Maintenance optimization of process rolls, with an application to electrolytic tinning lines

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Award date: 2017

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Maintenance optimization of process rolls, with an application to electrolytic tinning lines

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Abstract
This master thesis project has been conducted at Tata Steel IJmuiden. Tata Steel has thousands of process rolls installed with a wide variety in functions and technical specifications. The main function of these process rolls is to transport steel through production lines. In this project, a methodology has been developed to predict failure of process rolls in order to improve maintenance decision making. This methodology consists of four parts; the selection of a process roll type for research, identification of possible parameters that can predict failure of process rolls, modelling degradation of process rolls with these parameters, and optimizing the maintenance policy. This methodology has been tested for one process roll type.
Executive summary

Problem statement and research goal
This master thesis project has been conducted at the steel-making facility of Tata Steel in IJmuiden. This research focuses on process rolls. Process rolls are components that are used to transport steel (both strip and slab) through production lines. In IJmuiden alone, Tata Steel has thousands of process rolls installed with a wide variety in functions and technical specifications. This research focuses on the process rolls that are used in the four electrolytic tinning lines of the packaging division of Tata Steel.

In the current situation, process rolls are being replaced preventively based on a periodic interval. The periodic replacement intervals are determined based on the experience of experts and historic times until failure. The intervals are not optimized to minimize the expected costs using estimated failure time distributions of process rolls. In the current situation, two types of costs that can be reduced are distinguished; costs of performing corrective maintenance and costs of performing preventive maintenance too often. When a process roll fails before the planned periodic replacement, a corrective replacement is performed. Corrective replacements come with costs of unplanned downtime. In financial year 2016, the total unplanned downtime caused by failure of process rolls at the four ETLs equaled 310 hours and costed €1,873,328. These costs may be reduced by performing preventive maintenance, desirably just before failure. This can be achieved by using information about the condition of process rolls in relation to failure to estimate the remaining useful life of process rolls and thus to plan and perform maintenance “just-in-time”. This is called condition-based maintenance.

In order to perform maintenance of process rolls “just-in-time”, experts at Tata Steel Packaging started to perform an inspection right before the periodic replacement for certain process roll types with relatively high costs of repair and relatively long life-times. During such an inspection, experts estimate the condition of a process roll based on intuition and experience and decide whether to postpone the replacement. Intuition and experience is generally in the minds of the experts. There is a dependency on these experts when it comes to maintenance decision-making because soon or late every expert will leave the company and takes his experience and intuition with him. Furthermore, experts do not use any form of data to extract information to support the estimation of what they think are relevant conditions that relate to failure.

The goal of the research project is defined as:

\[
\text{Develop (and implement as much as possible) a methodology to predict failure of process rolls in order to improve maintenance decision-making.}
\]

Within the four electrolytic tinning lines, 185 different types of process rolls are installed. Types of process rolls vary from one to another in functions and technical specifications. They need to be considered separately when analyzing degradation and failure. Since time and resources are limited for this research project, one type of process roll is used as a case study that supports the development of the methodology to predict failure of process rolls.

The main research question is:

\[
\text{How can Tata Steel increase the predictability of failure of process rolls?}
\]
The developed methodology

Figure 1 shows a summary of the methodology to predict failure of process rolls that has been developed in this research project. This methodology is successfully tested for the case study and it answers the main research question.

![Figure 1: The developed methodology.](image)

**Step 1**
To select a process roll type for research, a type with high potential costs savings is preferred. Therefore, the operating costs for every process roll type are calculated using an Excel tool that is developed in this project. Operating costs consists of the costs of maintenance and costs of downtime. Analyzing the operating costs of process rolls is important as 11 out of 185 process roll types together caused 50% of all operating costs. Process roll types that have recently been modified or are about to be modified are excluded for this research project.

**Step 2**
An approach has been developed to identify failure predictors for a given process roll type, where failure predictors are parameters that describe the degradation process of the process roll type. First, the failure modes are defined, followed by identifying possible failure predictors for each failure mode. This is done with information from literature, maintenance orders and downtime notifications in SAP, and most important the experience of experts at Tata Steel. The experience of experts at Tata Steel is consulted by organizing a group session in which experts from different disciplines participated. Finally, the failure modes are ranked based on their impact on operating costs to determine which failure modes and failure predictors deserve the highest priority.

**Step 3**
Since the modelling of degradation of process rolls in this research project relied on the availability of data, all potential data sources are checked to find data regarding the identified failure predictors. When no data is available, Tata Steel can decide to install measurement equipment if the potential costs savings outdo the costs of installing measurement equipment. The main source for condition monitoring data is the IBA database which contains mostly data of process parameters. Degradation models are required to estimate the remaining useful life of process rolls, which is a key requirement for a condition-based maintenance policy. The preferred degradation model depends on the characteristics of the data and the operating context. The degradation models that are tried to develop in this report apply to the case study only.
**Step 4**
An overview of maintenance policies is provided together with a decision tree to select the appropriate maintenance policies given a process roll type and its characteristics. Of the selected maintenance policies, the optimal values for the decision parameters need to be determined, followed by selecting the optimal maintenance policy.

**The case study**
For the case study of this research project and to test the developed methodology, bridle rolls (type EB) of bridle sections 1, 2, and 3 of ETL13 are used. The function of EB rolls is to control the tension in the steel strip in the production line. The dominant failure mode of these rolls is that the coefficient of friction is too low to control the tension in the steel strip without damaging the strip. The failure predictor that is used for this failure mode is slip, which is defined as the difference in speed of the strip and peripheral speed of the bridle roll, as percentage of the strip speed. For slip, there is degradation-based load sharing among EB rolls and based on the available data it was not possible to develop the degradation models. However, based on the found relations between slip and degradation of EB rolls a condition-based maintenance policy is proposed. This policy could not be optimized since it requires the degradation models of EB rolls.
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## Definitions, acronyms, and variables

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<tbody>
<tr>
<td>Condition-based maintenance</td>
<td>A maintenance policy in which preventive maintenance decisions are triggered based upon the condition of equipment.</td>
</tr>
<tr>
<td>Condition parameter</td>
<td>A variable that directly indicates the condition of equipment.</td>
</tr>
<tr>
<td>Corrective maintenance</td>
<td>Maintenance that is performed after failure of equipment.</td>
</tr>
<tr>
<td>Degradation</td>
<td>Degradation is the reduction in performance, reliability, and life span of equipment (Gorjian, Ma, Mittinty, Yarlagadda, &amp; Sun, 2009).</td>
</tr>
<tr>
<td>Degradation model</td>
<td>A degradation model describes how a certain characteristic of equipment degrades over its lifetime.</td>
</tr>
<tr>
<td>Downtime</td>
<td>The time during which a production line is not performing its intended function.</td>
</tr>
<tr>
<td>Equipment</td>
<td>Tangible property (other than land or buildings) that is used in the operation of a business.</td>
</tr>
<tr>
<td>Failure mode</td>
<td>A failure mode is any event which causes a functional failure (Moubray, 1997).</td>
</tr>
<tr>
<td>Failure rate</td>
<td>The likeliness that equipment will fail in the next small time interval, relative to the length of that time interval.</td>
</tr>
<tr>
<td>Failure predictor</td>
<td>A parameter that can be used to predict how long equipment can run until failure occurs (Lubbers, 2016).</td>
</tr>
<tr>
<td>Financial year</td>
<td>Tata Steel’s financial year (i) is from the 1st of April of year (i - 1) until the 31st of March of year (i).</td>
</tr>
<tr>
<td>Functional failure</td>
<td>The inability of any asset to fulfill a function to a standard of performance which is acceptable to the user (Moubray, 1997).</td>
</tr>
<tr>
<td>Maintenance policy</td>
<td>A set of rules that describe when a maintenance activity should be executed.</td>
</tr>
<tr>
<td>Operating costs</td>
<td>The sum of downtime costs and maintenance costs.</td>
</tr>
<tr>
<td>Parameter</td>
<td>A variable representing a significant measurable system characteristic (British Standards Institution, 2012).</td>
</tr>
<tr>
<td>Position</td>
<td>The physical location in a production line where a process roll is installed.</td>
</tr>
<tr>
<td>Process parameter</td>
<td>A variable representing a significant measurable production process characteristic.</td>
</tr>
<tr>
<td>Production line</td>
<td>A production line consists of connected equipment that form a continuous process that is designed to perform a specific task. When one machine fails, the entire production line needs to be shut down.</td>
</tr>
<tr>
<td>Remaining useful life</td>
<td>The useful life left on a component at a particular time of operation (Si, Wang, Hu, &amp; Zhou, 2010).</td>
</tr>
<tr>
<td>Repair</td>
<td>The process of restoring equipment to an ‘as good as new’ state.</td>
</tr>
<tr>
<td>Replacement</td>
<td>When performing a maintenance action, the used process roll is being replaced by either an “as good as new” process roll or a brand-new process roll and it will be send for repair.</td>
</tr>
<tr>
<td>Revision</td>
<td>Planned maintenance stops in which all preventive maintenance tasks for a production line are clustered.</td>
</tr>
<tr>
<td>Set-point</td>
<td>A set-point is the value of a control parameter of equipment that must be achieved in order for equipment to operate properly.</td>
</tr>
<tr>
<td>Uptime</td>
<td>The time during which a production line is performing its intended function.</td>
</tr>
</tbody>
</table>

