor that should be taken into account is the supply length of new belts. Transporting a new belt from the production location to the customer introduces limitations to the maximum weight and size of the roll containing the new belt. Because of this, new long belts often consist of multiple parts. So a new belt can already have multiple splices. The number of splices in a conveyor belt is relevant for the maintenance interval of the splices. The more splices are present, the higher the chance maintenance has to be performed to one.

Age of the belt

The age of the belt is has an influence of both the state of the protective covers of the conveyor belt, as the state of the splices. The closer a belt is to the end of its lifetime, the lower the thickness of the protective cover. Over the lifetime of the belt, the carcass and splice can receive damage. How older the belt is, the more damage can be introduced to the carcass and spice.

Type of belt cover used

The type of belt cover used is mainly important for the material transported on the belt. One of the main factors that determines the type of belt cover used, is the temperature of the transported material. For warm material, special belt covers have to be used who are resistant to higher temperatures. The properties of these types of covers can be different than the normal covers. Different rubber properties and stresses or other forces introduced by the different cover types, can influence the maintenance interval of the splices.

4.7.4 Material transported

The main impact of the material transported on the maintenance interval of the splice is the temperature of the material. The type of material transported has a large influence on the lifetime of the belt; the impact on the splices can be very limited. In Figure 33 both factors are given.

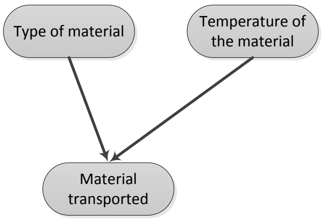


Figure 33: Material transported

Temperature of the material

The temperature of the material can have an influence on the maintenance interval of the splices. The temperature only has to be taken into account if the material is warm enough influence the properties of the rubber present in the conveyor belt. Under the influence of the warmth of the material, the rubber can become harder and more brittle. Cemented splices are above a certain temperature also no longer feasible, because the cement is influenced by the temperature.

Type of material

The type of material transported mainly influences the lifetime of the belt. One of the ways, the type of material transported can influence the maintenance interval of the splices, is by transporting large lumps of material. If the lumps of material are dropped on the belt from a large height, the impact can damage both the protective layer as the carcass. This damage also extents to the splices, causing a shorter maintenance interval.

In Figure 34 an overview of the complete model is presented. A larger version of this figure is included in Appendix A: The complete model.

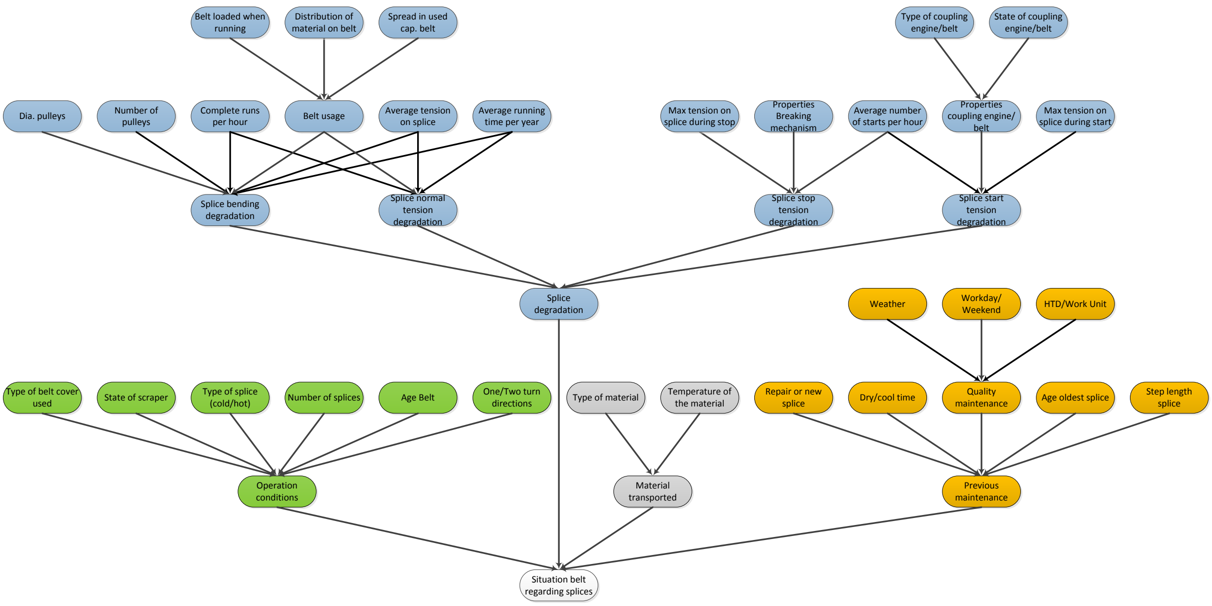


Figure 34: Overview of the complete model

4.8 Simplified model for conveyor belt splices

In the previous section a DAG representation of the model has been presented with the main factors that influence the maintenance interval of the belt regarding splices included. To prove the working of the model only a limited number of factors will be taken into account. To determine what factors of the complete model will be used, the earlier discussed recommendations are taken into account. The first criteria is that there is data for modeling this factor available. The simplified model will be made and verified using real data provided by Tata Steel so only nodes that have data available will be taken into account. Taking nodes without or with very limited information into the model, would require this information to be obtained from other sources. This is during the process of making this thesis not possible. The second criteria is that the factor have a large impact on the maintenance interval taking the situation at Tata Steel into account. The operation conditions for a BCS will be different for BCS located in a plant than in a mine. The particle size of the bulk material at Tata Steel will be in a much smaller range than directly after mining the bulk material.

4.8.1 Splice degradation

The first of the four factors that influence the situation of the belt regarding splices is splice degradation. Splice degradation can again be split in four different causes. The first cause is splice normal tension degradation. In the previous paragraph the different influences for splice normal tension degradation have been already discussed. Now we look at the factors that will be included in the simplified model. The main factors influencing the splice normal tension degradation are presented in Figure 27.

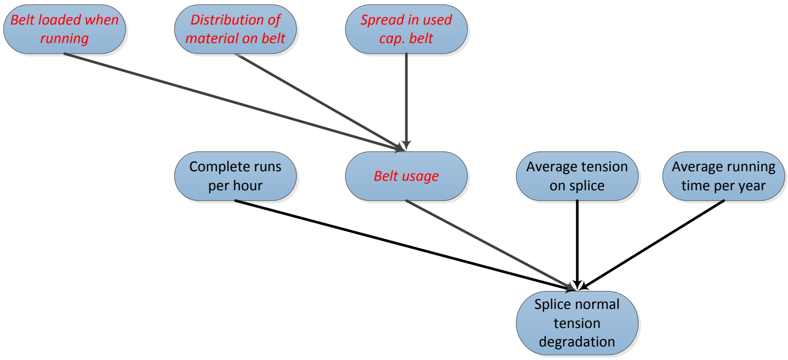


Figure 35: Splice normal tension degradation with the nodes not present in the simplified model in red

The factor that will not be included in the simplified model is belt usage. The reason for this is that there is currently no information available for this factor. Data about when a particular BCS is running is collected but the amount of material transported is only measured at a very limited number of BCS. Because of the complex network of BCS's at Tata Steel, determining for each BCS used for the model the material transported was not feasible for this thesis.

Splice bending degradation is caused when a splice is moving around a pulley. The rate of this splice degradation is influence by a number of factors. The most important factors are presented in Figure 36.

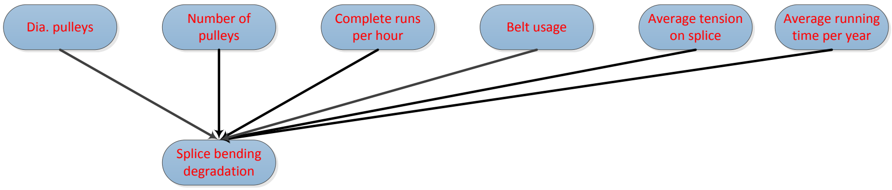


Figure 36: Splice bending degradation with the nodes not present in the simplified model in red

Splice bending degradation will in its entirety not included in the simplified model. The reason for this is that verifying this factor based on historical data will be hard. The differences between different belts are often limited. Determining what the effect of tension compared to bend is on the maintenance interval is in the current stage of research a challenge. The diameter of the pulleys for example have been checked during the data collection and are all following the norms and conveyor belt manufactures specifications for the belts included in the model.

When the belt is started, a larger tension than during normal operations can be present on the belt. The influence of this peak tension is influenced by the factors given in Figure 37.

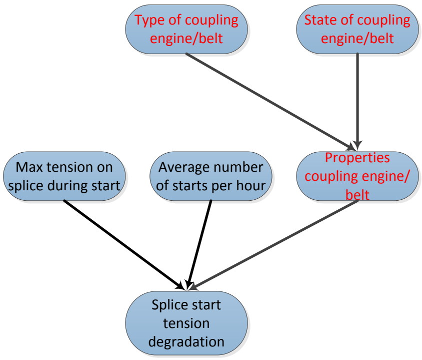


Figure 37: Splice start tension degradation with the nodes not present in the simplified model in red

The factor properties coupling engine/belt will not be included for the simple reason that this is already included in the maximum tension on splice during start calculation. Including this factor also in the model would make this variable count double.

Not only during the starting process of a BCS a peak tension on the belt can present, during the stopping of a belt a peak tension can also exist. The most important factors are given in Figure 38.

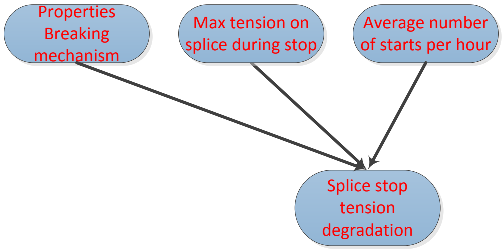


Figure 38: Splice stop tension degradation with the nodes not present in the simplified model in red

Splice stop tension degradation will in its entirety not included in the simplified model. The reason for this is that tension caused by stopping is not an issue at Tata Steel. This is mainly relevant for long conveyor belts transporting material downhill. No belts of this type are present at this plant. The second reason could be stop tension caused by an emergency brake. According to the experts present at Tata Steel, stopping of the belt had as far as they knew no too hardly any impact on the state of the splices.

4.8.2 Previous maintenance

Previous maintenance carried out to a conveyor belt has an influence on the state of the splice. The node previous maintenance can be traced back to a number of factors. These factors are listed in Figure 31.

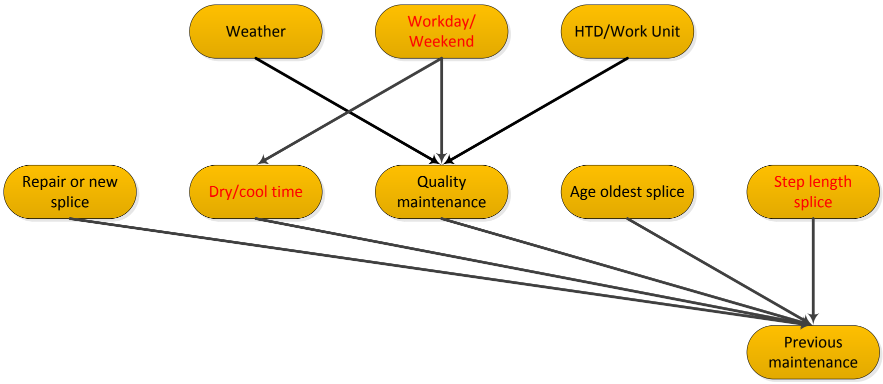


Figure 39: Previous maintenance with the nodes not present in the simplified model in red

For previous maintenance a number of factors will be removed before this cause is included in the simplified model. The first factor that is removed is dry/cool time simply because there is no data available. Age oldest splice will also not be included, partly because it is sometimes not clear how old the oldest splice is. Another reason is that the age of the belt is already included in the model. Workday or weekend is not included because of lack of information. It is used to indicate if a maintenance action is performed during work time or overtime. Unfortunately it is often not well documented if maintenance during a workday happens during the 8 hour shift of HTD or outside of their normal working hours. The final factor that will not be included is step length splice. The step length of a splice is based on specifications provided by the manufacture. The belt included in this research all have a step length equal to step length recommended by the manufacture.

4.8.3 Operation conditions

The conditions in which the BCS is operating can have an influence on the maintenance interval of the splices. The most important factors that have an influence on the maintenance interval have been given in Figure 40.

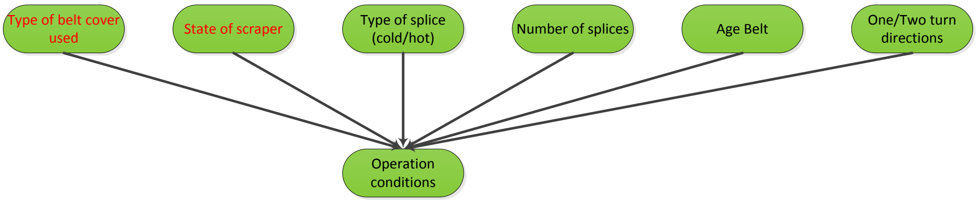


Figure 40: Operation conditions with the nodes not present in the simplified model in red

The first factor that will not be present in the simplified model is the type of belt cover used. The type of belt cover used for the belts included in the model is all the same. The main reason to use another belt cover for a belt transporting bulk material is high temperature which is excluded from the scope. The state of the scraper will also not be included since there is little to no data available for this factor.

4.8.4 Material transported

The main impact of the material transported on maintenance interval of the splice is the temperature of the material. The type of material transported has a large influence on the lifetime of the belt; the impact on the splices is often limited. In Figure 41 both factors are given.

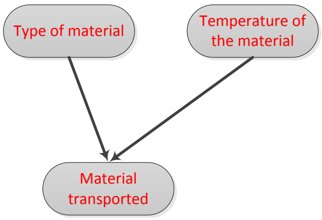


Figure 41: Material transported with the nodes not present in the simplified model in red

Material transported will be excluded completely from simplified model. Temperature of the material is outside of the scope of this research. The main impact of type of material on the splice is large chunks of material dropping on the belt at the transfer point. The bulk material handled at Tata Steel rarely has a large chunk size. If the chunks are too big, they get separated from the bulk material by the filters present in the BCS network. Because of the limited impact of this factor, material transported will be excluded from the simplified model.