*Table 1: List of used terms and their definitions.*
<table>
<thead>
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<th>Acronym</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>CFR</td>
<td>Constant failure rate</td>
</tr>
<tr>
<td>CM</td>
<td>Corrective maintenance</td>
</tr>
<tr>
<td>DFR</td>
<td>Decreasing failure rate</td>
</tr>
<tr>
<td>ETL</td>
<td>Electrolytic tinning line</td>
</tr>
<tr>
<td>FLC</td>
<td>Functional location code</td>
</tr>
<tr>
<td>IFC</td>
<td>Increasing failure rate</td>
</tr>
<tr>
<td>OEM</td>
<td>Original equipment manufacturer</td>
</tr>
<tr>
<td>RUL</td>
<td>Remaining useful life</td>
</tr>
<tr>
<td>RWB</td>
<td>Process roll replacement file <em>(rol wissel bestand)</em></td>
</tr>
<tr>
<td>TBM</td>
<td>Time-based maintenance</td>
</tr>
<tr>
<td>TSP</td>
<td>Tata Steel Packaging</td>
</tr>
</tbody>
</table>

*Table 2: List of used acronyms and their explanations.*
<table>
<thead>
<tr>
<th>Variable</th>
<th>Unit</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>$c_p$</td>
<td>€/stop</td>
<td>The fixed costs for every unplanned stop for production line $p$.</td>
</tr>
<tr>
<td>$dh$</td>
<td>€/hour</td>
<td>The hourly cost of downtime for production line $p$.</td>
</tr>
<tr>
<td>$cr_m$</td>
<td>€</td>
<td>Total corrective maintenance costs for process roll type $r$.</td>
</tr>
<tr>
<td>$cr_m$</td>
<td>€</td>
<td>Total maintenance costs for process roll type $r$.</td>
</tr>
<tr>
<td>$cr_r$</td>
<td>€</td>
<td>The costs of performing a corrective replacement for process roll type $r$.</td>
</tr>
<tr>
<td>$cr_r$</td>
<td>€</td>
<td>The costs of performing a preventive replacement for process roll type $r$.</td>
</tr>
<tr>
<td>$cr_downtime$</td>
<td>€</td>
<td>The downtime costs for process roll type $r$ for a chosen period.</td>
</tr>
<tr>
<td>$cr_maintenance$</td>
<td>€</td>
<td>Total maintenance costs for process roll type $r$.</td>
</tr>
<tr>
<td>$cr_operating$</td>
<td>€</td>
<td>Operating costs for process roll type $r$.</td>
</tr>
<tr>
<td>$cr_labor$</td>
<td>€</td>
<td>The labor costs of replacing process roll type $r$.</td>
</tr>
<tr>
<td>$cr_repair$</td>
<td>€</td>
<td>The costs of repairing process roll type $r$.</td>
</tr>
<tr>
<td>$g$</td>
<td>-</td>
<td>Gear ratio of a gearbox.</td>
</tr>
<tr>
<td>$l$</td>
<td>amp</td>
<td>Electric current used by an electromotor.</td>
</tr>
<tr>
<td>$m_f$</td>
<td>-</td>
<td>The failure threshold of a failure predictor.</td>
</tr>
<tr>
<td>$m_o$</td>
<td>-</td>
<td>The opportunistic threshold level of a failure predictor.</td>
</tr>
<tr>
<td>$m_p$</td>
<td>-</td>
<td>The fixed preventive threshold level of a failure predictor.</td>
</tr>
<tr>
<td>$n_f$</td>
<td>rpm</td>
<td>The rotational speed of a rotating object.</td>
</tr>
<tr>
<td>$p_e$</td>
<td>Watt</td>
<td>Electrical power used by an electromotor.</td>
</tr>
<tr>
<td>$p_m$</td>
<td>Watt</td>
<td>Mechanical power delivered by an electromotor.</td>
</tr>
<tr>
<td>$R$</td>
<td>-</td>
<td>Factor with which a bridle roll can maximally affect the tension in a strip.</td>
</tr>
<tr>
<td>$r_f$</td>
<td>m</td>
<td>Radius of a process roll.</td>
</tr>
<tr>
<td>$s$</td>
<td>%</td>
<td>The speed difference between the peripheral speed of a bridle roll and the strip speed (in % of the strip speed).</td>
</tr>
<tr>
<td>$T$</td>
<td>N</td>
<td>Tension in the steel strip.</td>
</tr>
<tr>
<td>$\Delta T$</td>
<td>N</td>
<td>Tension differential created by a bridle roll or bridle section.</td>
</tr>
<tr>
<td>$T_k^R$</td>
<td>days</td>
<td>The time at which the $k$-th preventive maintenance opportunities arises.</td>
</tr>
<tr>
<td>$\Delta T^R$</td>
<td>days</td>
<td>The preventive maintenance opportunity interval.</td>
</tr>
<tr>
<td>$TQ$</td>
<td>Nm</td>
<td>Torque.</td>
</tr>
<tr>
<td>$t_{downtime}$</td>
<td>Hours</td>
<td>The time that a production line is being stopped to perform a maintenance action. This includes the time it takes to shut down and start up the production line.</td>
</tr>
<tr>
<td>$t_{replacement}$</td>
<td>hours</td>
<td>The time it takes to replace a process roll.</td>
</tr>
<tr>
<td>$t_{d_f}$</td>
<td>hours</td>
<td>The total length of the downtime caused by process roll type $r$ on production line $p$.</td>
</tr>
<tr>
<td>$V$</td>
<td>volts</td>
<td>Voltage used by an electromotor.</td>
</tr>
<tr>
<td>$v$</td>
<td>m/s</td>
<td>Speed of the strip or peripheral speed of a process roll.</td>
</tr>
<tr>
<td>$\Delta X$</td>
<td>-</td>
<td>The increase in the degradation process in time interval $(t, t + 1)$.</td>
</tr>
<tr>
<td>$X_t$</td>
<td>-</td>
<td>The random variable describing the degradation level of equipment at time $t$.</td>
</tr>
<tr>
<td>$y_{rp}$</td>
<td>stops</td>
<td>The number of unplanned stops caused by process roll type $r$ on production line $p$.</td>
</tr>
<tr>
<td>$x_t$</td>
<td>-</td>
<td>The measured degradation level of equipment at time $t$.</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>rad</td>
<td>Angle of wrap of steel strip on a bridle roll.</td>
</tr>
<tr>
<td>$\epsilon$</td>
<td>-</td>
<td>Residual.</td>
</tr>
<tr>
<td>$\mu$</td>
<td>-</td>
<td>Coefficient of friction between a bridle roll and steel strip.</td>
</tr>
<tr>
<td>$\omega$</td>
<td>rad/sec</td>
<td>Angular velocity.</td>
</tr>
</tbody>
</table>

*Table 3: List of used variables, their unit, and meaning.*
1 Introduction

1.1 The company

The project has been conducted at Tata Steel Packaging (TSP), the packaging division of Tata Steel's steelmaking facility in IJmuiden, The Netherlands. The steelmaking facility in IJmuiden was founded in 1918 and the company was named Koninklijke Nederlandse Hoogovens en Staalfabrieken N.V. This company fused with British Steel in 1999 and changed its name to Corus. Since 2007 this facility has been part of the Tata Steel Group; an Indian steel company with operations in India, Europe, and South East Asia. Figure 2 shows the relevant part of the organogram of the Tata Steel Group. The facility in IJmuiden belongs to Strip Products Mainland Europe, which is one of the four main production hubs of Tata Steel Europe. The facility in IJmuiden has an annual production capacity of 7.5 million tons of steel and it produces approximately 7 million tons of steel in the form of coils 24 hours per day, 7 days a week. TSP is formally part of the hub Downstream Operations, but its factory is located at the steelmaking facility in IJmuiden. TSP produces tinned steel (tinplate) for the packaging industry with applications in aerosols, beverage, food, and paint. Annually, TSP produces more than 0.8 million tons of tinplate.

Figure 2: The organogram of Tata Steel Group (based on the organogram at Tata Steel intranet (1-6-2016)).

1.2 The steelmaking process

The steelmaking process at Tata Steel IJmuiden is divided into seven main production steps that are executed by nine work units. See Figure 3 for an overview of these production steps and work units. Raw materials are prepared before entering the blast furnaces where liquid pig iron is produced. Subsequently, the oxygen steelmaking plant turns this liquid pig iron into liquid steel. Liquid steel is either casted into slabs by the oxygen steelmaking plant itself, or it will go to the direct sheet plant where liquid steel gets casted and immediately hot rolled into coils. Slabs of steel that are casted by the oxygen steelmaking plant are hot rolled and coiled at the hot rolling plant. TSP receives coils from the hot rolling plant which get cold rolled and coated with a layer of tin. When steel is not destined for the packaging industry, its gets cold rolled at the cold rolling plant and coated in the coated products plant.

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1 A work unit exists of a collection of equipment and employees that is characterized by the collective tasks and its physical location such as a factory building.
1.3 Problem introduction

This research focuses on process rolls. Process rolls are components that are used to transport steel (both strip and slab) through production lines. Process rolls are discussed in paragraph 2.2. If one process roll fails, the entire production line needs to be stopped. Thus, process rolls are critical components. In IJmuiden alone, Tata Steel has thousands of process rolls installed with a wide variety in functions and technical specifications. Figure 3 shows the work units that use process rolls in their production processes. This research focuses on the process rolls that are used in the four electrolytic tinning lines (ETL) of TSP. The reasons for this choice are given in paragraph 1.5 and a detailed description of ETLs is given in Chapter 2.

In the current situation, process rolls are being replaced preventively based on a periodic interval. The periodic replacement intervals are determined based on the experience of experts and historic times until failure. The intervals are not optimized to minimize the expected costs using estimated failure time distributions of process rolls. In the current situation, two types of costs can be reduced: costs of performing corrective maintenance (situation (a) in Figure 4) and costs of performing preventive maintenance too often (situation (b) in Figure 4).

When a process roll fails before the planned periodic replacement, a corrective replacement is performed. Corrective replacements come with costs of unplanned downtime. In financial year 2016, the total unplanned downtime caused by failure of process rolls at the four ETLs equaled 310 hours and costed €1,873,328. These costs may be reduced by performing preventive maintenance, desirably just before failure.

2 A production line consists of connected equipment that form a continuous process. In general, when one piece of equipment fails to perform its function, the entire production line needs to be shut down.

3 Financial year 2016 is from 1-4-2015 until 31-3-2016.

4 Based on data from the electronic logbook and the calculation that is discussed in paragraph 3.2.
The lifetime of a process roll is wasted when a preventive replacement is performed while the condition of the process roll is sufficient to last for at least another revision interval. In other words, replacing process rolls too early results in more preventive replacements than necessary leading to higher costs. Tata Steel’s process roll repair company, IJssel Technologie, restores process rolls to an “as good as new” condition. For every process roll, there are predefined specifications which need to be met in order to be considered “as good as new”. IJssel Technology says that they occasionally receive process rolls for repair that are already close to those specifications and need little repair. This indicates that the useful lifetime of these process rolls is wasted and that preventive maintenance actions are often performed unnecessarily.

![Figure 4: Two situations using periodic replacement interval $\tau$.](image)

Both types of costs can be reduced by performing maintenance “just-in-time”. This can be achieved by using information about the condition of process rolls in relation to failure to estimate the remaining useful life (RUL) of process rolls and thus, plan and perform maintenance “just-in-time”. This is called condition-based maintenance (CBM), because preventive maintenance decisions are made based upon the condition of equipment. Jardine et al. (2005) state that a CBM policy, if properly established and effectively implemented, can significantly reduce maintenance costs by reducing the number of unnecessary planned preventive maintenance operations.

In order to perform maintenance of process rolls “just-in-time”, experts at TSP started to perform an inspection right before the periodic replacement for certain process roll types with relatively high costs of repair and relatively long life-times. During such an inspection, experts estimate the condition of a process roll based on intuition and experience and decide whether to postpone the replacement. This is a repetitive process. When these process rolls do not fail in the length of the postponed period, the production line manager can increase the replacement interval for future process rolls.

Next to the high costs of downtime, the demand for this project is mainly determined by two additional factors:

- Intuition and experience is generally in the minds of the experts. There is a dependency on these experts when it comes to maintenance decision-making because soon or late every expert will leave the company and takes his/her experience and intuition with him/her.

---

5 At TSP, all preventive maintenance tasks for a production line are clustered in planned revisions. Preventive replacements of process rolls can only be performed during these revisions.
6 RUL is the useful life left on a component at a particular time of operation (Si, Wang, Hu, & Zhou, 2010).
7 Examples are examining the shape and surface of the process roll body’s surface and feeling the temperature of bearing-houses.
Experts do not use any form of data to extract information to support the estimation of what they think are relevant conditions that relate to failure. At TSP, several sources of data are identified that can potentially support the estimation of conditions of process rolls in relation to failure and aid in maintenance decision-making. However, none of these data sources are explored and used for maintenance, yet.

In conclusion, the problem statement is:

**Failure of process rolls caused €1,873,328 of downtime costs that can be reduced by performing preventive maintenance “just-in-time” by using information about the condition and performance of process rolls.**

### 1.4 Research goal

The goal of this project is to develop a methodology to predict failure of process rolls by modelling the relations between failure predictors and failure of process rolls. A failure predictor is a parameter that describes the deterioration process of a process roll in relation to failure. If these relations exist, they can be used to predict failure of process rolls and thus aid in maintenance decision-making.

**Develop (and implement as much as possible) a methodology to predict failure of process rolls in order to improve maintenance decision-making.**

### 1.5 Scope

The moment between the measurement a failure predictor and the moment in which a process roll fails is called the remaining useful life. Predictions of the RUL are used to aid in maintenance decision-making (Wang, Scarf, & Smith, 2000). To estimate the RUL at any given point in time, a model is needed that describes the degradation process of the failure related characteristic(s) of process rolls. These models are called degradation models. To model degradation of process rolls, condition monitoring data are used, where condition monitoring data is defined in a broad sense of any data which may have a connection with the estimation of the RUL such as operational-, performance-, and degradation data (Si, Wang, Hu, & Zhou, 2010). For this project, only data that has already been collected are used.

Process rolls are used in production lines in seven out of nine work units in the entire site of Tata Steel in IJmuiden. As mentioned in paragraph 1.3, this project focuses on process rolls that are installed in the electrolytic tinning lines (ETL) of TSP. The reason for this choice is that data regarding the usage, condition, and failure of process rolls are gathered best at these production lines. A description of the ETLs is provided in paragraph 2.1. Within the ETLs, 185 different types of process rolls are installed. Types of process rolls vary from one to another in functions and technical specifications. They need to be considered separately when analyzing degradation and failure. Since time and resources are limited for this research project, one type of process roll is used as a case study to support the development of the methodology to predict failure of process rolls.

### 1.6 Deliverables

To reach the goal of the research, two deliverables are defined:

---

8 In general, a parameter is a variable representing some significant measurable system characteristic (British Standards Institution, 2012).

9 Degradation is the reduction in performance, reliability, and life span of equipment (Gorjian, Ma, Mittinty, Yarlagadda, & Sun, 2009).
1. A method that enables Tata Steel to predict failure of process rolls in order to improve maintenance decision-making.
2. An optimized maintenance policy for the selected process roll type based on the outcomes of the analysis of failure predictors for this type.

1.7 Research questions
Based on the goal of the research project, the main research question is formulated:

| How can Tata Steel increase the predictability of failure of process rolls? |

To answer the main research question, produce the deliverables, and reach the project’s goal, four research questions are defined. The answer of each research question serves as input for answering the next research question. The first two questions concern the selection of the process roll type that will serve as case study to support the development of the methodology to predict failure.

1. Which process roll type should be for this research project?
2. What are the failure predictors for the selected type of process roll?
3. What are the relations between the failure predictors and degradation of the selected process roll type?
4. What is the optimal maintenance policy, based on the found relations between predictors and failure?