4.8.5 The resulting simplified model

The model resulting from taking the above described simplifications into account is presented in Figure 42. A larger version of this figure is included in Appendix B: The simplified model.

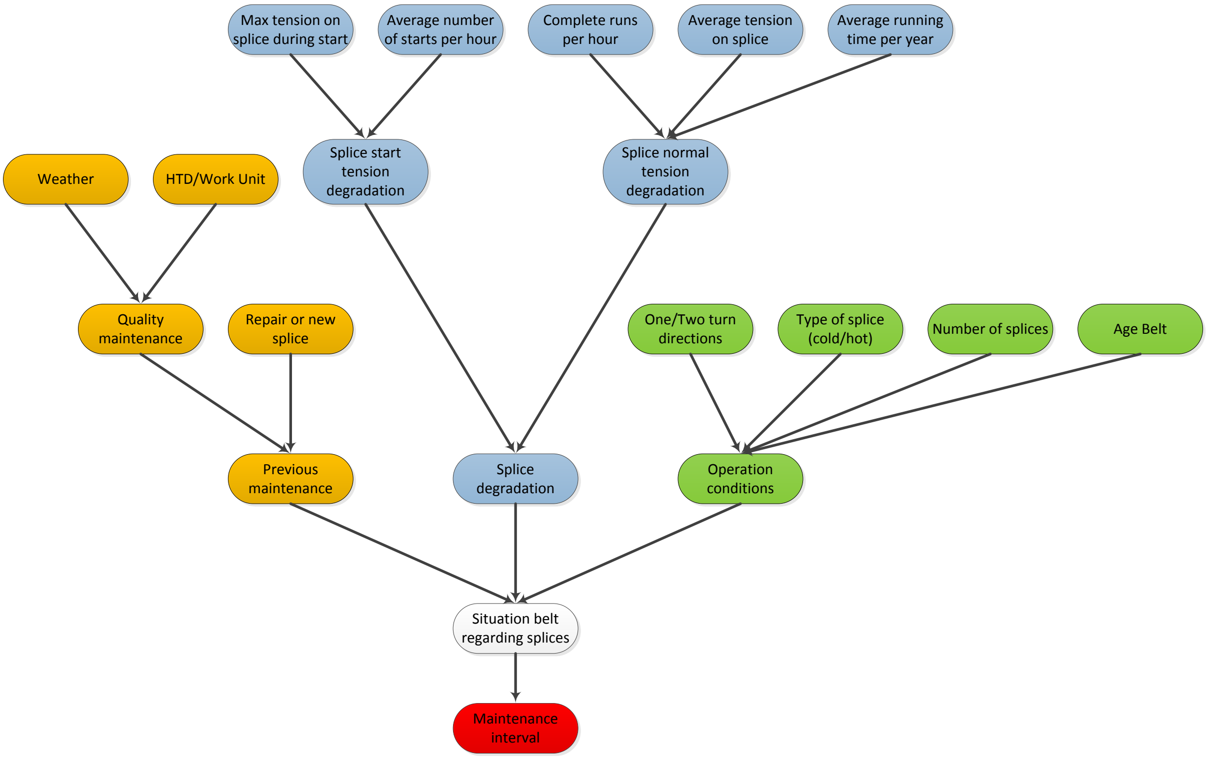


Figure 42: Simplified model

If the model is followed from bottom to top the first node present is the maintenance interval. The maintenance interval is based on the situation of the belt regarding splices. The better the state of the belt is, the longer the interval of the maintenance. The situation of the belt regarding splices in turn depends on three nodes: previous maintenance, splice degradation and operation conditions. Each of these nodes depends on the nodes above them. The above presented model will now be implemented.

5. Implementation of test cases

In the previous chapter a simplified model has been made following the earlier discussed method. The next step in the model making process is obtaining the data for the model. In this chapter first an overview of the conveyor belts included in the model is given. Then the process of obtaining and processing the data for the belts included in the model is given. The way the model has been made is then shown. Also the input and output of the model is presented. Finally the output of the model is analyzed and based on this output, the model is verified.

5.1 Choosing belts for research from data

Tata Steel has a large number of belt conveyors operational. Collecting and processing the data for each belt is not feasible so a limited number of belts have been selected. In section 2.4 the different departments and the number of BCS they own is shown. The department with the most BCS, GSL has been selected as source for the data used for making the model.

The first step is determining what BCS are the most "interesting" for the model. HTD has of nearly every belt present at GSL a file with the date and type of each maintenance action performed by HTD. The maintenance actions performed by HTD go back in time till the initial construction of most BCS. Some belts where constructed in 1966 meaning that there is sometimes for nearly 50 years of data. Before all this data could be used it had to be combined to a single database. In the original Excel files the data is spread over multiple sheets, each spanning a decade. Because all the data was put in manually there are also a large number of inconsistencies in the data. The final step for processing this data was limiting it to a limited time period. The quality of the belt, the maintenance performed and the operation conditions have most likely been changed over the last 40 to 50 years. Most of the other data sources are only available for a far shorter time frame. Using data to far back in time, would leads to a great limitation on the available data. Because of these reasons only the data from the year 2000 till the start of this research, beginning of 2014, has been taken into account.

Using the made database all the belt present at GSL have been compared to select the most suitable BCS's for the model. This selection process has been performed using the following criteria.

The first criteria is that the belt is included in the scope, so a fabric belt transporting cold material between two transfer points or silo's.

The second criteria is that a decent amount of maintenance actions happens to the belt. There are for example belts that only had a single maintenance action since the year 2000.

The last criteria is the importance of the belt. In this case the importance is how long the belt is allowed to be non-operational.

For the last criteria some extra information had to be added to the earlier created database. This information has been extracted from a file used to assign each belt a FMEA (Failure Mode and Effects Analysis) score. The score each belt gets is between 1 to 4. What that score indicates is explained in Table 5.

Table 5: FMEA number with the description

FMEA	Description
1	Disturbance if out of commission for more than a week
2	Disturbance if out of commission for more than 48 hours
3	Disturbance if out of commission for more than 24 hours
4	Disturbance if out of commission for more than 4 hours

Using the created database and the earlier discussed selection criteria, nine belts have been selected. These nine belts both fulfil the requirements of the scope as score the highest on the other criteria. The nine belts used for collecting data for this research are shown in Table 6.

Table 6: Belts included in this research

Belt Name	Length (m)	FMEA	Transported material
A-463	1400	3	Coal
A-471	704	3	Coal
A-504	1200	2	Ore
E-300	1225	3	Ore
E-502	1800	3	Ore
L-5	86	3	Ore
L-20	52	2	Ore/Cokes
S-502	38	2	Ore
U-700	306	4	Pellets/Sinter

All the belts at Tata Steel have a name based on a letter followed by a number. The letter in the belt name gives a rough indication where the belt is located. The U in U-700 for example indicates belts that are located near the blast furnaces. The length given in Table 6 is the conveyor belt length; this is around two times the length of the BCS. The material that the belt transports is mainly important for the lifetime of the belt. This has less influence on the maintenance interval of the splices.

5.2 Data HTD

Now that the BCS that will be used have been determined, the focus can switch to collecting data for these nine belts. For this data we first focus on the data available at HTD.

5.2.1 Maintenance performed to conveyor belts by HTD

The main source of information from HTD about the maintenance performed is the earlier discussed files containing every maintenance action performed by HTD to the different belts since 1966. Now content of this data will be explained in more detail. In
Table 7 part of the Excel file has been presented.

Table 7: Example of recording maintenance performed by HTD

datum	bs.nummer														wak/eov	uren	mat.	fabr.	magazijn nr.	opmerkingen
		1	2	3	4	5	6	7	8	9	10	11	12	13						
04-04-12.	2594948		X												E.O.V.	12		las 2 oude rep beschadiging repareren.		
18-06-12.	2639596		X												E.O.V.	12		las beschadiging repareren.		
30-08-12.	2697240										16				E.O.V.	VP	afd.zelf	Conti	47.01.12.421.2	slecht stuk.

The first thing you notice is that details about the full extent of the maintenance performed are limited. The first column indicates at what date the maintenance action has been performed. The tbs. number can be used to trace back the order for this maintenance action. The order contains information about the cost of the maintenance, extra equipment like a crane needed and some extra information. This contains very limited information about the maintenance itself. The type of maintenance performed can be one of thirteen types. The type of maintenance is indicated by a cross in the cell under the relevant number. Maintenance action ten is replacing a piece of belt, the number in that cell is the length replaced. In Table 8 the different types of maintenance actions are presented. On the right site there is an indication of the number of hours used for the maintenance action. Some very rough details about the scope of the maintenance and in case of a new belt the manufacture and the material number for ordering the new belt.

Table 8: Types of maintenance performed by HTD

Lose splice rep.	1
Damaged splice rep.	2
New protection strip	3
Protection strip rep.	4
Top layer rep.	5
Tear rep.	6
Hole in belt rep.	7
Burned spot rep.	8
New splice	9
Piece in between	10
New belt	11
Molded edge rep.	12
Shortening belt	13

The relevant data that can be extracted from this source is that data a repair is performed and the type of repair. The exact extent of the repair performed is unknown. A damaged splice repair for example can be everything from reattaching a small corner of the splice to repairing extensive damage to the splice. The cause of the repair is only mentioned sometimes during special circumstances. The final piece of information that could be extracted is the manufacturer of the belt. If a new belt or piece of belt is installed, the manufacture of the belt is mentioned. Most belts that are being used are from Continental or Dunlop. There are also some belts that are from China where no manufacturer is mentioned. The type of splice used for each belt is recorded in a dedicated Excel sheet. If during maintenance another splice type is used than normal, this is also recorded for that maintenance action. This data is available for all belts that are maintained by HTD.

5.2.2 Other data from HTD

There are a number of other data sources that contain information useful for this research. The first source is an Excel sheet that contains all BCS at Tata steel. For each BCS present the type of splice and belt used is recorded. The type of belt can also be determined from a number of other sources but some, like the technical drawings are sometimes outdated. Since this document for both the type of splices and belt type is in active use, it is updated to the latest situation.

Another source of data is the Excel sheet made by Dennis Oudhoff for his thesis [30]. This sheet contains the running speed of all belts present at Tata Steel. He collected the speeds by going over the design drawings of each BCS where the design speed is given. The design drawings used will be discussed later.

The last source of data that is interesting to mention but cannot be used in this research are the forms filled in by the maintenance crew of HTD after each maintenance action. Rob de Pagter who is responsible for the planning of the maintenance, has maps containing all the forms tracing back multiple years. At this form the maintenance crew can write observations about the maintenance performed. Grade the surroundings of the maintenance location and write down the temperature and humidity at the time of the maintenance action. The temperature and humidity is only written down during repair actions and not during belt replacements, so this data is incomplete. During a talk with the maintenance crew it was indicated that the surroundings where nearly always average. There was always something that could be better so it was never good. Since the surroundings are nearly always filled in as average, the usability of this data is low. Because of these reasons, this source of data has not been used for the model.

5.2.3 Other data available

The first type of other data than from HTD available is the data contained in the database system SAP. For the exchange of information and orders the enterprise software system SAP is being used. SAP is used by all departments to share information both internal as between the different departments.

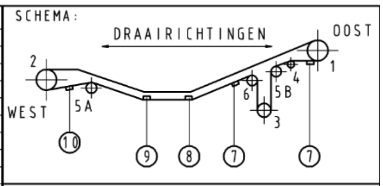
SAP is used the register nearly everything that happens at Tata Steel. In SAP all notifications concerning the BCS are recorded. There is data available in SAP since 2002, the year SAP was first used. Most notifications concerning the belt are about a certain problem someone has detected during the daily inspections or during their normal work. The notification is often someone mentioning that they detected what could be a problem on the belt. After this notification someone of the department or HTD takes a closer look at the reported problem and often reports back in SAP. Unfortunately both the initial notification as the response is often very limited. Often the response is simply that there is no problem detected. If there is a problem detected the response is most of the time: needs further attention of either HTD or the department themselves. No further information is provided about the severity or cause of the problem. If a repair has to be performed, the information concerning this repair is mostly exchanged by email or oral and not using SAP. In SAP only the data like hired and used equipment, number of man-hours and cost can be traced back. Details about what sort of maintenance performed are not recorded in SAP.

Processing the data from SAP is a lot of work. Each BCS is separated in components in SAP. The amount of notifications present in SAP in the directory dedicated to the belt of a particular BCS is often limited. But problems involving the belt are also often present in the other directories of the BCS. The total number of notifications that has to be processed can be up to 1200 per BCS. SAP has a tool to export these notifications to Excel for easier processing; this is unfortunately only limited to the sort description present at the notification. This short notification is often very cryptic like: problem belt. For more details the long description is required. To add the long description to Excel, one first has to open each notification, than copy the text to Excel and repeat. Once every description is added to Excel, the real data processing can begin. The first step is filtering out all the notifications that are not relevant for the conveyor belt. Once this step has been completed, the double notification has to be filtered out. More than one notification is sometimes created for one problem. This is caused by either different persons or because the original creator of the notification thought there was not action undertaken after the first notification. Once the double notifications have been filtered out, the remaining notifications have to be compared to the maintenance data supplied by HTD. A notification is often the source for a maintenance action performed by HTD. If both the original notification and the maintenance action itself are taken into account separately, the maintenance action performed is counted double. The final challenge is to determine who carried out the remaining maintenance actions following the notifications. Some of these maintenance actions are performed by HTD although they are not present on the sheets containing the maintenance actions performed. This is either cause they are emergency maintenance and not planned or too small to specifically plan. The end result is a list of maintenance actions resulting from notifications and who performed them. Some notifications contain a description of what caused the maintenance action but most notifications simply point to damage to a belt without any cause.