1.8 Research methodology
To answer the research questions and achieve the goal and deliverables, a framework that provides a structural approach is needed. The operational research framework presented by Sagasti and Mitroff (1973) as shown in Figure 5 will serve as a guideline for this project. The framework consists of four phases: conceptualization, modelling, model solving, and implementation. In the conceptualization phase, the relation between reality and the conceptual model is established. Reality includes all aspects from the real world that form the problem situation. The goal is to form an abstraction of reality, to bring structure to the problem, and identify the relevant aspects of the problem for modelling. In the modelling phase, the relation between the conceptual model and the scientific model is established. The scientific model is a formalized representation of reality. In this project, controllable and uncontrollable variables need to be identified together with the relations and rules between those variables. This scientific model needs to be validated in order to check its accuracy with reality. In the model solving phase, a solution is obtained from the scientific model. This solution needs to be implemented in the implementation phase. During this phase, the solution is linked back with reality.
The success of this project and the future use of the tool depend strongly on the cooperation and input of Tata Steel. Therefore, it is important to use methods and analyses which are already used by Tata Steel as much as possible.

1.9 Report outline
Table 4 shows an overview of the outline of the report. The report is divided into four parts where each part discusses and answers a research question.

<table>
<thead>
<tr>
<th>Chapter</th>
<th>Chapter title</th>
<th>Research question answered</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chapter 1</td>
<td>Introduction</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td><strong>Part I – Process roll selection</strong></td>
<td></td>
</tr>
<tr>
<td>Chapter 2</td>
<td>System description</td>
<td>-</td>
</tr>
<tr>
<td>Chapter 3</td>
<td>Analysis of operating costs</td>
<td>-</td>
</tr>
<tr>
<td>Chapter 4</td>
<td>Selection of the process roll type</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td><strong>Part II – Identify failure predictors</strong></td>
<td></td>
</tr>
<tr>
<td>Chapter 5</td>
<td>Introduction to bridle rolls</td>
<td>-</td>
</tr>
<tr>
<td>Chapter 6</td>
<td>Analysis of failure modes and failure predictors</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td><strong>Part III – Degradation modelling</strong></td>
<td></td>
</tr>
<tr>
<td>Chapter 7</td>
<td>Data of failure predictors</td>
<td>-</td>
</tr>
<tr>
<td>Chapter 8</td>
<td>Degradation modelling with slip</td>
<td>3</td>
</tr>
<tr>
<td>Chapter 9</td>
<td>Degradation modelling with roughness</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td><strong>Part IV – Maintenance optimization</strong></td>
<td></td>
</tr>
<tr>
<td>Chapter 10</td>
<td>Maintenance policy selection</td>
<td>-</td>
</tr>
<tr>
<td>Chapter 11</td>
<td>Condition-based maintenance policy</td>
<td>4</td>
</tr>
<tr>
<td>Chapter 12</td>
<td>Implementation of the methodology</td>
<td>-</td>
</tr>
<tr>
<td>Chapter 13</td>
<td>Conclusions and recommendations</td>
<td>Main research question</td>
</tr>
<tr>
<td>References</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Appendices</td>
<td></td>
<td>-</td>
</tr>
</tbody>
</table>

*Table 4: Outline of the report.*
Part I – Process roll selection

This part discusses the selection process of the process roll type that served as a case study in this research project.

Part I starts by creating an understanding of the research area, as Chapter 2 provides a more extensive explanation of electrolytic tinning lines and the different process roll types. As mentioned, only one process roll type is selected to serve as the case study for the development of the methodology to predict failure of process rolls. The first part of the selection is to identify the improvement potential expressed in expected costs savings. This is done by analyzing the operating costs per process roll type where the operating costs consists of the maintenance costs and downtime costs. This is discussed in Chapter 3.

In Chapter 4, the process roll types with the highest operating costs are checked for improvement projects. Improvement projects are changes in for example the design or the repair process of a process roll with the goal to increase the performance of the process roll. At the end of Chapter 4, the first research question is answered:

| Which process roll type should be used for this research project? |
2 System description

In this chapter, the research area will be explained into greater detail with emphasis on the characteristics of ETLs, process rolls used in the ETLs, and the process roll repair company IJssel Technologie.

2.1 Electrolytic tinning lines (ETLs)

The main function of the electrolytic tinning lines is to add a layer of tin to the surface of the steel strip through an electrolytic process. Each of the four ETLs has its own properties such as maximum production speed, width of coil it can handle, and types of finish it can give to the tinplate (for example, bright, stone, and matte). Figure 6 shows an abstract example of the different production sections that form an ETL. This figure is not to scale and does not represent the amount of process rolls installed, but it provides general understanding of the production process performed on an ETL.

At the entry section, coils of steel are unwound into the ETL. To create a continuous flow of steel strip in the ETL, the beginning of a new coil is welded to the end of the previous coil at the welding machine. In sections 2 to 6 (called process sections), the steel strip flows through several tanks and sections where it is processed. When the flow of steel strip is interrupted in these process sections, the strip will have quality issues and will be rejected. Since the welding machine needs to interrupt the flow to make the weld, a buffer is placed after the welding machine in the form of an entry loop. This buffer will provide a continuous flow of steel strip for sections 2 to 6 when the flow is being stopped at the welding machine. After the input section, the steel strip is cleaned, pickled, and tinned. The layer of tin receives the correct finish at the melting section and gets chemically after-treated. The exit loop acts as a buffer for the cutting and rewinding process. Bridle sections ensure that the steel strip is at the right tension throughout the entire ETL.

![Figure 6: A simplified example of an electrolytic tinning line and its sections (not on scale) (based on technical drawings of ETLs).](image-url)
2.2 Process rolls
As discussed in the previous chapter, process rolls are components that are used to transport steel (both strip and slab) through production lines. Every process roll consists of at least one set of bearings, a shaft, and a body (also called face of the process roll). Figure 7 shows an abstract example of a process roll.

![Figure 7: Example of a process roll.](image)

When looking at the applications of process rolls in the ETLs, five additional functions next to transportation are distinguished\(^\text{10}\), and process rolls are categorized based on these additional functions. The functions are:

- To press the steel strip against another process roll: **press roll**
- To wring (steel strip flows between two wringer rolls to be discarded of liquid): **wringer roll**
- To conduct electricity for the electrolytic tinning process: **conductor roll**
- To sink the steel strip in liquid filled tanks: **sink roll**
- To control tension in the steel strip: **bridle roll**
- To solely transport the steel strip: **transport roll**

The main function of a process roll determines the technical specifications of that process roll. For example, only conductor rolls contain collectors and a cooling system. Each of the six functional categories is sub-divided into different process roll types by the minor differences in technical specifications. For example, the type of rubber that is used for the body of a wringer roll can differ from another wringer roll due to different stresses. Each type of process roll has its unique set of technical specifications and is labelled with a letter combination as shown in Figure 8. Examples of applications of process rolls from the six different functions in an ETL are shown in Figure 6.

![Figure 8: Categorization of process rolls in type and function.](image)

\(^{10}\) Process rolls do not mill steel.
2.3 Repair of process rolls

Process rolls are components that can be repeatedly restored to an “as good as new” condition. Although a process roll consists of multiple subcomponents, it is a technical component that is considered as one piece, which is replaced completely and sent for repair. Repair is defined as the process of restoring a used process roll to the “as good as new” state. Examples of repair activities are replacing bearings and grinding the process roll’s body. The average lifetime of a process roll varies from 8 to over 400 weeks, depending on the function, type, and position\(^{11}\) in the ETL. Cost of repair varies from €1,350 to €20,000 per repair, depending on the process roll type and the repair activities. Until 2012, the repair of process rolls was outsourced to dozens of different suppliers. Since 2012, Tata Steel Ijmuiden has outsourced the repair of all process rolls to Ijssel Technologie in a 10-year contract. Approximately 2,800 process rolls are repaired annually by Ijssel Technologie.

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\(^{11}\) A position is the physical location in a production line where a process roll is installed.
3 Calculation of operating costs

In general, the impact of failure can be described with its impact on safety, the environment, and operating costs. Process rolls are non-critical components when it comes to safety and the environment. Therefore, the improvement potential is defined solely as the expected costs savings. To define the improvement potential of expected costs savings, the operating costs for process rolls are calculated. Operating costs are the sum of maintenance costs and downtime costs. A Pareto analysis of operating costs is performed to separate the major causes (vital few) from the minor ones (trivial many) (British Standards Institution, 2012).

3.1 Maintenance costs

For process rolls, maintenance costs consist of the labor costs of performing maintenance (performing replacements of process rolls) and the costs of repair of process rolls. Costs of repair include all costs made in the repair process to bring a used process roll to the “as good as new” state and transportation costs from and to the repair shop. In general, only when the shaft of a process roll breaks, a new process roll is purchased and the costs of purchase replaces the costs of repair. Costs of materials that are used to perform replacements (for example, a crane to lift process rolls) are not made for individual process roll replacements because these are included in overhead costs of TSP. Material costs are therefore not accounted for in the calculation of operating costs.