Another source of information is the technical drawings of each BCS. For each part of a BCS technical drawings are present that have been used to build and maintain the BCS. For each BCS there is an overview drawing that gives an overview of the most important properties. From this drawing one could for example extract the height difference between the take-up and transfer point of the BCS. Another useful feature of these drawings is a table containing the dimensions of the most important parts of the BCS. The size and number of pulleys is also documented here. One thing to keep in mind is that some of these drawings are outdated. Basic properties like number of pulleys and belt speed will not change often. The type of belt used on the other hand is sometimes changed during the lifetime of the BCS. An example of a table is shown in Figure 43.

TRANSPORTBAND:	E300
BREEDTE:1200 MM	TROGVORM: 30°°
SNELHEID:2,2 M/S DRAAIR.O	
SNELHEID:2,2 M/S DRAAIR.W	
SPANGEW:89 KN.BER.90,5KN.DRRW	
SPANGEW:89 KN.BER.91,6KN.DRRO	
KWALITEIT:EP 1250	DEKLAGEN: 5
LENGTE:1225 M.(ZONDER LAS)	
BEREKENDE CAPACITEIT:	
1178 M3/HR 1774 T/HR DRAAIR.W	
1178 M3/HR 2529 T/HR DRAAIR.O	

SCHEMA:



MUT.DATUM: 26-07-2005 TEK.477763-19

BANDAANDRIJVING:	FABRIKAAT EN TYPE	KW	N	I	TEK.NR.	OPM.
MOTOR OOST:	IEC 225M+IEC 315M	45+132	1485			
MOTOR WEST:	IEC 355/1	160	1500			
TANDWIELKAST OOST:	2xBIERENS C2A3-110	132 KW		36	272830+486846	
TANDWIELKAST WEST:	1XBIERENS K2A3-125	199 KW			320767	
PRIMAIRE KOPPELING:	OOST: 2XVOITH 487 TV1				672935	
PRIMAIRE KOPPELING:	WEST: 1XVOITH 562 TV1				672936	
SECUNDAIRE KOPPELING:	OOST: TACKE SB 200				200750	
SECUNDAIRE KOPPELING:	WEST: TACKE SB 200				200750	
RIJDWERKAANDRIJVING:						
MOTOR:						
KRUIPGANGMOTOR:						
WORMKAST:						
KOPPELING:						
REM:						
LOOPWIEL:						

TROMMELS:	AAND.	DIAM.	ASTAP	TEZOS	BEKL.	AANT.	TEK.NR	OPM.
AANDRIJF-	1	ϕ 1000	200K/200K		JA	1	307467	
AANDRIJF-	2	ϕ 1250	200 /200K		JA	1	A15028	
SPAN -	3	ϕ 630	ϕ115			1	801431	
INSNOER -	4	ϕ 400	ϕ 90		JA	1	801427	
INSNOER -	5A	ϕ 400	ϕ 90		JA	1	801427	
BUIG -	5B	ϕ 500	ϕ 90		JA	1	243581	
BUIG -	6	ϕ 500	ϕ 90		JA	1	413566	

Figure 43: Basic properties of a BCS

From the table and the drawing a number of relevant data can be determined. The basic properties of the belt like width and type used are present. The height difference between the transfer and take-up point can also be determined using the drawings. The speed of the belt, capacity and length are also present. Finally the number of pulleys and their respected size is given.

Lastly the weather data has been collected. To determine the weather during the maintenance work outside, the data from two measurement stations has been used [31]. The average wind speed during a day is measured at a station in IJmuiden. The temperature and rain is measured at Wijk aan Zee since May 2001. Strangely, neither measurement station collects the full weather data. For this reason the data sets of the two stations had to be combined. The area that contains nearly all BCS on the terrain of Tata steel is located between the two stations.

5.2.4 Data collected from GSL

Not only data from HTD has been used, also some data from the owners of the BCS's has been used. The first type of data that is relevant to the conveyor belt is the power of the drives installed at the BCS. Every BCS has at least one motor to power the conveyor belt. Some BCS have up to three motors that are only used for powering the conveyor belt. Sometimes there are also some motors present in the BCS that are used for vibrating the dribble chute or to move the frame of the BCS to service different belts/bunkers. These motors are not relevant for this research. Only the installed power of the motors is known; the actual power they provided during operations is not measured. The installed power of the drives is also presented on the technical drawings. This second data source can be used to check if the power on the drawings is up to date. The last replace date of the motors is also available; this shows that most motors have a long lifetime. Some are still from the initial construction.

The second type of data available at GSL is the usage of the BCS. The BCS only run if they are required for the transportation of material. The amount of time a belt is in used depends on the location of the belt. Some belts are used rarely while others are in nearly continues use. The running time of the belt also depends on the position of the BCS in the series of belts. An example of a series of belts is given in Figure 44. In this series of belt, material is transported from the left silo over the three belts to the right silo. During the startup and stop from the series of belts, the material flow has to be taken into account. If for example belt A is started while belt B is still standing still, material will collect at the transfer point. The material from belt A will form a heap on belt B, blocking the belt and potentially damaging it. To prevent this from happening, first belt C has to be started. Once belt C is up to speed, belt B can be started. After belt B is up to speed, finally belt A can be started and the material transfer can begin. For stopping the belt the same is true, only now the other way around. So first belt A has to stop, than belt B and so forth. For long series of belts this can lead that the final belt is nearly always running while the first belt is mostly standing still, waiting for the other belts to start or stop.

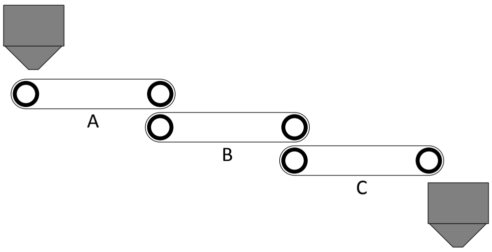


Figure 44: Conveyor belt setup with three belts

The quantity of the transported material depends mostly on the source of the material and the maximum capacity of the lowest capacity belt in the series. Some belts are supplied by a silo; this will lead to relative even loading. If a belt is supplied by for example by a quay crane or bucket wheel excavator, the loading is much more uneven. Often it consists of a part of the belt loaded with material, followed by an empty part.

The running time of each BCS is documented on a 5 minute interval. For every BCS the running time is collected and stored. For the material transported, a number of weight installations are installed at some BCS on strategic places. This makes sure it is exactly known how much material is transported between two locations. Each transfer from material from one location to another is a so called order. The amount of orders each day is in the thousands. GSL is mostly interested in how much material is present at each location, not in how much material passes each BCS. The only BCS of which the amount of material that passes over them is known, are the BCS used for weighing the material. Determining the amount of material that passes over a BCS without a weighing mechanism can be a challenge. Most BCS are part of a complex network leading to a lot of possible series of belt conveyors. To determine the material transported by a particular belt conveyor, you would have to collect the data of each possible series this BCS is involved in. Because of the complexity of the network, determining the possible series is a difficult task. The person responsible for this system does not have the time available to perform this task. That is why there is very little data available of the amount of material transported by the BCS.

The running time of the 9 most interesting BCS have been provided by Ron Schuurmans for the period of October 2013 to May 2014. This consist of a Excel containing all 9 BCS with either a 0 for not running or 1 for running, to indicate if a belt was running during those particular 5 minutes. Using this data an average running time of each belt per year can be determined.

5.3 Preparing the data for usage

Before the data can be used its first has to be processed. Some of the data available contains multiple variables that are all relevant but could be combined to a single variable describing the effect of these combined. Other variables are spread over different data sources. The data is processed in such a way that it can be used in the model proposed in chapter 4. The quality of some of the data sources is also discussed.

The first step in the data processing is determining the date that maintenance to a certain belt has been taken place. This is determined by combining the processed data of both HTD as SAP to create a list of each maintenance action. This list then can be filled in for each variable determined in chapter 4 to be relevant for the model. The first variable is weather.

Weather

The variable weather describes what type of weather it is during the maintenance action to the splice. It should be noted that the weather data that has been collected is for a time period of 24 hours. The maintenance action itself takes place during only a small period of this interval. The quality of this node could be improved by documenting the exact weather conditions during the maintenance action.

Weather has been divided in three ranges. The weather is either: good, average or bad. To determine the type of weather during a day, two factors are taken into account. The amount of rain and the wind chill temperature. The wind chill temperature can be determined using the following formula:

$$G_{m/s} = 13{,}12 + 0{,}6215T - 13{,}96W^{0{,}16} + 0{,}4867TW^{0{,}16} \text{ [32]} \quad (5\text{-}1)$$

In this formula the T is the average temperature during the day and W is the average wind speed. $G_{m/s}$ is the perceived temperature when a human is subjected to wind. The formula above has been made using a spreadsheet comparing the real temperature and the effect of wind on a human body. This is the same formula used by the KNMI to determine the wind chill temperature in the Netherlands. The reason that the wind chill temperature is taken into account is because maintenance to BCS outside is during normal circumstances unprotected from the weather. The second factor is the amount of rain during the day. Rain during the creation of the splice could reduce the quality of the splice.

Weather is bad if the wind chill temperature is either below -6 ˚C or above 28 ˚C. The temperature of below -6 ˚C originates from the collective agreements for the construction workers in the Netherlands [33]. At that temperature they do not have to work anymore. At Tata Steel there are no rules concerning working in low temperatures. Personnel performing work outside just has to put on a thick coat but that does not mean that the work does not suffer from low temperatures. For warm weather, rules do exist at Tata Steel. Depending on the intensity of the work performed, limitations on the amount of work performed are taken. For the maintenance of BCS these limitations come into effect at 28 ˚C.

Average weather consists of either a temperature between -6 ˚C and 10 ˚C or more than 1 mm rain during a day. If there is rain predicted, a tent has to be built to protect the splice. Sometimes the scaffolding builders who are responsible for the tent are occupied with other projects. Other times they start too late with building the tent or the rain is unexpected. In these cases the decision is to the workers to start the maintenance operation or postpone it to another day. If the rain is in their opinion limited, the maintenance is often still carried out. The splice is dried as good as possible with some towels and portable heat blowers. The newly created splice is then cover with some fabric to protect is a good as possible against the rain.

Finally a day is considered good if the average temperature is between 10 ˚C and 28 ˚C and less than 1 mm rain did fall. If the amount of rain during the day is less than 1 mm, the chance that it is raining during the splice repair is limited. The amount of rain is also so little that the influence on the splice is limited. The temperature during the day is not to cold and not too hot to work.

HTD/Work unit

This variable indicates who performed the maintenance action. It is either HTD or Work unit. Determining who exactly performed the maintenance can sometime be tricky if the data is provided by SAP. There is often no clear indication of who performed the maintenance action. As discussed earlier, the workers of HTD specialize in conveyor belt maintenance while it is often a sub task for the work units. Because of the difference of knowledge and experience, the type of maintenance performed is also often different between the two departments. HTD does all types of repairs while the work units do only the easy and emergency repairs. The emergency repairs performed by the work units are usually performed because of a number of reasons. The belt is either crucial for operations, so a long delay caused by HTD to come to the site and perform the repair is not possible. The other main reason is that HTD has no personal available to perform the maintenance. The repair often consist of cementing some strips to the belt hoping the splice survives till HTD has time or cutting the lose parts away.

Repair or new splice

The maintenance action can either be repairing an existing splice or making a new splice. It should be noted that making a new splice is not only performed when a new belt is installed. There are a number of other maintenance actions to the belt that require the creation of a new splice. A conveyor belt is put under a certain tension by a tensioner. This tensioner has a certain range. If the belt stretches too much during operations, the tensioner can no longer keep the belt under the correct tension. The belt has to be shortend to put sufficient tension on the belt again. Normally a splice is torn open, one of the ends of the belt is shortened and a new splice is created. Inserting a new piece of belt in an existing belt to replace a damaged or worn out part of the belt, also leads to the creation of new splices. Finally a splice is sometimes so bad that it had to be completely destroyed since repair was no longer feasible. A new splice is in this case also created. Determining if a new splice is created or a repair is performed is sometimes hard. The details about the extent of a repair action to a slice often do not contain the information if the splice has been completely renewed or simply repaired.

One or two turn directions

This variable describes if the belt moves either one or to both directions. The amount of directions the belt moves is mainly of importance for the effect of the scrapper. If the belt is only moving in a single direction, the scrapper can in theory not get stuck on the splice. If the belt is moving in both directions, one direction is safe for the scrapper while the other could potentially be destroyed by it. If the scrapper gets stuck on the splice, the splice gets torn apart. The direction of the belt can be determined by looking at the construction drawings.

Type of splice

The variable type of splice indicates if the splice is created using cementing or vulcanizing. The difference between the two methods has been discussed earlier. Belts have been designated a splice type depending on their operating conditions and demands of their owner. This type is present in an overview sheet in Excel but is not always true for hot splices. A belt that should receive hot splices sometimes is maintained using a cold splice. This is done sometimes by mistake, other times no equipment or time for a hot splices was available. If another splice type than the normal one is used, this is often indicated in either the sheets of HTD or in SAP.

Number of splices

This variable is for longer belts sometimes extremely hard to determine. Short belts only have a single splice but longer belts can have at the end of their lifetime more than ten splices present. A new long belt is already created with more than one splice. Because of the cost of replacing the entire belt, small parts of new belts are often inserted to replace damaged parts. Each new belt part increases the number of splices in the belt by either one or two. One if the replaced damaged part contained a splice. Details about what part of the belt has been replaced are most of the time not present, so it is unknown if a maintenance action involving a new belt parts adds one or two splices to the belt. Long belts can have a large number of new pieces inserted leading to a high possible variation between the number of splices present in the entire belt.

Age of the belt

The age of the belt indicates how long the belt is already in operation. During operations the belt will wear and the splice will suffer from degradation. The older a belt is, the shorter the maintenance interval will be. The age of the belt is limited to a single year for the model. Once a belt is older as a year the model will simply take the belt into account as old. For longer belts the age of the entire belt can be hard to determine. If a new piece of belt is inserted in the belt, is the age of the belt then zero or still based on the oldest part. One could even look at the age of each part of the belt and depending on the size of each part determines an average age. The length of each new part of belt is known but not which part of the belt the new part replaces. Because of this reason the age of the belt is linked to the last replace maintenance action of the entire belt.