Two types of maintenance costs are distinguished: corrective maintenance costs which are made when maintenance is performed after failure occurs and preventive maintenance costs which are made when maintenance is planned and performed before failure occurs. Let $c_{r}^{cm}$ denote the corrective maintenance costs and $c_{r}^{pm}$ the preventive maintenance costs for process roll type $r$, during a chosen period. Then, the total maintenance costs for process roll type $r$, $c_{r}^{maintenance}$, during that period are:

$$c_{r}^{maintenance} = c_{r}^{cm} + c_{r}^{pm}$$  

3.2 Downtime costs

Downtime is defined as the period during which a production line is not performing its intended function. Tata Steel distinguishes three categories of downtime: process- and product related downtime, production related downtime, and technical downtime. Figure 9 shows the definitions of these categories. Since the overall goal is to optimize maintenance, only downtime related to failure and maintenance will be considered (technical downtime). When looking at technical downtime, a distinction between planned and unplanned downtime is made. Planned downtime refers to periodic maintenance stops called revisions and unplanned downtime concerns downtime caused by failure of components because of a corrective maintenance action that needs to be performed immediately.

---

12 When estimated cost of repair exceed 75% of the purchase price of a new process roll, the old one will be considered scrap and a new one is bought. The price of a new process roll depends on the type of process roll.
Downtime costs are only accounted for when process rolls are being replaced correctively. Preventive replacements are performed during revisions and, in general, the duration of such a revision is fixed. The number of preventive process roll replacements performed during one revision does not influence the duration of the revision and therefore no downtime costs are made directly for each preventive process roll replacement. Thus, only costs of unplanned downtime will be included (from now on called downtime costs). Downtime costs consist of the hourly costs of being down\(^{13}\) and fixed costs for every stop due to a steel strip that is rejected and is sold for a lower price or scrapped.

The following variables are used to calculate the total downtime costs for process roll type \(r\):

- \(t_{rp}^d\) The total length of downtime caused by process roll type \(r\) on production line \(p\) (in hours).
- \(y_{rp}\) The number of times that process roll type \(r\) caused unplanned downtime on production line \(p\) (in units).
- \(c_{p}^{dh}\) The hourly cost of downtime for production line \(p\) (in €/hour).
- \(c_{p}^{df}\) The fixed costs for every unplanned stop of production line \(p\) (in €).

Let \(c_{r}^{downtime}\) denote the downtime costs for process roll type \(r\) during a period. Then,

\[
c_{r}^{downtime} = t_{rp}^d \cdot c_{p}^{dh} + y_{rp} \cdot c_{p}^{df} \quad \forall p, r
\]

Note that for this project, \(p = \{ETL11, ETL12, ETL13, ETL14\}\).

### 3.3 Operating costs

The operating costs for process roll type \(r\) are denoted by \(c_{r}^{operating}\). It is equal to the sum of the total maintenance costs and downtime costs for that type during a period (see equation (3)).

\[
c_{r}^{operating} = c_{r}^{maintenance} + c_{r}^{downtime}
\]

The operating costs provide an indication of the process roll types which are interesting to focus on, based on a cost-perspective. Downtime costs and corrective maintenance costs are interpreted as costs that can be avoided by performing preventive maintenance, where the cost of preventive maintenance is lower than corrective maintenance costs. When the operating costs of a process roll consists mostly of preventive maintenance costs, it can be questioned whether preventive

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\(^{13}\) Downtime is defined as the time in which no production order is produced by the production line. Thus, downtime includes the process of shutting down and starting up the production line.
maintenance is performed too early and useful lifetime is wasted (see Figure 4 on page 3).

3.4 Data sources
Tata Steel uses enterprise resource planning software SAP for the generation and administration of maintenance actions and registration of failures. Another source of information is the electronic logbook, which keeps track of downtime of production lines. However, the electronic logbook does not administrate the position of the process roll nor its type when downtime is caused by a process roll, and thus, the electronic logbook cannot be used to calculate downtime costs for process roll types.

Every maintenance action and failure registration in SAP includes a functional location code (FLC). The FLC of a maintenance action or failure notification denotes the corresponding piece of equipment and its location in the production line. The FLC has a hierarchical structure of which an example is provided in Table 5. Theoretically, every maintenance order and failure notification in SAP that concerns a process roll can have an FLC which is detailed enough that the type and position of the process roll being replaced are known.

<table>
<thead>
<tr>
<th>Functional location code</th>
<th>Description of the functional location</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>253</td>
<td>BEKLEDEN/KNIPpen</td>
<td>Coating/cutting</td>
</tr>
<tr>
<td>253-02</td>
<td>EV11 ELEKTROLYTISCHE VERTINBAAN 11</td>
<td>ETL11</td>
</tr>
<tr>
<td>253-02-02</td>
<td>EV11-INTRIESECTIE 1101/1235</td>
<td>Entry section</td>
</tr>
<tr>
<td>253-02-02-12</td>
<td>EV11-INTR-BRIDLESECTIE 1 1154/1159</td>
<td>Bridle section</td>
</tr>
<tr>
<td>253-02-02-12-06</td>
<td>EV11-INTR-BRID1-ROLLEN 1154/1159</td>
<td>Process rolls</td>
</tr>
<tr>
<td>253-02-02-12-06-06</td>
<td>EV11-INTR-BRID1-RLLN-AANDRUKROL M 1155</td>
<td>Press roll type M position 1155</td>
</tr>
</tbody>
</table>

Table 5: Hierarchical structure of the location code for process roll type M in position 1155.

3.4.1 Maintenance orders in SAP
Every maintenance action is planned with and administrated in a maintenance order. A maintenance order is created before the maintenance action is performed. It includes information about who is performing maintenance, which maintenance actions should be performed on that part of the production line, and the estimated costs. When maintenance is performed, the costs of the maintenance actions are added to the order. There are two types of maintenance orders relevant for this project: orders related to corrective maintenance actions (order type PM10 in SAP) and orders related to preventive maintenance actions (order type PM20 in SAP). Table 6 shows the attributes of maintenance orders that are used in the calculation of the operating costs.

<table>
<thead>
<tr>
<th>Order ID</th>
<th>Order type</th>
<th>Date of maintenance</th>
<th>Functional location code</th>
<th>Description of the functional location</th>
<th>Actual cost (€)</th>
</tr>
</thead>
<tbody>
<tr>
<td>60000000</td>
<td>PM10</td>
<td>01-01-2016</td>
<td>253-02-02-12</td>
<td>EV11-INTR-BRIDLESECTIE 1</td>
<td>1234.56</td>
</tr>
</tbody>
</table>

Table 6: Relevant variables of maintenance orders in SAP.

3.4.2 Notifications in SAP
Notifications serve as a form of communication between the operating department of a production line and the production line managers. They capture technical observations such as the presence of failure, the effect, the possible causes of failure, and actions to take. There are two types of notifications:

| 14 Orders do not include downtime costs, only costs of maintenance (see paragraph 3.1). |
| 15 The format of dates is dd/mm/yyyy. |
• **M1** notification. This is a request for preventive maintenance. There is no downtime. An **M1** notification can result in a preventive maintenance action (*PM20*) that will be performed during a planned revision such that no additional downtime is caused.

• **M2** notification. This is a notification of failure, where the production line does not meet its technical specifications anymore. This usually results in the performance of a corrective maintenance action (*PM10*).

Table 7 shows the attributes of a notification that are used for the calculation of the operating costs.

<table>
<thead>
<tr>
<th>Notification ID</th>
<th>Notification type</th>
<th>Order ID</th>
<th>Date</th>
<th>Functional location code</th>
<th>Description of the functional location</th>
<th>Downtime (hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>12000000</td>
<td>M2</td>
<td>6000000</td>
<td>01-01-2016</td>
<td>253-02-02-12</td>
<td>EV11-INTR-BRIDESECTIE 1</td>
<td>5.0</td>
</tr>
</tbody>
</table>

*Table 7: Relevant variables for notifications in SAP.*

### 3.4.3 Data filtering

While *PM20* orders are used for calculating preventive maintenance costs, *PM10* orders are used for calculating corrective maintenance costs, and *M2* notifications are used to calculate the total downtime and subsequently cost of downtime. These orders and notifications should be selected for every process roll type. The question is: how can one select only those maintenance orders and notifications which concern process rolls and identify the type of process roll? As discussed earlier in this section, the FLC characterizes the equipment that the maintenance order or notification concerns. A list of FLCs is constructed manually for each of the ETLs that will serve for filtering the orders and notifications that concern process rolls. See Table 8 for an example.