Complete runs per hour

The number of complete runs a belt performs during an hour is based on the normal belt speed and it length. A complete run is once a spot on a moving conveyor belt passes a certain location for the second time. The length of the belt has been extracted from the technical drawings. There are a number of sources for the belt length but most take extra length for the creation of the splices during installation into account. For the speed of the belt the data collected by Dennis Oudhoff has been used. Combining the speed in m/s and the length in m in the following formula gives the number of runs per hour:

$$\frac{V \times 3600}{L} = N_{runs} \qquad (5\text{-}2)$$

Average running time per year

To determine the average running time per year the data provided by Ron Schuurmans has been used. The data did not spawn a complete year because of limitations of the allowed sheet length of Excel. The time period provided was large enough to determine an average over a year. Looking over extended periods of times little differences can be detected since the production of the plant in question is not based on seasonal goods. The average running time can be easily determined by looking how much time a particular belt was moving and when it was standing still. It should be noted that the average running time per year is based on when a belt is moving, not when a belt is transporting material. A belt at the end of a long chain of BCS can be running nearly always while only transporting very little material. Unfortunately data about when a belt is acutely transporting material was not available.

Average tension on the splice

The average tension on the splice indicates how much of the allowed tension is on the splice during normal operations. Since there is no data about the tension on the belt available, this value had to be calculated. For the calculation for the tension on the formula from CEMA [34] has been used.

Before this calculation can be performed first the power provided by the drive during normal operation has to be determined. The amount of hp supplied to the belt during normal operations is currently not measured. To determine the hp during normal operations an earlier made and validated model at Tata Steel has been used. This model has been made under supervision of Pieter van Ammers. This model was made to calculate the power used by a BCS during normal operations. The inputs required for this model can be determined using the above mentioned data sources. One of the key components for this calculation is the amount of material the belt is transporting per hour. Since no real data is available for this, the design capacity has been used. This is most likely too high, but because of the different operating conditions of the BCS used for the model it was not feasible to determine the real capacity for each BCS.

The first step in calculating the average tension on the splice is calculating the effective tension on the belt using the following formula:

$$hp = \frac{T_e \times V}{33{,}000} \quad (5\text{-}3)$$

hp is the horsepower of the engine, T_e is the effective tension and V is the speed in fpm. The speed of the belt is known, the maximum hp of the engines installed at the BCS is also known. The maximum tension on the belt can then be calculated using the following formula:

$$T_{max} = T_e + T_e \times C_w \quad (5\text{-}4)$$

C_w is the wrap factor of the belt around the drive pulley. In Table 9 the table used for determining the wrap factor is been presented.

Table 9: Wrap factor for a rubber surfaced belt

Type of Pulley Drive	θ Wrap	Automatic Takeup		Manual Takeup	
		Bare Pulley	Lagged Pulley	Bare Pulley	Lagged Pulley
Single, no snub	180°	0.84	0.50	1.2	0.8
Single with snub	200°	0.72	0.42	1.0	0.7
	210°	0.66	0.38	1.0	0.7
	220°	0.62	0.35	0.9	0.6
	240°	0.54	0.30	0.8	0.6
Dual*	380°	0.23	0.11	0.5	0.3
	420°	0.18	0.08	—	—

The maximum tension on the splice is now known. It should be noted that this is the short method for calculating the tension in a belt. This method gives a good indication of the tension of the belt. For an exact tension the long method can be used better, but because of the large amount of input required this method is less useful for the model.

The final step before this input can be used in the model is to determine the allowed tension on the splice. The allowed tension on the splice depends on the belt type and the number of layers of the fabric. For example a belt of the type: EP 800/4 means the fabric is made of Polyester-Nylon (synthetic yarns). 800 indicate the allowed tensile strength of the belt and 4 is the number of plies. In a fabric belt the splice is a weak point. At the splice steps the tension in the belt is only conveyed by 3 plies instead of 4. The allowed tension on that location is ¾ of the allowed tension in the rest of the belt. The average tension calculated has then been compared with the allowed tension in the splice of the belt.

Maximum tension on the splice during start

For the calculation of the maximum tension on the splice during the starting process of the belt, the method used for calculating the average tension can be used. Only now the hp provided by the engine does not depend on the power supplied during normal operations but on the maximum during the start of the BCS. Since no data about the power supplied during the start the installed power of the engines is used. During the start-up process of the BCS the engine provides a peak power higher than the installed power. The height of this peak is determined by how the engine is connected to the drive pulley. If it is a direct connection this peak can be between 2-3 times the installed power. A fluid coupling can limit this to around 1.5 times the installed power. Finally a soft starter can reduce the peak to around 1.2 times. The maximum tension calculated has then been compared with the allowed tension in the splice of the belt.

Average number of starts and stops per hour

The average number of starts and stops per hour can be determined by looking at the data about the running times. Simply count the number of times the belt has been started during a curtain time period and use that number to calculate the average per hour.

5.4 Variations detected in data

During the processing of data a lot of variations between maintenance actions were detected, even if on paper the maintenance action were the same. This variation can be explained by a number of factors.

The maintenance action itself can be of insufficient quality causing another maintenance action to follow soon after. This insufficient quality can be caused by a number of reasons. The workers performing the maintenance can for example have a bad day or in a rush. The workers are humans so they can for example rush a maintenance action if they want to be home on time to watch a football match. Another reason is that there is insufficient time to perform proper maintenance. If a belt is desperately needed, insufficient time can be provided to perform the maintenance. The full extent of the damage to the splice is sometimes not clearly visible, the maintenance performed is to shallow to fully repair the splice. The belt can also be located on a location that is not easily accessible. Some belts are located within machines causing the workers to perform the maintenance in a cramped space. Finally the maintenance performed is all done manually without a real quality check. Even the smallest error during the splice creation can grow over time under influence of the movement and tension of the belt.

Another reason for a maintenance action happening much sooner than expected is that the belt or splice has gotten so bad that repairing the splice fully is no longer feasible. Because of the schedule or lack of replacement belt, the belt has to be repaired to such extent that it can operate a little longer. Once a timeslot or replacement belt is available, the cause of the maintenance can be removed.

It is also possible that unexpected maintenance is caused by external damage to the belt and splice. This can be caused by a foreign object in the bulk material damaging the belt or unaligned running of the belt. Another object that can be the cause of unexpected maintenance are the scrappers. Badly set-up scrappers can destroy a conveyor belt in a single day. If a belt runs in both directions, the scraper can also easily damage the splice.

A splice can also be destroyed or damaged by incorrect usage of the belt. A transfer point that is for some reason full of material should be emptied manually, in practice that belt is started a couple of times till it manages to remove most of the material. Another example is a belt that transports both coals as iron ore. The two bulk materials have different densities, during the loading of the belt; this is sometimes not taken into account.

5.5 Making the model for the test case

In this chapter the process of making the model for the test case itself is discussed. The model has been made in Excel but the general method of making this model for the test case will be discussed. The first section of the model discussed is the input.

Inputs for the model

In Figure 45 the input of the model has been presented. Each input consists of one of the variables that influence the state of the belt concerning splices for this test case.

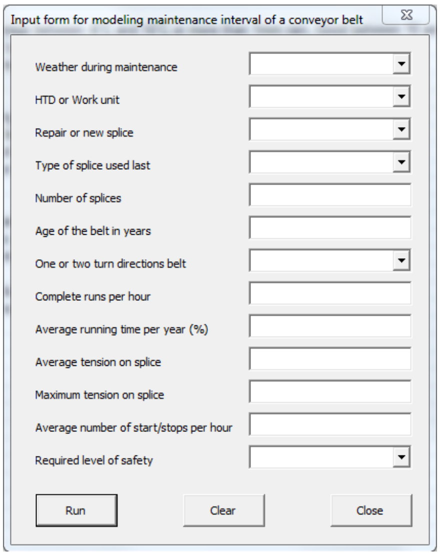


Figure 45: Input form of the model

It should be noted that the show form is purely made for the input of data, on the sheet containing this form extra information is provided about the properties of each input variable. The last input variable is used to indicate the safety level of the belt in question. During this test case this safety level is used to indicate the spread of the maintenance interval since this could not be determined using the data.

Fuzzification

The second step while using the model is fuzzification if the input so it can be used for the Bayesian network. First a separation has to be made between inputs that only have a fixed number of possibilities and those that have a wide range. An example of an input that has a fixed number of possibilities is the number of turn directions of the belt. This value is either 1 or 2. This are the only possibilities, 0 turn directions means that that belt never moves and more than 2 is for a BCS impossible. An input with a wide range is for example the number of complete runs per hour. This could in theory be anything between 0 and unlimited. Fuzzification in the case of a fixed number of possibilities is unnecessary if the number is low enough.

To indicate how the fuzzification is performed in the model, the variable average running time per year is used. This variable indicates how much percent of the time a conveyor belt is running on average. It should be noted that no separation between loaded and unloaded running is made since data for this was not available for this test case.

The average running time per hour is represented in three ranges; in Table 10 these three ranges are shown. A conveyor belt that is running 50% of the time is considered as medium, so the membership in this situation is equal to 1.

Table 10: Example of the evidence and range of average running time per year

Evidence	Range
Short	0
Medium	0.5
Long	1

But what is the membership if the average running time is not exactly equal to a range. To determine the membership in this situation, equation 3-2 to 3-4 are used. An example of the usage of these formulas is given in equation 3-11. The calculated memberships are used to determine the estimated likelihood densities at an later part of the model.

Estimated likelihood density functions and Posterior probability

With the fuzzified inputs available we can now look at how the BBN method is used for the model. Before the method can be used first the tables containing the prior probability and conditional probability have to be included in the model. To show the workings of this test case only a limited number of nodes are shown. The part of the model worked out in the next section is shown in Figure 46.

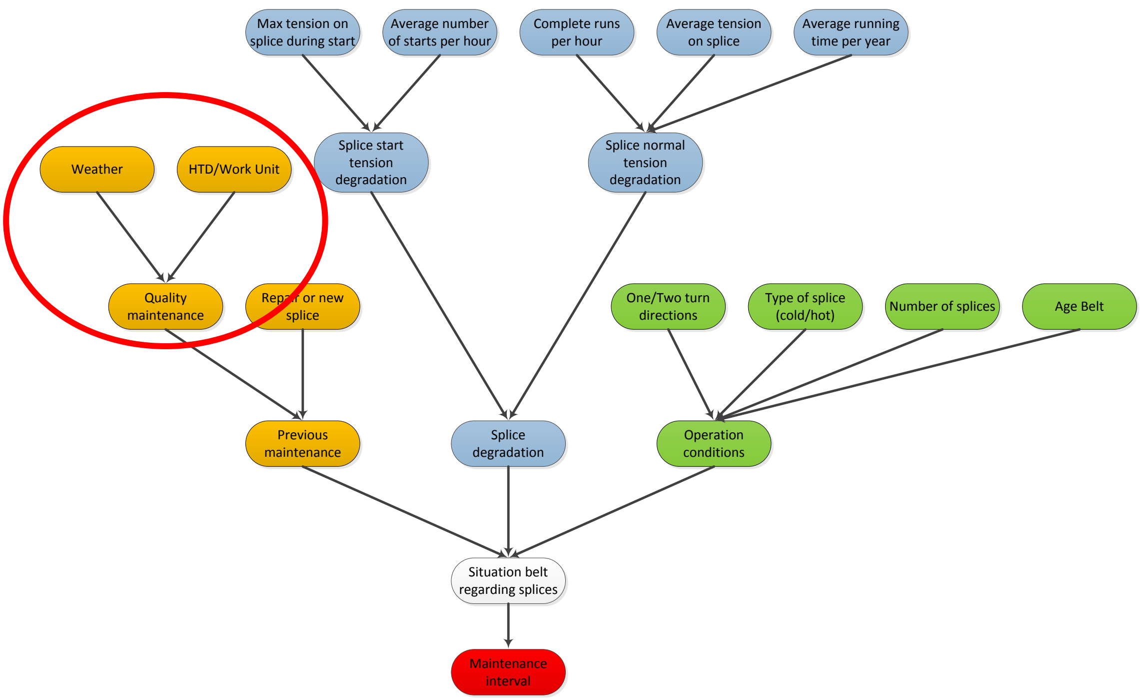


Figure 46: The encircled part of the model is shown in this section

The prior probability and conditional probability tables are used together with the input to calculating the quality of the maintenance performed during the last maintenance action. This quality of the maintenance performed is then combined with the type of maintenance performed to determine the state of the previous maintenance action. Combining this state of the last maintenance action with the operating conditions and splice degradation leads to a state of the belt concerning splices which is defuzzified for determining the optimum maintenance interval.

The quality of the previous maintenance action is based on who performed the maintenance and the weather during this maintenance action. The first step is including the prior probability for the quality of the maintenance performed (QM), this prior probability is show in Table 11. The QM can have two different ranges, either the QM is good (QM-G) or QM is bad (QM-B).

Table 11: Prior probability of Quality Maintenance performed

Quality maintenance	
P(QM-G)	0,53
P(QM-B)	0,47

The prior probabilities are based on the quality of the maintenance performed. To determine the prior probabilities the historical data is analysed to detect how often the maintenance performed was either good or bad. Determining this probability for this test case proved to be a challenge. The cause of nearly all corrective maintenance actions are not documented, so it is often unknown if the corrective maintenance action is performed because of a bad previous maintenance action or for another reason. By analysing all the maintenance actions of the 9 belts used for this test case over the last 14.2 years, an estimation of the prior probabilities has been made.

The next step is including the conditional probability table for the quality of the previous maintenance action to the model. The table containing this conditional probability for the quality of the maintenance performed is show in Table 12.

Table 12: Conditional probability of Quality Maintenance performed

Quality maintenance							
Weather		Good	Good	Avg.	Avg.	Bad	Bad
HTD/Work unit		HTD	Work	HTD	Work	HTD	Work
Quality maintenance (QM)	QM-G	0,97	0,25	0,54	0,38	0,22	0,27
	QM-B	0,03	0,75	0,46	0,62	0,78	0,73

In the table for the conditional probability the weather can have three different possibilities while HTD/Work unit have two possibilities. To cover each possible combination of these two variables, six columns in the table have to be used. For each combination of possibilities the conditional probability has to be determined. This can be performed by either utilizing historical data or using an expert opinion. The conditional probability tables of this test case have mainly been made based on historical data. Ideally a combination of historical data and expert opinions are being used. The reason that little expert opinion was used during the process of making this test cases is because it was impossible to get any numbers from the main expert concerning belt maintenance. The expert in this case could talk in great detail about the creation of splices and the extreme circumstance that could be involved during this creation. Because of these extremes and the high variation in the lifetime of the splices he did not want to provide any numbers. Providing no number avoids the problem that they are later used against you.

In Table 12 QM-G indicates that the quality of the maintenance performed is good, GM-B indicates bad maintenance. If one looks at the first combination in the table: Weather-Good, HTD/Work-HTD, the value QM-G is 0.97. This means that if both the weather is good at the moment of the maintenance and the maintenance is performed by HTD, there is a 97% chance that a good splice is been created. QM-B is in this case 0.03 or 3% since the sum of QM-G and QM-B is always equal to 1 for each combination.

The next step is calculating the estimated likelihood density. The estimated likelihood density can be calculated using equation 3-8. With the estimated likelihood density functions now ready for usage the final step of calculating the posterior probability according to equation 3-10. The posterior probability can be used to trace back the main sources of the state of the belt concerning splices and the resulting optimum maintenance interval. An example of the usage of equation 3-8 and 3-10 is given in section 3-5, Example of Bayesian Network.

State of belt regarding splices to maintenance interval

The above described method is repeated for the entire DAG describing the model. Once the complete model has been created a posterior probability for the state of the belt regarding splices is calculated. This state is very interesting but hard to use in practice. A practical output of this model would be a maintenance interval either in days, weeks or another timescale depending on the usage of the model. For this test case the maintenance interval will be given in days since the historical corrective maintenance interval is also in days.

We have a state of the belt and we want to transform that to a maintenance interval. A logical method to use is fuzzy logic since the inputs of the model are already fuzzified. By performing defuzzification on the output, a maintenance interval can be obtained. This defuzzification process must be based on either knowledge or historical data. Since for this test case the main source of historical data consist of the corrective maintenance intervals for 9 conveyor belts, this data has been used. For each corrective maintenance interval, the state of the belt regarding splices has been determined. With the usage of around 450 data points the defuzzification table has been created. Those 450 data points originate from the 9 belts over a period or around 14.2 years, there are situations where there where 3 maintenance actions in a single week. Because of these extremes present in the data all the data points are used to diminish the influence of the extremes present in the data. The state of the belt could not translated directly to a defuzzified maintenance interval based on the corrective data. The corrective maintenance interval originate from the moment maintenance is required to the belt because of damage detected. For a preventive maintenance interval, the maintenance has to take place before corrective maintenance has to be carried out. So the defuzzified maintenance interval must be shorter than the real corrective maintenance interval. The defuzzified interval is based on weeks since the maintenance planning at Tata Steel is also performed at an interval of a week. The interval is however represented in days since the corrective maintenance interval is also in days. In Table 13 the defuzzification table is shown.

Table 13: Defuzzification table for state of belt regarding splice to preventive maintenance interval

State of belt	PM interval
0	21
0,4	28
0,5	70
0,6	88
0,7	140
0,8	154
0,9	210

So how does Table 13 work in practice? The first row of Table 13 can be described as SB_i and the second row as PM_i. The output of the model describing the state of the belt regarding splices is defined as SB-G. SB-G indicates how high the posterior probability is that the belt is in a good state. So the higher the SB-G the longer the maintenance interval as you also can see in Table 13. By determining the i using the following statement $SB_i \geq \text{SB-G} > SB_{i+1}$ the PM_i can be determined.

Let us assume we an output of the model in the shape of SB-G = 0.35. SB_i in this situation is 0 and SB_{i+1} is 0.4, so the PM_i is 21. This means that the defuzzified output of the model is a maintenance interval of 21 days.
Another example is a SB-G=0.59, SB_i in this situation is 0.5 and SB_{i+1} is 0.6, so the PM_i is 70, so a preventive maintenance interval of 70 days.

Output of the model

With the model made, the output of the model can be presented. The output of the model consists of a maintenance interval in days and a safety margin. Earlier the method used in this test case for the safety margin has been discussed. The output form is shown in Figure 47.

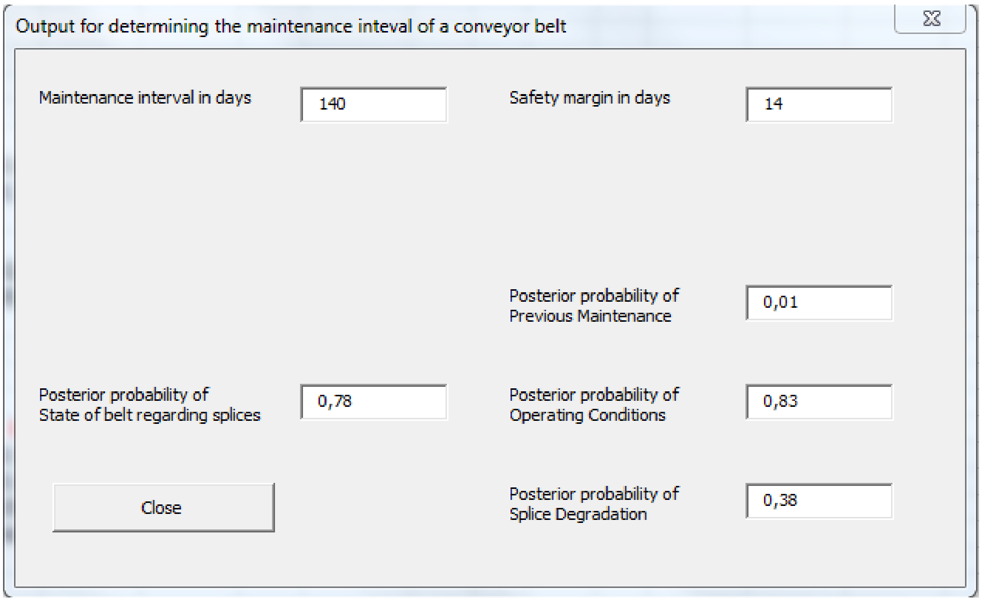


Figure 47: Output from of the model

In the top left corner of the form shown in Figure 47 the maintenance interval in days is presented. This maintenance interval is the defuzzified situation of the belt regarding splices. The defuzzification is performed using the earlier discussed Table 13. The state of the belt regarding splices used to determine the optimum maintenance interval is shown on the bottom left side. This is the posterior probability of the good state of the belt, meaning the higher this value, the longer the maintenance interval. On the top right side the safety margin in days is presented. This safety margin is for this test model determined using the required level of safety input. In section 5.7 some methods for improving this safety margin are discussed. On the bottom right corner the posterior probability of the pervious maintenance, operation conditions and splice degradation are shown. These probabilities are used to determine the state of the belt using the BBN method and give a good indication what causes the current state. The three posterior probability´s indicate how high the impact of each of the three sources of maintenance is on the state of the belt regarding splices. The posterior probability of previous maintenance for example is 0.01. This indicates that the previous maintenance is nearly optimal so if one would only look at the previous maintenance, the state of the belt regarding splices would be also nearly optimal. The state of the belt is however influenced by multiple factors. The posterior probability of operation conditions is for example 0.87 in Figure 47. This means that the operation conditions are far from optimal. The three factors that influence the state of the belt regarding splices are combined to determine this state. As you can see in Figure 47, the state of the belt regarding splices is 0.78 meaning that the state is relative good leading to an optimal maintenance interval of 140 days.

So why is the state relative good while the operation conditions are far from optimal. The reason for this is that the state is determined by taking all three factors into account. In this particular case, the operation conditions are not very good but the last maintenance action was nearly optimal. The influence of the nearly optimal maintenance performed leads to a maintenance interval that is still relative high. The splice will require maintenance sooner because of the sub optimal operating conditions but the start state of the splice after the last maintenance action is so good that it will last a decent time even under these operating conditions. The end result is a state of the belt regarding splices of 0.78 and an optimal maintenance interval of 140 days.

Impact data on model

The model of the test case has been created mainly using the historical data available at Tata Steel. This data is collected for the daily operations and not for the creation of a model. A lot of information is either communicated orally without documentation or through e-mail. In section 5.1 to 5.4 the process of collecting the data and processing it for usage is described. From this process it is already clear that a lot of simplifications had to be performed to have some remaining variables for the model. The normal and peak tension on the belt for example is completely based on assumptions since with the current available information it is impossible to calculate those accurately. Another problem with the available data about the maintenance performed is the lack of cause for the maintenance. Nearly always only the type of repair is mentioned not the cause of the repair. Because of this, the prior and conditional probability tables are based on every corrective maintenance action carried out on the nine belts included in the scope. Ideally these tables are based only on the maintenance actions that are directly influenced by the node the table is describing. So if you know a maintenance action is caused purely by too much tension on the belt during start-up, this interval is only assigned to splice degradation during start-up instead of all causes. The historical data is also of corrective maintenance instead of preventive maintenance. The timing of these maintenance actions is because of earlier discussed reasons different, ideally predictive historical data should be used for the model.

5.6 Verification and Validation of the model

Before the model can be used in practice it first has to be validated. The process of validation is performed using three steps. The first step is matching the output from the model to the expected output from the user. The second step is verification of the model. After this the reason why this model could not be validated will be discussed. Finally some remarks are presented on how the model could be improved in the current situation.

5.6.1 Matching

The first step of validating the model is matching. During this process the model is checked against what you logically expect. If an input variable is changed, the user of the model often has a feeling about how the output of the model would change. This change can often be reasoned by using logic or the experience of the users. First a number of input variables are selected and then they are checked using the model. During the matching process all the input variables are kept constant except the variable that is checked. The matching process is performed using two sets of input. The first set of input variables for the matching process is based on the BCS L-5. The reference situation is based on a maintenance action that consists of installing a new belt. The input variables used are presented in Table 14. For the output the state of the belt regarding splices is used. This is that output of the model that is defuzzified to obtain the optimum maintenance interval for preventive maintenance.

Table 14: Input variables of BCS L-5 used for matching

Variable description	Input variable
Number of splices present	1
Age of the Belt (year)	0
Cold/Hot Splice	Cold
Repair action or new splice	New
One/Two turn directions belt	one
HTD/Work Unit	HTD
Weather during maintenance	Good
Average running time per hour	0,51
Complete runs per hour	88
Average tension on splice	0,13
Max tension on splice	0,53
Average number of starts per hour	0,21

The matching process will be performed by looking at three different input variables. The first input that is looked at is the number of turn directions of the conveyor belt. Normally this belt only runs in a single direction. If the input variable is changed to two you would expect the maintenance interval of the belt to become shorter. If the belt is running in both directions, one of the directions has a high chance to damage the splice trough the scraper. The output of the model in the reference situation is a state of the belt of 0.78. Changing the input variable to two turn directions reduced this state to 0.76. The state of the belt regarding splices has become lower, just as one could logically predict. The second input that is taken into account is the weather during the maintenance. In the reference situation the weather is good; this leads to an earlier mentioned state of 0.78, but what if the weather was bad instead of good. The state of the belt during this situation is 0.73. So bad weather during the splice creation will lead to a lower state of the belt, this sounds logical. The third variable looked at is the average number of starts per hour. In the reference situation the BCS is started around 0.21 times per hour. When the number of starts per hour is increased to 0.5 times per hour, the state of the belt decreases to 0.77. An increase of the number of starts per hour leads to a decrease of the state of the belt.

The second set of variables used as reference situation is from the BCS A-471. The variables used as input are presented in Table 15. Compared to the L-5, the A471 is a much longer belt. The L-5 has a belt length of around 90 meter while the A-471 has a belt length of around 700 meter.

Table 15: Input variables of BCS A-471 used for matching

Variable description	Input variable
Number of splices present	5
Age of the Belt (year)	1
Cold/Hot Splice	Hot
Repair action or new splice	Repair
One/Two turn directions belt	one
HTD/Work Unit	HTD
Weather during maintenance	Average
Average running time per hour	0,51
Complete runs per hour	17,30
Average tension on splice	0,47
Max tension on splice	0,86
Average number of starts per hour	0,13

Since this belt is much longer than earlier discussed L-5 the number of splices present in the belt chances over time. So the first input variable that is checked by matching is the number of splices present in the belt. If the number of splices is decreased to 1, the state of the belt determined by the model is 0.43. The state the belt in the reference situation with 5 splices is 0.41. So a lower number of splices in the belt will lead to a better state. The number of splices is now increased to 10. The output of the model is now a state of 0.39. This is shorter than the reference situation, as one would expect. The second input variable that is used is the age of the belt. In the reference situation the belt is at least one year old. If the belt was only a halve year old the output of the model regarding the state of the belt would be 0.54. You would expect a higher state on a newer belt; in the case of the model this is also true. The final variable that is checked is the average running time per hour. During the reference situation the BCS runs around 51% of the time but what if it only runs 25% of the time. The state of the belt in this case increases to 0.42. As expected since a belt that runs less will degraded slower. If the BCS is running 75% of the time the state of the belt regarding splices provided by the model is 0.4. A bit shorter than the reference situation as expected.

For matching, six different input variables of two different belts have been used to check if their influence on the model is logical. All changes to these input variables had a logical effect on the output of the model. Because of this the model matches the expected effects by the user.

5.6.2 Verification

Verification is the process of determining that a model implementation accurately represents the developer's conceptual description of the model and its solution [35]. The model is verified with the use of data from two belts. From these belts the real time between two maintenance actions is compared with interval determined with the use of the model. It should be noted that the real data is based on corrective maintenance while the model indicates a maintenance interval for preventive maintenance. The first belt that will be discussed is the L-5. The timeframe for this case is from the beginning of 2007 to end 2013. During this period 24 maintenance actions to the belt have been performed that involve the splices. In Figure 48 a graph is presented where the maintenance interval of the real data is compared with the interval determined by the model.