<table>
<thead>
<tr>
<th>Functional location code</th>
<th>Description of the functional location</th>
<th>Process roll type</th>
</tr>
</thead>
<tbody>
<tr>
<td>253-02-02-04-04-10-06</td>
<td>EV11-INTR-AFRO-DVRL1-OMBUIGROL TA 1103</td>
<td>TA</td>
</tr>
</tbody>
</table>

*Table 8: Variables in the list of FLCs used for data filtering.*

For the preventive maintenance orders (*PM20*), an additional filter is used. There exists a *periodic maintenance plan*[^16] in SAP which automatically generates *PM20* orders for equipment based on the periodic replacement interval determined for its corresponding equipment. A list is created manually which contains all *periodic maintenance plans* for process rolls of ETLs. See Table 9 for an example. The plan in Table 9 generates a *PM20* order every 104 weeks to replace process roll M in position 1155 of ETL11. When corrective maintenance is performed for this process roll, the timer of the *periodic replacement plan* is set to 0, starting a new interval of 104 weeks.

<table>
<thead>
<tr>
<th>Text periodic maintenance plan</th>
<th>Functional location code</th>
<th>Description of the functional location</th>
<th>Process roll type</th>
</tr>
</thead>
<tbody>
<tr>
<td>EV11 104w wiss. rol 1155(M) rws</td>
<td>253-02-02-12-06-06</td>
<td>EV11-INTR-BRIDGE-RLLN-AANDRUKROL M 1155</td>
<td>M</td>
</tr>
</tbody>
</table>

*Table 9: Variables in the list of periodic maintenance plans for data filtering.*

The FLC list and the *periodic maintenance plan* list are used to filter maintenance orders and notifications from the SAP database. Figure 10 shows a graphical overview of how these lists are used to find both notifications and maintenance orders for process rolls. Note that *PM20* orders are selected based on corresponding **M1** notifications, and that *PM10* orders are also selected based on corresponding **M2** notifications. This is done to maximize the probability that all relevant maintenance orders will be found. After having done the analysis, it turned out that all maintenance orders (both

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[^16]: In Dutch (and used by TSP): *periodek onderhoudsplan* (PO-plan).
PM20 and PM10) that are found based on notifications, were already selected based on the FLC list and therefore these connections are faded in Figure 10.

**Figure 10: Graphical representation of the connection between FLC, failure notifications, and maintenance orders.**

### 3.5 Tool
A tool has been developed in Microsoft Excel that executes the steps as shown in Figure 10. The tool calculates the total operating costs per process roll type for all process rolls used in the four ETLs given the input data. The input data for analyzing operating costs are M1 and M2 notifications and PM10 and PM20 maintenance orders that are exported from SAP. The tool filters all notifications and maintenance orders with the use of the periodic maintenance plan and FLC list. An extensive description and a user manual of this tool can be found in Appendix C.

### 3.6 Determination of the time window
The time window that will be used for analyzing the operating costs for process rolls needs to be determined carefully. First, the time window will be a multiple of one financial year (1st of April to 31st of March), because one financial year consists of one full revision cycle (including an annual revision) in which maintenance tasks are scheduled.

Table 10 shows that for process rolls, the shortest and longest periodic replacement interval are 10 and 500 weeks, respectively. The longest periodic replacement interval tends to set a lower bound on the length of the time window. However, there is another factor that should be considered in the decision on this lower bound. This second factor is the risk of including outdated data in the calculation of operating costs. Data becomes outdated since many improvement projects regarding the performance of process rolls have been executed throughout the years, significantly influencing the performance and the operating costs. In other words, past problems that no longer exist should be
excluded in the analysis of operating costs as much as possible. To determine the time window for analysis of operating costs, there is a trade-off:

- Keep the time window short enough to exclude outdated data.
- Keep the time window long enough to include costs of those process rolls that have relatively long replacement intervals.

<table>
<thead>
<tr>
<th>Production line</th>
<th>Shortest replacement interval</th>
<th>Longest replacement interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>ETL11</td>
<td>10 weeks</td>
<td>400 weeks (7.7 years)</td>
</tr>
<tr>
<td>ETL12</td>
<td>10 weeks</td>
<td>500 weeks (9.6 years)</td>
</tr>
<tr>
<td>ETL13</td>
<td>12 weeks</td>
<td>364 weeks (7.0 years)</td>
</tr>
<tr>
<td>ETL14</td>
<td>16 weeks</td>
<td>260 weeks (5.0 years)</td>
</tr>
</tbody>
</table>

Table 10: Shortest and longest periodic maintenance interval for process roll types of the ETLs.

Even though the longest replacement interval exceeds a length of 5 years, few process rolls are replaced after such an interval. Figure 11 shows the distribution of time until replacement for every process roll that has been installed in the four ETLs during the period 1-4-2008 to 31-3-2016 (there is no replacement data from before 1-4-2008). As a result of this the trade-off, the time window for analysis of operating costs is set to three years. The three most recent financial years are from April 1st 2013 until March 31st 2016. This includes 95.5% of all replacements and there are no abnormal maintenance costs associated with the replacements in the other 4.5%.

3.7 The results of the calculation of operating costs of process rolls

Because the downtime notifications in SAP are created and maintained manually, errors are made and incorrect downtime is registered. For the calculation of operating costs in the determined period, five outliers (created by human errors) were deleted based on a comparison of downtime in the electronic logbook at the same date and the description in the notification and corresponding order. The downtimes of the 5 outliers are 223, 1129, 3242, 26, and 27 hours.

Not all maintenance orders and downtime notifications contain the appropriate FLC. In these exceptional cases, the FLC is too short and therefore does not refer to a process roll but to a bigger
piece of equipment or section in which the process roll is installed. There is no other way to include these maintenance orders and downtime notifications on a large scale, and therefore these data are not included in the calculation of operating costs.

To calculate the downtime costs, the costs that are shown in Table 11 are used. These costs are defined by TSP.

<table>
<thead>
<tr>
<th>Production line p</th>
<th>$c_{ph}^p$ (€)</th>
<th>$c_{pf}^p$ (€)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ETL11</td>
<td>4,000</td>
<td>1,000</td>
</tr>
<tr>
<td>ETL12</td>
<td>5,000</td>
<td>1,000</td>
</tr>
<tr>
<td>ETL13</td>
<td>6,000</td>
<td>1,000</td>
</tr>
<tr>
<td>ETL14</td>
<td>7,000</td>
<td>1,000</td>
</tr>
</tbody>
</table>

*Table 11: Hourly and fixed downtime costs for ETLs.*

The results of the calculation are shown in Figure 12. Note that only the 50 (out of 185) process roll types with the highest operating costs are shown. Based on these results, it is straightforward to select process roll type MB or AF for this research project.

![Figure 12: Operating costs for the top 50 types of process rolls.](image)

### 3.8 Chapter conclusion

Selecting a process roll type will not only be relevant for this research project, but will be relevant for all future analysis of process rolls. Figure 12 shows the result of the operating costs for process rolls at the ETLs for 1-4-2013 until 31-3-2016. There is a strong difference in operating costs as 11 out of 185 process roll types are responsible for 50% of all operating costs. Process roll type MB is the type with the highest operating costs and, therefore, based on these costs only is most interesting to use as case study.
4 Selection of the process roll type

4.1 Improvement projects

The trade-off that is discussed in paragraph 3.6 regarding the analysis of operating costs includes the argument to keep the time window short enough to exclude outdated data of costs. This is due to problems (that cause corrective maintenance and downtime costs) that are no longer problems.

The main task of the process roll maintenance specialist of TSP is to increase the performance of process rolls by performing improvement projects. Improvement projects include the modification of the design of process rolls, but also improvements in the repair process (the way repair is performed). The main trigger for improvement projects are the reoccurring faults that are identified by the specialist (who performs root-cause analyses). Another trigger can be that new technologies and materials have been developed that can increase the performance. In the last couple of years, many improvement projects have been finished successfully and lifetimes of these process rolls increased significantly. Data\textsuperscript{17} regarding this process roll that is collected before the improvement project do not represent the current process roll (and its repair process or environment, depending on the improvement) and thus these data cannot be used to model degradation to predict failure. Based on the presence of improvement projects, the following additional selection criteria is defined:

When, for a process roll type, an improvement project has recently been performed, is currently being performed, or is planned to be performed in the near future, this type is eliminated for this research project.

4.2 Selecting a process roll type

With the help of process roll maintenance specialist of TSP, the process roll types with the highest operating costs (as estimated in the previous chapter) are checked for recent, current or planned improvement projects. The results are shown in Table 12. According to these results, the process roll type LH is most appropriate for this research project, followed by the type EB. Remember that the calculated operating costs are estimates of the actual costs, because the FLC that is used to find costs to process rolls, is not used properly consistently. This leaves the decision between the LH and EB roll open for discussion. Remember that the goal of the project is the development of a methodology to predict failure of process rolls. During an interview with the process roll maintenance specialist additional factors for the decision of the most appropriate type were discussed that led to the selection of the type EB for research. These factors are; availability of process data and scalability.