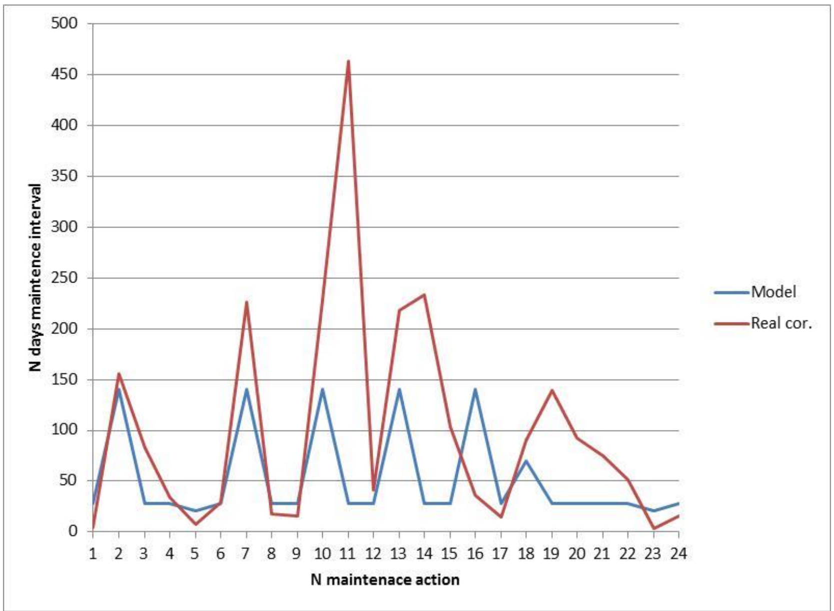


Figure 48: Real interval compared with the interval determined by the model of belt L-5

In Figure 48 the horizontal axis is the number of each maintenance action. The vertical axis describes the number of days between the maintenance action on the horizontal axis and the next maintenance action. So if you look at the second maintenance action, the N days is around 150 for the real data and around 140 days for the model data. This means that the time between the second and the third maintenance action was in reality 150 days, the model gave an optimum interval of 140 days. If preventive maintenance was carried out around this interval the corrective maintenance action that happened around 10 days later could have been avoided. The time between the third and the fourth maintenance action was around 80 days for the corrective maintenance and 30 days for the optimum preventive maintenance interval. So if preventive maintenance was carried out according to the model, the corrective maintenance action could have been avoided. Let us take a closer look at the 24 comparisons between the real corrective maintenance and the modelled optimum preventive maintenance interval. The number of corrective maintenance actions that could have been avoided is 16. 8 times or 33% of the time the optimum interval according to the model was too late. In section 5.4 a number of reasons have already been discussed why extremes in the available corrective data exist. Extreme corrective maintenance situations can be noticed at maintenance interval: 1, 5, 16 and 23. 1, 5 and 23 because the interval is extremely short, 16 because according to the model a new belt was installed while the corrective maintenance interval was relative short. The corrective maintenance action 17 was also after a relative short period so there is a high possibility something went wrong during the creation of the new splice at maintenance action 16. Removing the earlier discussed 4 extremes from the discussion, only 4 of the remaining 20 determined optimum maintenance intervals too late. This means that the optimum maintenance interval for preventive maintenance provided by the model has an accuracy of 80%.

The real data and the modelled data from Figure 48 will be compared with each other using correlation. The correlation test is performed using Pearson product-moment correlation coefficient. The Pearson product-moment correlation coefficient measures the linear correlation between two variables, in this case the real number of days and the modelled number of days. If there is complete positive correlation the coefficient will be +1 will complete negative correlation leads to -1. In this case a coefficient closest to +1 is preferred. The formula for the Pearson product-moment correlation coefficient commonly represented as r is

$$r = \frac{\sum_{i=1}^{n}(X_i - \bar{X})(Y_i - \bar{Y})}{\sqrt{\sum_{i=1}^{n}(X_i - \bar{X})^2}\sqrt{\sum_{i=1}^{n}(Y_i - \bar{Y})^2}} \tag{5-5}$$

The resulting correlation from the data is a coefficient of 0.347. This means that the correlation between the real data and the output of the model does exist. The correlation is not perfect but is noticeable. In the corrective data however some extremes are visible. The most extreme situation is the corrective maintenance action 11. According to the model this should be a maintenance action to a belt already in use, the corrective maintenance interval is two times longer than the longest maintenance interval on a new belt. Removing this data point from the correlation calculation nearly doubles the correlation coefficient to 0.612. Some other extremes that influence the correlation are present at maintenance action 14 and 19. Removing maintenance action 11, 14 and 19 from the correlation equation gives a correlation coefficient of 0.777 which indicates a strong correlation.

The second belt that is discussed is the L-20. The same timeframe as with the belt L-5 is used. In Figure 49 the comparison between the real maintenance interval and the output of the model is shown.

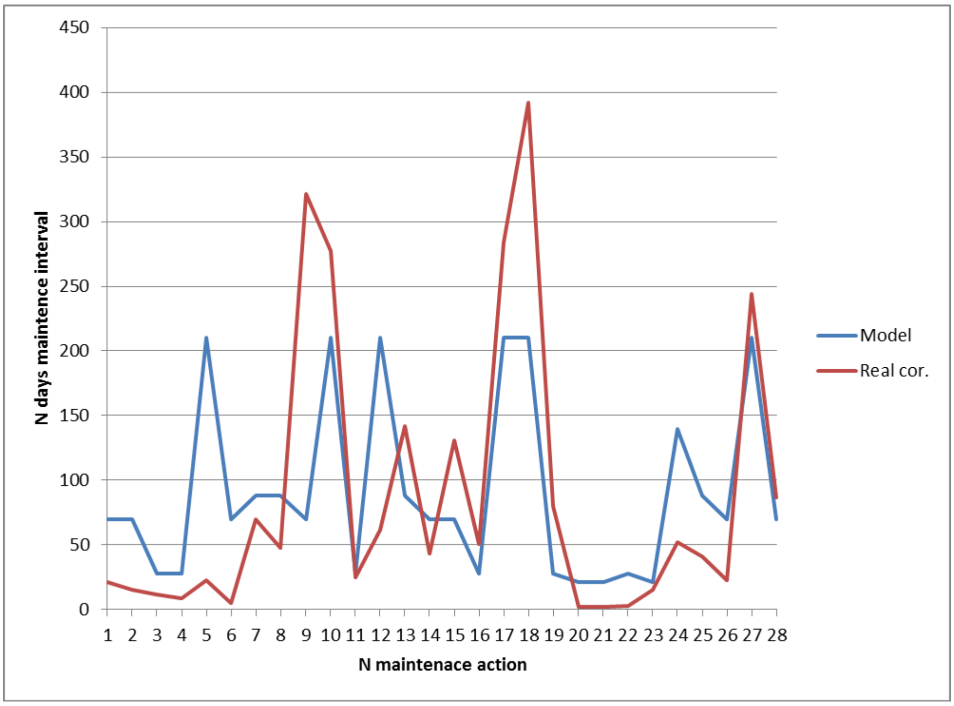


Figure 49: Real interval compared with the interval determined by the model of belt L-20

When looking at Figure 49 it becomes clear that in this case the optimum preventive maintenance interval is often too late. Only 10 times the preventive maintenance is carried out on time if the optimum maintenance interval determined by the model is used. Another fact that can be seen from Figure 49 is the extreme variations in the corrective maintenance interval. A corrective maintenance interval of around 320 days can be seen at maintenance action 9, the maintenance interval determined by the model for this maintenance action is around 70 days. Other corrective maintenance intervals are very short; the total time between the 20 and the 23 corrective maintenance actions was 7 days. These three maintenance actions and also probably the one that followed it can be considered extreme situations. The first 6 corrective maintenance actions can also be consider as extreme because of their short interval, the total maintenance interval for the first 6 maintenance actions is around 12 weeks.

A possible reason for why the optimum preventive maintenance interval is too late for this particular belt is because the model is created using the data of nine belts. The belt in question has to transport multiple types of material, has a moving head pulley and a transfer point under an angle. This combination of factors that in the current test model are not included can cause a shorter optimum preventive maintenance interval then that is currently determined. So the accuracy of the preventive maintenance interval could be improved by taking more factors into account.

The optimum preventive maintenance interval might be often too late in the current model; Figure 49 does show a correlation between the real and the modelled maintenance interval. From the data of the L-20 also a correlation coefficient has been determined. In this case the coefficient is 0.623 meaning that there is a moderate to strong correlation between the real data and the modelled data. So based on the correlation this model has been verified.

5.6.3 Validation

Validation is the process of determining the degree to which a model is an accurate representation of the real world from the perspective of the intended uses of the model. Validation of this model is currently not possible. The real data available deviates too much of the output from the model. The model is used to determine the preventive maintenance interval for splice maintenance. The real data is based on corrective maintenance actions to the splices. Validating preventive maintenance based on data of corrective maintenance is not possible. Because of this reason the model has not been validated.

5.7 Improvements for the model

As discussed in chapter 5.6.2 some of the outputs of the model show large variations between the real maintenance intervals. This can be explained trough a number of reasons. The most important reasons have already been discussed in chapter 5.4. But even so, there are a number of improvements possible for the model that is currently not implemented. This is either because of the time constrain or because it was currently not feasible. Most of these improvements have already been discussed in chapter 4.4. The reason why these improvements are not implemented in the current model and how this can be improved in the future will now be discussed.

One of the reasons for the large variation between the real maintenance interval and the preventive maintenance interval is the simple fact that corrective maintenance is compared with preventive maintenance. This are two completely different maintenance strategies so comparing these two can only give an indication on how close the preventive interval is to the real maintenance point.

Another reason is that the number of influences taken into account on the state of the belt regarding splices is limited. Increasing the number of influences taken into account would increase the amount of work involved with making the model. The quality of the output however would likely increase. One of the limitations for the current influences taken into account was the data available. This research is performed at a single company; the data available depends heavily on what they record. The main focus of data collection of companies is often to optimize the daily operations, not making a model. A lot of the extra information concerning a maintenance action is communicated through oral contact or by e-mail, this makes is very hard to incorporate this in a model. The quality of the output from the model could be increased by improving the documentation of the maintenance.

Another limitation of the current model is that it is mostly based on historical data. A splice for example can be created during average weather condition and last 100 days in this particular case. Because of the large amount of influences on the belt it is not certain that the maintenance interval of 100 days is really caused by the weather or by another factor. During this research the effect is tried to mitigate by taking a number of belts for a decent period of time into account. It should be noted that for not every combination of ranges historical data was available. For other combinations the amount of historical data was of a low quantity. The conditional probability tables for the different nodes have been filled in using the historical data. For the combinations where no data was available, the values have been based on the other data points and expert opinion. This process could be improved with the use of extra data sources. The source could for example be the usage of laboratory test to determine the effect of an individual factor.

The influence of dry time on a splice could for example be determined using a laboratory. Testing this in the field would introduce a large number of disturbances. When one uses the data determined by a laboratory, the difference between laboratory conditions and the conditions in practice should be taken into account. Laboratory tests for determining the influence of some of nodes on the model was unfortunately not possible during the creation of this thesis.

Another source of information that is currently only used in a limited fashion is expert opinion. At the company where this research was performed the amount of knowledge available is significant. The main problem is that this knowledge is often spread out over a lot of personnel and departments. Another challenge is processing this knowledge to useful data. From my experience getting hard data from people can be hard, often the reply is in the form of some extreme situation that is used to explain that hard data is impossible to give.

A final method to increase the output of the model is changing how the model works. The current model is operating according to tables that have to be manually created. Because of this, there is only one version of this table available that is used on every belt. The data of a number of real conveyor belts have been used for making the model, but the properties of the belt conveyors very widely. The conveyors have large differences in length, in the operation conditions and more. Some of these differences have been included in the model, but the outcome is still rougher than a model tailored for one particular conveyor belt. Manually making a model for each individual belt is a lot of work. It is possible to make the model self-learning. The user provides the data required and the model itself determines the conditional probability tables used for determining the optimum maintenance interval for preventive maintenance. For the earlier discussed belt L-20 for example, the maintenance interval could potentially be lowered using this method to make sure preventive maintenance is carried out before the corrective maintenance action.

The current model is using the most basic form for determining the spread of the output. The reason for this is that with the current data it was impossible to determine the real spread. Calculating the real spread let to a spread that was most of the time larger than the maintenance interval. So taking the real spread into account is with the current information not possible.

The reliability of the output of the model has not been taken into account since the spread of the model is so massive that using it in practice is nearly impossible. Adding the reliability with the current available data would serve no purpose.

6. Conclusion and recommendations

First the conclusion of this research will be presented, followed by a number of recommendations for future research.

6.1 Conclusion

The main objective of this thesis was to improve the customer satisfaction of a conveyor belt maintenance department. This improvement is accomplished by increasing the performance of the planning of the maintenance by introducing preventive maintenance instead of corrective maintenance. The main question while performing preventive maintenance is: what maintenance interval should be taken into account? To optimize this maintenance interval a method for making a model has been proposed.

The model used for optimizing the maintenance interval for parts, in this case conveyor belts, is based on the Bayesian Theory. To be more specific, the Bayesian Belief Network has been used for the model. Belief networks are graphical representations of models that capture the relationships between the models variables. The variables that interact directly are identified and are limited to the variables to which they are directly connected. The Belief network is constructed as a DAG using properties that determine the state of the belt regarding splices as nodes. The network can easily be changed in size to take a variable number of properties into account. This means that the method is not limited to a single case but can be tailored to each particular requirement.