\textsuperscript{17} For example, failure time data and condition data.
### Table 12: Check for recent, current, or planned modifications.

<table>
<thead>
<tr>
<th>Process roll type</th>
<th>Operating costs (€)</th>
<th>Modified</th>
</tr>
</thead>
<tbody>
<tr>
<td>MB</td>
<td>1,232,754</td>
<td>Yes</td>
</tr>
<tr>
<td>AF</td>
<td>1,170,859</td>
<td>Yes</td>
</tr>
<tr>
<td>P</td>
<td>877,690</td>
<td>Yes</td>
</tr>
<tr>
<td>AA</td>
<td>824,461</td>
<td>Yes</td>
</tr>
<tr>
<td>S</td>
<td>627,568</td>
<td>Yes</td>
</tr>
<tr>
<td>EG</td>
<td>600,620</td>
<td>Yes</td>
</tr>
<tr>
<td>MA</td>
<td>528,825</td>
<td>Yes</td>
</tr>
<tr>
<td>MC</td>
<td>493,600</td>
<td>Yes</td>
</tr>
<tr>
<td>ME</td>
<td>439,631</td>
<td>Yes</td>
</tr>
<tr>
<td>LH</td>
<td>425,031</td>
<td>No</td>
</tr>
<tr>
<td>EB</td>
<td>357,148</td>
<td>No</td>
</tr>
<tr>
<td>EV</td>
<td>337,219</td>
<td>Yes</td>
</tr>
<tr>
<td>Y</td>
<td>310,420</td>
<td>Yes</td>
</tr>
<tr>
<td>KN-A</td>
<td>307,988</td>
<td>Yes</td>
</tr>
<tr>
<td>RG</td>
<td>267,851</td>
<td>No</td>
</tr>
</tbody>
</table>

### Availability of process data

The database of the operating and control system of an ETL is a potential source for data of failure predictors, as data from all kinds of processes on the ETLs are logged on a continuous base. LH rolls are only used in ETL14. ETL14 received a new operating and control system which is approximately 3 months old by the time of writing. This means that logging data of signals started three months ago. This eliminates the opportunities to model degradation with process data for LH rolls that have an average time-to-replacement of 97.4 weeks. EB rolls are only used in ETL13. The operating and control system of this ETL has not been changed, and therefore the opportunities to model degradation of EB rolls with process data are not eliminated.

### Scalability

EB rolls are process rolls that control the tension in the steel strip. These process rolls are generally called bridle rolls. Every production line that unwinds and rewinds a coil of steel has bridle rolls installed. This means that when using EB rolls for this project, the opportunity exists that the lessons learned can easily be transferred to other bridle rolls in all other production lines.

There is one remark about selecting EB rolls for this project and that is that there has been a recent improvement project for the EB rolls on the type of rubber that is used for its body. EB rolls that were installed in the exit section of ETL13 after the oil machine faced problems with oil on the rubber body. According to the process roll maintenance specialist, the new type of rubber will only influence the performance at EB rolls at the exit section in relation to oil. Therefore, the EB rolls in these sections are excluded for research. Excluding these sections will reduce the operating costs, making EB roll lower in rank of operating costs. By the time that the decision for EB rolls was made, it was not investigated what the impact of the excluded EB rolls on the costs was.

### 4.3 Chapter conclusion

Based on an analysis of operating costs, a check for improvement projects, and the discussion about LH and EB rolls, the process roll type EB has been selected and served as a case study for this project. This is the answer to the first research question.
Part II – Identify failure predictors

The selection process described in Part I resulted in process roll type EB being used for the case study. Part II is the starting point of the case study. From now on, each step will start with a description of the general approach that is used in that step, followed by the analysis and results for the case study: EB rolls.

Part II begins with Chapter 5 which provides an extensive description of EB rolls, including their functions, characteristics, and application in the ETL.

The next step in this research project is identifying the potential failure predictors for these EB rolls. Failure predictors are parameters that can be used to predict how long equipment (EB rolls) can run until failure occurs (Lubbers, 2016). In order to identify the potential failure predictors for process rolls, the failure modes are defined. The analysis of failure modes and failure predictors is discussed in Chapter 6. At the end of this chapter, the second research question is answered:

| What are the failure predictors for the selected type of process roll? |
5 Introduction to bridle rolls

5.1 Function of bridle rolls
The selected type of process rolls for this research project are EB rolls. These EB rolls are the bridle rolls in ETL13. The main function of bridle rolls is to control the tension in the steel strip in production lines.

In a production line like an ETL, forces are applied to the steel strip, resulting in tension in the steel strip. Tension is a force transmitted through the steel strip, and can be compared to pulling on both ends of a rope. When pulling at these ends with a force of 10 N, the tension in the rope will equal 10 N. Because the stress created by tension is distributed over the cross-sectional area of the steel strip, tension can also be expressed in N/mm² (where mm² equals the cross-sectional area of the steel strip). Tension in steel strip in production lines rises unintentioned and is controlled by several means. Controlling the tension of steel strip in a production line is essential for the tracking of the steel strip through the entire production line. When the tension of steel strip is too low, the steel strip can derail in the production line. This will damage the strip and is also likely to damage equipment in the production line. When the tension is too high, the strip can stretch and subsequently break, causing both damage and downtime. There is a desired tension level for every type of steel strip (mainly determined by the width and thickness of the strip) and for every section in a production line. Different sections require different tensions due to the varying processes performed in each section. A full explanation and numerical example of tension and tension control is given in Appendix B.

5.2 Characteristics of bridle rolls
In this paragraph, the theory of creating tension with a bridle roll is discussed to create an understanding of the characteristics of bridle rolls important for functioning. One of the determining characteristics of bridle rolls is the angle of wrap: the contact that the steel strip makes with the bridle roll. The larger the angle of wrap, the higher the maximum tension differential that can be created. In general, a bridle roll can affect the tension in the steel strip as defined by equation (4). Figure 13 shows a graphical example of the variables used to calculate how a bridle roll can affect tension in steel strip.

\[ T_2 = T_1 \cdot e^{\alpha \mu} \]  

Where;
- \( T_1, T_2 \) The tension (in N/mm² or N) in the steel strip before and after the bridle roll.
- \( \alpha \) The angle of wrap (in radians) of the steel strip on the bridle roll.
- \( \mu \) The coefficient of friction between the bridle roll and the steel strip (dimensionless).

The tension differential that a bridle roll can create, \( \Delta T_{1,2} \), is equal to \( T_2 - T_1 \). The coefficient of friction and angle of wrap determine the maximum tension differential a bridle roll can create, where the tension can be increased or decreased. The tension differential that a bridle roll must create is determined by the characteristics of the production process and the dimensions of the steel strip. For every bridle roll in ETL13, the angle of wrap, \( \alpha \), is a constant as the positions of these rolls are fixed. The desire to have a large angle of wrap is the reason why bridle rolls have the largest diameters of all process rolls. The coefficient of friction, \( \mu \), is variable due to wear and tear. Its value depends on the surfaces of the steel and the condition of the rubber of the process roll’s body. The conclusion that can be drawn from equation (4) is that only the coefficient of friction determines whether a bridle roll can create this tension differential.
Sufficient friction and angle of wrap alone do not create a tension differential, they only define the maximum tension differential that can be created. To create a tension differential, a bridle roll needs to be driven by a motor. In case of the EB rolls in ETL13, these motors are DC electromotors. A gearbox with a fixed gear is placed in-between the electromotor and the bridle roll (as shown in Figure 14) that reduces the angular velocity of the electromotor shaft.

Figure 22 shows a photo of three EB rolls in ETL13 during the annual revision. Note the blue bearing houses and the rubber body. In this photo, the electromotors are positioned on the other side of the EB rolls.
Figure 15: A photo of 3 EB rolls in bridle section 1. (photo made during the annual revision of ETL13 on 26-10-2016 by A.P.J. Avontuur).

5.3 Bridle rolls at ETL13
ETL13 contains 6 bridle sections of which the last 3 bridle sections in the ETL faced problems with an oily strip, as discussed in paragraph 4.2. The case study includes bridle sections 1, 2, and 3. Figure 16 shows the entry section (with bridle section 1 and 2) and beginning of the process section (with bridle section 3) of ETL13. For the sake of clarity, the position numbers of EB rolls that are used by Tata Steel are replaced by \( i, j \), where \( j \) is an EB roll position in bridle section \( i \) (counted in the direction of the steel strip).