The method discussed for making the model has been tested on a real case at a company. The model is created based on variables of a number of BCS each with their own properties. Between the BCS there are large differences between the length and operation conditions. Because of this reason, the maintenance interval is not tailored for each individual conveyor belt. This leads to a maintenance interval that is sometimes too long or too short for a particular conveyor belt. There are also in the current model only a limited number of variables taken into account. Increasing the number of variables involved would increase the quality of the output of the model but also requires more data to be available. Even with the limited number of variables and the wide approaches for BCS, the model has been verified. This means that the model performed the task it was designed to do but more research is needed to use this model into practice. So using the Bayesian Belief Network to model the optimum maintenance interval for conveyor belts has been approved as feasible.

6.2 Recommendations

Bayesian Belief Networks are feasible to be used for modeling the optimum maintenance interval for conveyor belts but during the developed of the test case it was discovered that the current method has still some limitations. The main challenge during the creation of this type of model is collecting sufficient data with useful information. Further research could be performed on how to collect and mainly how to process a limited amount of information for determining the conditional probability tables for the model. Another interesting topic is how to transfer knowledge to usable data.

The current model is labor intensive. The data for the different variables and tables have to be manually collected and processed. Because of the different formats, double recordings and missing details effective using the data requires a lot of extra work. Standardizing projects for the way data is recorded where already implemented recently at the company where the research was carried out but because of the use of historical data this was only of limited use for this research. If these recording standards are followed strictly trough all departments, data processing could be improved dramatically. Because of the labor intensity of the current model, the model has been developed to include belts of a wide range. The length of the belts for example can deviate a lot between the different belts. By making a self-learning model, multiple models aimed at belts with the same properties can be created. Because the range of the variables involved in these models is limited, the accuracy of the output of the model can be increased.

The common practice for maintaining conveyor belts is corrective maintenance combined with random maintenance. Since no preventive maintenance to conveyor belts is carried out, validating the model was not possible. The only way the current output of the model could be verified was checking the correlation between the real data and the output of the model. It is recommended that the current method is validated using another case where data on preventive maintenance is available.

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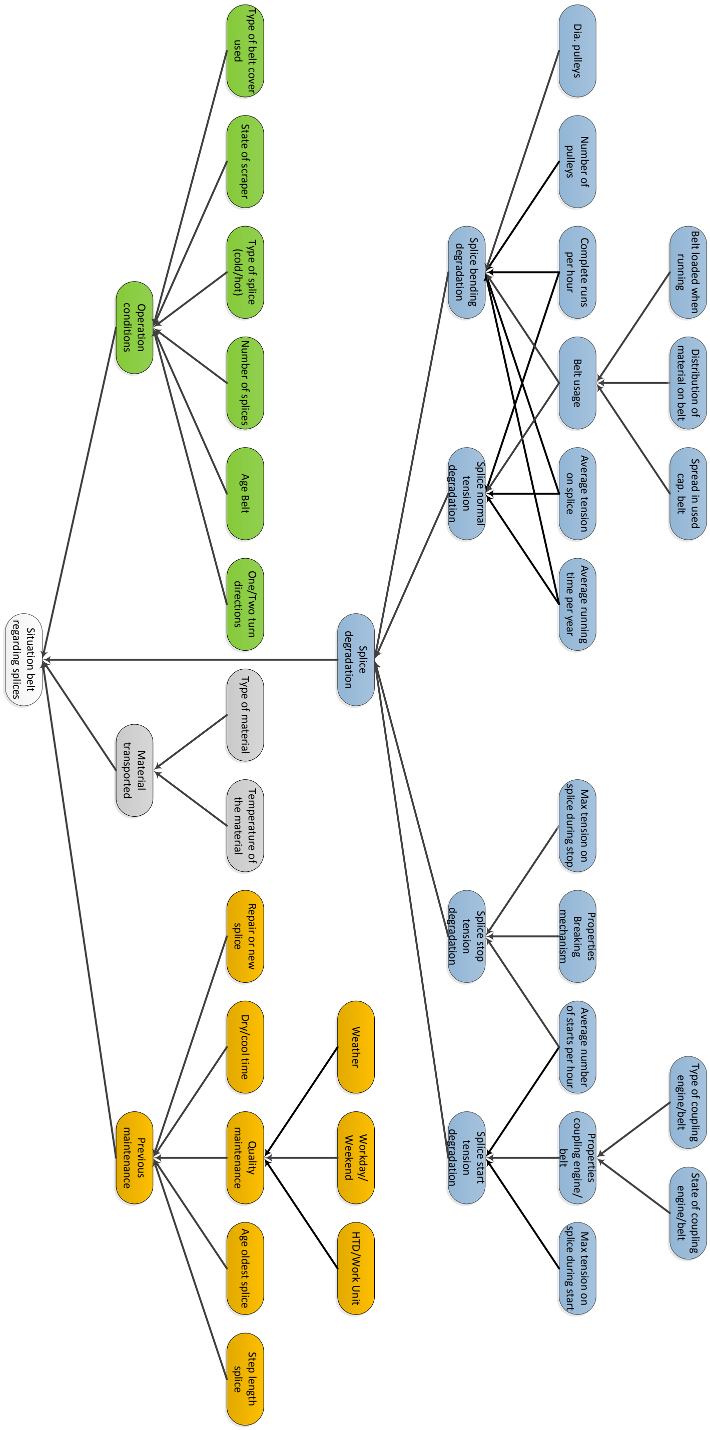
Figures and Tables

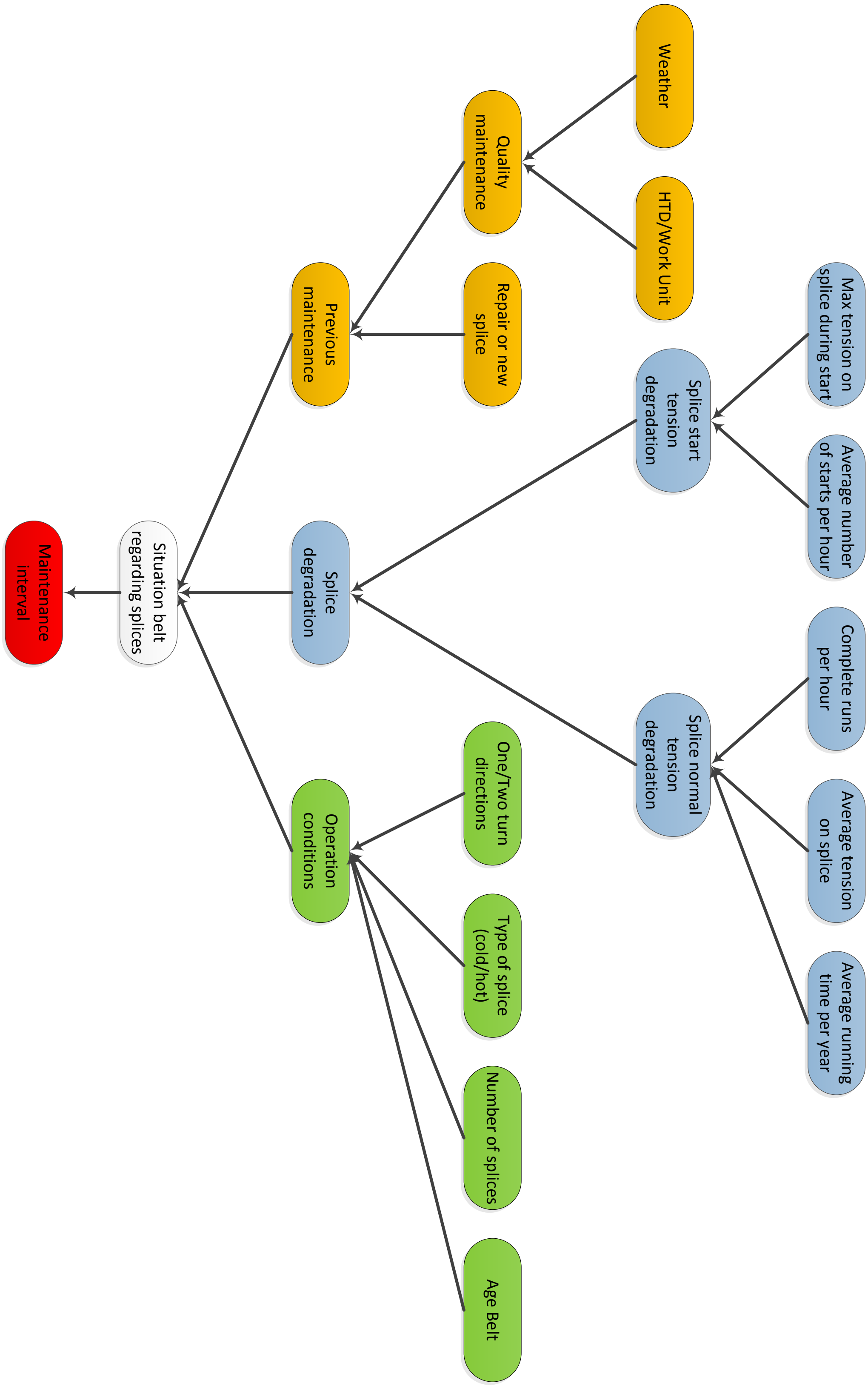
Figures

Tables

Appendix A: The complete model



Appendix B: The simplified model



Optimizing the maintenance interval by modeling the state of a conveyor belt regarding splices

Coen Berenbak, Yusong Pang, Gabriel Lodewijks

***Abstract*—Maintenance to conveyor belts is sometimes carried out by performing corrective maintenance. Using the corrective maintenance strategy has a number of disadvantages like lower system reliability and a highly fluctuation maintenance work load. Performing preventive maintenance can both increase the system reliability as reducing the fluctuation on the work load. The main challenge for performing preventive maintenance on conveyor belts is determining the optimum maintenance interval. If the interval is too short the number of maintenance actions performed overtime increases, too late and corrective maintenance has already been performed. This paper will introduce a method for creating a model based on the Bayesian Belief Network that can be used to determine the optimum maintenance interval. To incorporate variables in the model that are continues or have data from different sources, fuzzy logic is introduced to the model. The method for creating the model is designed in such a way, that the model can easily be used in practice. To prove the workings of the method, a test case at a company has been performed.**

I. Introduction

BELT conveyor systems (BCS) are used for transporting large quantities of bulk material between two locations. The BCS are often critical for the normal operations for the plant where they are located. Malfunctions to the system can cause expensive downtime since the normal operations are disturbed. To prevent degradation of the system, inspections and maintenance has to be carried out. Inspections to monitor the state of the system, maintenance to bring the system back up to standards once a problem has been detected. One of the strategies for inspections and maintenance for conveyor belt is corrective maintenance. The belt is regally inspected till damage to the belt is so severe that maintenance is required. At this point either emergency maintenance is performed or there is a short interval available to perform maintenance. Dr. Gabriel Lodewijks states that random maintenance is also an often used maintenance strategy for BCS [1]. Random maintenance is opportunity based, so once a possibility arises, maintenance to the system is performed. Since the planning of the maintenance only starts once damage to the belt has been selected, the available time for this planning is limited. Waiting too long can lead to extra damage or failure of the system. Because maintenance is postponed to the point where damage to the belt is already severe, the overall reliability of the system will decrease. Combined with the limited flexibility in planning, this can cause disturbances to the normal operations of the BCS. Another negative factor of this type of maintenance approach is the high variation of maintenance work. Maintenance is only carried out if either a belt fails or severe damage to a belt has been detected. During periods when there are few of such cases, the overall maintenance requirement of the system is low. If on the other hand a lot of damaged belts are detected, the maintenance requirement is high. If the maintenance to the belts is performed by a maintenance crew with a fixed capacity, the variations in the workload will often lead to capacity problems.

II. Improving the maintenance process

The quality of corrective maintenance can be improved using a number of methods. The first possibility is improving the frequency and quality of the inspections. By detecting the damage earlier, more time is available for planning the maintenance. The chance that a belt fails because damage is not detected on time is also lowered. The improvement of the inspections can for example be accomplished by monitoring the system continuously instead of manual inspections. A method for monitoring the system continues is proposed by Dr. Yusong Pang [2]. Another method is changing the maintenance strategy involved with maintaining the conveyor belt. With the use of preventive maintenance the disturbances to the normal operations of the BCS can be limited. When performing preventive maintenance to a conveyor belt, the maintenance is performed before severe damage to the belt is present. This increases the reliability of the conveyor belt and improves the flexibility of the planning. One of the challenges when performing preventive maintenance is determining at what point the maintenance has to take place. If the belt is maintained too soon, more maintenance then necessary is carried out to the belt. This will reduce the availability of the belt and increase the cost. If the maintenance is performed to late, there is a high chance corrective maintenance is already required. A conveyor belt is often subjected to a large number of influences that impact the maintenance interval. A method for translating those influences to a maintenance interval is by determining the state of the belt. This state is can be determined by both taking the state of the belt directly after the last maintenance action as by the operation conditions into account. The aim of this research is to develop a method to model the state of a conveyor belt to determine the maintenance interval. Before this method can be presented, first the scope of this research first is given. The scope of this research is limited to fabric conveyor belts. For the test case the scope is limited to splices of conveyor belts that are situated in operations equal as at Tata Steel that transport cold material between two transfer points.

III. Determining the best method for the model

Before a method for making a model can be discussed, first the type of model used must be determined. To determine the best type of model, three methods will be discussed. The first method that will be discussed is Exploratory Factor Analysis (EFA). EFA originated from psychometrics and can be used for applied science that handles large quantities of data. The main advantage of EFA is that you do not have to know exactly what a variable included in the model represents. By looking at groups or so called batteries of variables, relationships between the different variables can be determined. Since the relationships between different variables for the preventive maintenance interval can often be reasoned, the main benefit of EFA is not very relevant for this model.

The second type of model is the Fault Tree Analysis (FTA). A FTA is a top down, deductive failure analysis where an unwanted state of a system is analysed. Preformed correctly, FTA often identifies problems with a system other design and analytical methods may have overlooked [3]. The pitfall when using a FTA is making it so big that it becomes troublesome to work with. Another downside of the model is that it is more of an identification type of model than to calculate the maintenance interval of a part.

The final type of model discussed is the Bayesian Belief Network (BBN). Belief networks are graphical representations of models that capture the relationships between the model's variables [4]. The variables that interact directly are identified and are limited to the variables to which they are directly connected. Believe networks may use directed or undirected graphs to represent a dependency model. The directed acyclic graph (DAG) provides a better representation than the undirected graphs. The DAG is also more flexible and is able to represent a wider range of probabilistic independencies. An undirected graph is one where the edges have no direction meaning (A, B) is equal to (B, A). The BBN is a specific type of causal belief network. As for any causal belief network, the nodes represent stochastic variables and the arcs identify direct causal influences between the linked variables. The fundamentals of the Bayesian methodology is too enable prior knowledge of a certain event to calculate the posterior probability of a hypothesis based on the probability of the event. The model can be used to determine the maintenance interval for preventive maintenance based on the models input. Since BCS is expensive equipment with often a long lifetime, historical data and knowledge concerning the BCS is in general available. So the BBN method will form the basis of the method of making a model.

A. *Fuzzy Logic*

Fuzzy logic was introduced by Zadeh in 1965 [5]. Fuzzy logic is very useful to express a degree of truth between the values of 0 and 1. A fuzzy set is introduced to describe the degree of membership to an event. This can be very useful to evaluate continues variables like length. A conveyor belt for example is short if the length is smaller than 25m, average length if between 25m and 100m and long if the length is greater than 100m. Incorporating continues variables in the model is not the only reason to use fuzzy logic. Fuzzy logic can also be used to combine different information sources, obtain consistent information from different data sources and helps with the interpretation of information.

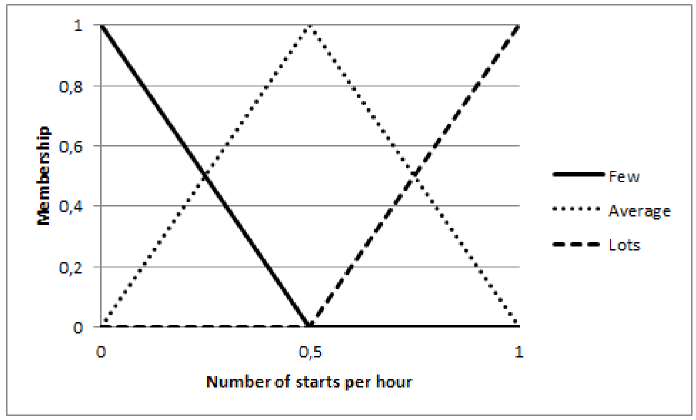


Fig. 1. *Memberhip function of number of starts per hour.*

For the making of the model the fuzzy membership function is being used. The fuzzy membership function is used to define fuzzy values for the variables used in modelling the maintenance interval for preventive maintenance. The variable is described by a number of fuzzy ranges based on its evidence. A basic method of representing the number of starts per hours is a start every 4 hours or 0.25 starts per hour. To transform this representation into a fuzzy membership function first the fuzzy ranges has to be determined. Assume in this case that the variable number of starts per hour has three ranges. The first range is few starts representing the evidence of 0 starts per hour. The second range is an average number of starts representing the evidence of 0.5 starts per hour. The last state is lots of starts representing the evidence of 1 start per hour. Once the evidence for a variable is true, the membership of this range is equal to 1. So if there are 0.5 starts per hour, the membership of an average number of starts is 1. For evidences that are between two ranges, the degree of true of each range determines the value of the membership. The sum of all the ranges should always be equal to 1. A graphical representation of the membership with the ranges of number of starts per hour is presented in figure 1.

The above discussed example can be represented in the model using the following formula. For each area of range (r_i) boundaries, if the value $x \in [r_i, r_{i+1})$ is considered with its evidence (e_i) description, we construct the membership function as [6]

$$g_{e_i}(x) = \frac{1}{r_i - r_{i+1}}x - \frac{r_{i+1}}{r_i - r_{i+1}} \quad (1)$$

$$g_{e_{i+1}}(x) = \frac{-1}{r_i - r_{i+1}}x - \frac{r_i}{r_i - r_{i+1}} \quad (2)$$

Where we have

$$g_{e_i}(x) + g_{e_{i+1}}(x) = 1 \quad (3)$$

The ranges can be determined by analyzing the available information and data. Another method that can be used to establish the ranges is the usage of expert opinions. This is mainly useful if insufficient data or information is available. By deriving fuzzy values from the membership function, each value covers a range of the observed parameter. The size of the range is

$$S_{e_i} = r_{i+1} - r_i \tag{4}$$

B. The Bayesian belief network

The Bayesian Theory was named after an Englishman Thomas Bayes (ad. 1702-1761.), a statistician, philosopher and Presbyterian minister. Bayes theorem is stated mathematically as shown in the following equation [7]:

$$P(H|E) = \frac{P(E|H) \times P(H)}{P(E)} \tag{5}$$

This formula denotes the conditional probability that H occurs, given that E is known to occur. In the conveyor belt inspection process, if H refers to a inspected variable and E represents the new observed data, then P(H) is the prior probability that H occurs; P(H|E) is the posterior probability of H occurs, given E ; and P(E|H) is the conditional probability that E occurs, given H . This formula enables us to use the prior knowledge of an event to calculate the probability of the other event(s) [8].

The Bayesian Theory is actively used on multiple fields in the industry. An example of the usage of the Bayesian Theory is to estimate the failure probabilities of safety systems and end-states in chemical plants [9]. The Bayesian Theory can also be used to process the data collected through continues monitoring of a device for condition based maintenance [10].

Formally, Bayesian networks are directed acyclic graphs in which each node represents a random variable, or uncertain quality, which can take on two or more possible values [11]. A DAG, is a directed graph with no directed cycles. In a Bayesian network the nodes are events that have a probability of occurrence and these nodes are connected with directed arrows that indicate the influence direction. Using fuzzy values of evidence and the likelihood density when hypothesis H happens, given the evidence e_i, the posterior probability is calculated. Given the value x of evidence e_i, by using the membership function and conditional probabilities, the likelihood sampling distribution is estimated as

$$f^{`}(e_i|H) = \sum_i g_{e_i}(x) P(e_i|H) \tag{6}$$

After defining a fuzzy set of prior probability which assigns each value of x for the evidences with rang [0,1] the likelihood is computed. The estimated likelihood density for fuzzy valued evidence is computed as the weighted likelihood according to the following formula

$$f^{*}(e_i|H) = W_{e_i}(x) f^{`}(e_i|H) \tag{7}$$

Where $w_{e_i}(x)$ is the weight coefficient defined as

$$W_{e_i}(x) = \frac{S_{e_i}}{S_{e_i} + S_{e_{i+1}}} \tag{8}$$

The weight coefficient is used to define the two ranges of the fuzzy values of each evidence. The weight coefficient is used to evaluate the proportion to the corresponding size of the interval of the fuzzy values.Once the likelihood probability has been determined using the above described method, the posterior probability can be calculated. The formula for calculating the posterior probability is as [12]

$$P(e_i|H) = \frac{f^{*}(e_i|H)P(H)}{\sum_j f^{*}(e_i|H_j)P(H_j)} \tag{9}$$

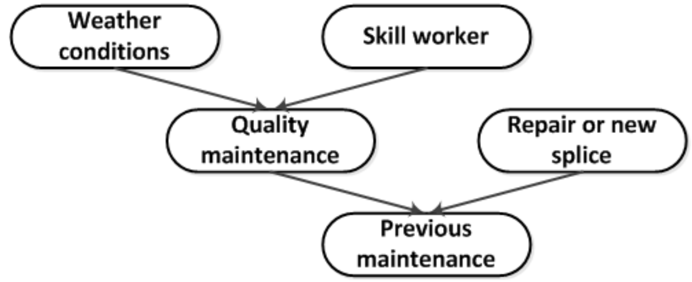


Fig. 2. *Example of a DAG representation.*

IV. Applying the theory for creating a model

The theory used for creating the model has been described above, now we look at how this theory can be used in practice. The first step while creating a model is designing the DAG representing the system. This DAG will converge to a single node that is used for determining the output of the model. An example of a DAG for a previous maintenance action is shown in figure 2. The nodes represent a number of factors that influence the quality of the performed previous maintenance. During the creation of the DAG it is recommended to take the available information and data into account to save both a lot of time and money. Missing data can be collected using other method, like laboratory test and installing new sensors, but this can be time consuming and costly. Once the DAG representing the model has been determined, data for the nodes can be collected. Data and information can in general be gathered from three different sources: historical data, laboratory tests and expert opinion. BCS are an expensive piece of equipment, therefor it is likely historical data is collected and preserved that can be used for the creation of the model. The people involved with the maintenance of the BCS can provide indications about the maintenance interval and other information based on their experience. Once all the data and information is collected, it should be processed to be usable for the model. Using either the processed data or knowledge the membership functions g(x) should be determined using equation 1 to 3. The processed data and available information should also be used to create the prior probability and the conditional probability tables required for the model. For the prior probability tables the frequency of the resulting hypothesis has to be determined. This can be accomplished by looking at the historical data or use the other available data. The conditional probability depends of the effect of the combination of ranges with states on the hypotheses they influence. This conditional probability can be determined using a combination of historical data, laboratory tests and expert knowledge, depending on what is in this case available. By

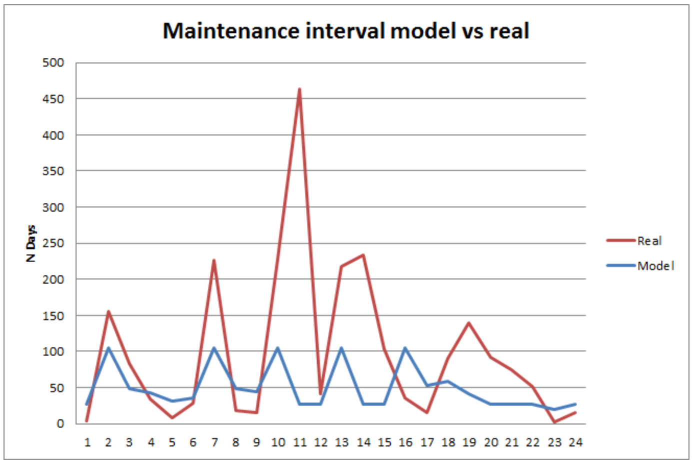


Fig. 3. *The optimum preventive maintenance interval determined by the model compared with the real corrective maintenance interval.*

creating a table with all the possible combinations of parent nodes that influence the node in question, combined with the ranges and hypotheses an overview is made of all combinations. For each combination the conditional probability has to be determined for each hypothesis. Based on the earlier discussed data sources, the effect of each combination has to be determined and then added to the table. Conditional probability tables can become big fast if multiple parent nodes with ranges are involved. Some combinations most likely have insufficient data or information to determine the conditional probability for. In situations like this, expert opinions or trends can be used to complete the tables. With the conditional probability and the membership functions, equations 6 to 8 are used to determine the estimated likelihood density functions. Using the estimated likelihood density functions and the prior probability, the posterior probability is created according to equation 9. The final step before the output of the model can be used in practice is transforming the posterior probability calculated by the model to a value useful in practice. For determining the optimum preventive maintenance interval for conveyor belts, the state of the belt is been determined by the model. This state must be translated to an interval represented for example in days. Since the input of the model is fuzzified, a good method for transforming the state of the belt to an interval is defuzzifying the state. The values used for the defuzzifying process can be determined from historical data or with the uses age of an expert opinion. If historical data is used, one must carefully asses the maintenance strategy used during these maintenance actions. If corrective maintenance is performed, the preventive maintenance interval must be shorter to carry out the preventive maintenance before the corrective maintenance.

V. Testing the model creation in practice

To prove the workings of the model, a test case at the company Tata Steel IJmuiden has been performed. For this test case, the data and information of nine conveyor belts has been used. The main method of performing maintenance to conveyor belts during this research at Tata Steel was corrective maintenance. The design of the DAG representing the system was heavily influenced by the available data, also for this test case only the splices of the conveyor belts are modeled. Data collected in practice is often different than the data required for a model. Based on the available historical data and expert opinions present at the company, a model has been created according to the earlier described method. The resulting state of the conveyor belt is then transformed to a maintenance interval based on the corrective maintenance intervals of the historical data. In figure 3 a comparison between the corrective maintenance interval and the optimum preventive maintenance interval according to the model has been shown. In figure 3 the Y axis indicates the number of the maintenance action and the X axis indicates the number of days between the maintenance action presented on the Y axis and the next maintenance action. The time between the second and third maintenance action is around 150 days for the corrective maintenance action. The model determined a preventive maintenance interval of around 100 days, so if the model had been used, this corrective maintenance action could have been avoided. The time between the third and fourth corrective maintenance action is around 80 days, the model determined an interval of around 50 days. In this instance the usage of the model could have prevented the corrective maintenance again. At corrective maintenance action 5, the maintenance interval is only a couple of days. This could be considered as an extreme situation, maybe the maintenance crew had insufficient time for their maintenance or the conveyor belt was worn out. The same situation could be present during maintenance action 8, 9, 17 and 23. While only considering the normal maintenance actions, the model determines a maintenance interval that is around 80 percent accurate. Using the real corrective maintenance data and the preventive maintenance interval determined by the model, the model has been verified. Validation was not possible because of the different type of maintenance strategies. The verification of the model showed correlation between the real maintenance interval and the modeled interval. Because of the limited amount of data available, the output of the model created for this test case was accurate enough yet to be used in practice.

VI. Conclusion and further work

Determining the optimum maintenance interval for preventive maintenance can be a challenge for conveyor belts. The process discussed of making a model based on the Bayesian Belief Network can provide useful information. Because of the usage of fuzzy logic, the resulting model is very flexible so a high variation of parts can be modelled. The model made has been verified using a test case, for validating the model a test case with preventive maintenance data is required. The current method of making the model is very labour intensive, from collecting and processing the data to determining the prior and conditional probabilities. By transforming the current method to a self-learning model, the amount of labour involved can be reduced. The model also depends heavily on the quantity and quality of the data, more methods to process the available data can improve the output of the model.

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