Figure 16: Abstract overview of bridle sections 1, 2, and 3 of ETL13 (not on scale, based on technical drawings of ETL13).
6 Analysis of failure modes and failure predictors

In this chapter, the developed approach to determine the failure modes and failure predictors of process rolls is discussed. Subsequently, this approach is used to determine the failure predictors of EB rolls.

6.1 The approach

To estimate the condition of process rolls in relation to failure to aid in maintenance decision-making, it is essential to understand what failure is and what causes failure. When the identification of a predictor to monitor is not based on the fundamental understanding of failure equipment, an erroneous parameter may be monitored, leading to faulty failure predictions (Mathew, Alam, & Pecht, 2012). Thus, to identify failure predictors for process rolls, a fundamental understanding of failure must be established. This understanding is created by analyzing the failure modes of process rolls. Any event that causes a functional failure is called a failure mode (Moubray, 1997). The failure predictors are identified based on the failure modes.

The steps to identify failure predictors of process rolls are shown in Figure 17. In general, two actions are distinguished; (1) define failure modes and (2) define failure predictors. For defining failure modes and failure predictors, generally three sources of information can be used; (1) literature, (2), experience, and (3) the original equipment manufacturer (OEM). Literature is used to find information about the failure modes and failure predictors of process rolls in general because literature on process rolls used in the steel industry is not found. Experience can be divided into two kinds: experience of employees and experience in the form of logged (historic) maintenance orders and downtime notifications (in SAP). The OEM of process rolls can be a valuable source of information on failure of its manufactured process rolls. The two actions as shown in Figure 17 are discussed in the next two paragraphs.

![Figure 17: The developed approach for identifying possible failure predictors of a process roll type.](image)

6.1.1 Define failure modes

Every process roll consists of multiple subcomponents. Each of the subcomponents has a function that contributes to the functioning of the process roll. When a subcomponent fails to perform its function (functional failure\(^{18}\)), the process roll fails to perform its function. Therefore, when analyzing the failure modes of a process roll type, failure of its subcomponents needs to be analyzed. To define these failure modes, four steps are defined and are shown in Table 13.

---

\(^{18}\) The inability of any asset to fulfill a function to a standard of performance which is acceptable to the user (Moubray, 1997).
Step | Description of the step
---|---
1. Subcomponent | Define all subcomponents of the process roll type.
2. Function | For each of the subcomponents, define its function(s).
3. Functional failure | For each of the functions, define what functional failure is.
4. Failure mode | For each of the functional failures, define the failure modes.

Table 13: The identified steps to define failure modes.

6.1.2 Identify failure predictors
Where the fundamental understanding of failure begins with analyzing a process roll’s failure modes, it continues with analyzing the causes and effects of these failure modes. The cause and effect can support in assessing the detectability and measurability of deterioration. Detectability means that any irregularity can be detected by, for example, the senses of employees or quality control camera’s. These irregularities must describe a potential failure in the near future. Four steps are defined for the identification of failure predictors. These steps are shown in Table 14.

<table>
<thead>
<tr>
<th>Step</th>
<th>Description of the step</th>
</tr>
</thead>
<tbody>
<tr>
<td>5. Cause</td>
<td>For each of the failure modes, describe the cause of the failure mode.</td>
</tr>
<tr>
<td>6. Effect</td>
<td>For each of the failure modes, describe the effect of failure.</td>
</tr>
<tr>
<td>7. Detectable</td>
<td>For each of the failure modes, assess if any irregularity can be detected.</td>
</tr>
<tr>
<td>8. Measurable</td>
<td>For each of the failure modes, assess if deterioration can be measured. If yes, what to measure, both directly and indirectly.</td>
</tr>
</tbody>
</table>

Table 14: The steps to take to define predictors

6.2 Execution of the approach
Literature, experience, and the OEM serve as input for the analysis of both failure modes and failure predictors (see Figure 17). To structure the execution of the analysis of failure modes and predictors, information coming from these three sources are collected in one table. Table 15 contains the 8 steps defined in the previous paragraphs. It serves as a starting point for the analysis of failure modes and failure predictors for every process roll type.

<table>
<thead>
<tr>
<th>Sub-component</th>
<th>Function</th>
<th>Functional failure</th>
<th>Failure mode</th>
<th>Effect</th>
<th>Cause</th>
<th>Detectable</th>
<th>Measurable</th>
</tr>
</thead>
<tbody>
<tr>
<td>Body</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bearings</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shaft</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 15: Starting point of the analysis of failure modes and failure predictors.

Figure 18: Schematic representation of the execution of the approach.
See Figure 18. A distinction is made between steps that can be performed individually without the experience of employees and steps that require the experience of these employees. Performing the individual steps (gaining knowledge from literature, SAP, OEM) will result in a first idea of the failure modes and failure predictors and a partially filled in table (Table 15). This partially filled table is used for interviewing employees about their experience. It is desirable to have as much understanding about failure of the process roll type as possible before any expert is being consulted. It is presumed that time of employees is limited and thus interviewing them must be as efficient as possible. Preferably, a group session is organized in which employees of different disciplines participate. In this way, discussions can take place when different employees have different experiences about for example a failure mode. For such a group session, it is important to select the employees that have the most and relevant experience and make sure to select employees from different disciplines so that different experiences are consulted. Examples of appropriate employees are operators, technical assistants, production line managers, and maintenance managers. After the experience of employees has been consulted, all failure modes and failure predictors must be defined. For every failure mode, it should become clear that the failure mode forms an actual problem, or can form an actual problem. Interviews with maintenance engineers at TSP revealed that a common pitfall of analyzing failure modes in group sessions is the dedication of a large amount of time to potential failure modes that are not or are rarely occurring and have relatively minor effect.

6.3 Analysis of failure modes and failure predictors for EB rolls
The analysis is performed as described in the previous paragraph. For EB rolls, it was not possible to obtain failure information from the OEM. The manufacturer of EB rolls was commissioned by Tata Steel to produce several EB rolls from technical drawings delivered by TSP. The manufacturer has no information about the degradation and failure of EB rolls. A first understanding of the different failure modes was constructed based on a literature study and the relevant maintenance orders and downtime notifications in SAP. Finally, the experiences of employees are consulted by organizing a group session. The following employees participated in this session:

- Process roll maintenance specialist of the four ETLs
- Production line manager of ETL13
- Technical assistant of ETL13
- Maintenance manager TSP

The results of the analysis of failure modes and failure predictors of EB rolls are described in the following paragraphs. The results are also summarized in Appendix D.

6.4 Coefficient of friction too low
The body of an EB roll has two functions. (1) To provide friction between the process roll and steel strip without damaging the steel strip and (2) to transport the steel strip without deforming or damaging the steel strip. This paragraph discusses function (1). Friction is needed to create a tension differential in the steel strip as is explained in Chapter 5. The body fails to perform this function when the required tension differential cannot be achieved. This happens when the coefficient of friction between the EB roll’s rubber body and the steel strip is insufficient (see equation (4) on page 21). In general, a coefficient of friction is determined by multiple factors such as the roughness of the material’s surface, mechanical properties of the materials, and the contact pressure between two materials (in the case of resilient materials such as rubber) (Ivkovic, Djurdjanovic, & Stamenkovic, 2000). While there are multiple factors that determine the coefficient of friction, only the factors that cause the coefficient of friction to decrease are interesting to investigate as a possible failure predictor.

According to Ivkovic et al. (2000), roughness of a material’s surface is a suitable parameter to
investigate the coefficient of friction. When an EB roll’s body degrades, its surface roughness decreases to a point where it can get too low and the coefficient of friction becomes insufficient. Therefore, the failure mode *coefficient of friction is too low* is identified. Roughness is a potential predictor of this failure mode. When the roughness gets too low to generate the required tension differential, the EB roll starts to slip. Slip means that there is a difference in speed of the steel strip and peripheral speed of the EB roll. When slipping extensively, the required tension is likely to not be achieved. Another effect of insufficient friction is that the surface of the steel strip can become scratched by the slipping process roll. When this happens, the steel strip will either be scrapped or sold for a lower price. When the required tension cannot be controlled anymore and/or the steel strip is scratched by slipping of the EB roll, a corrective replacement must be performed. A second potential failure predictor for the failure mode *coefficient of friction is too low* is the slip between EB rolls and the steel strip.

The roughness of an EB roll body’s surface can degrade due to wear and tear but also due to oil pollution of the body. Oil on the body’s surface acts as a lubricant film between the EB roll’s body and the strip, causing the coefficient of friction to drop. This is the case when coils of steel that are cold-rolled on the production line DKG11\(^{19}\) are used. For the rolling process on the DKG11, oil is applied on the steel strip. This oil tends to pollute the EB rolls in bridle section 1 of ETL13, but as soon as non-DKG11 steel is being processed at ETL13, the pollution wears off. Only 13.5% of all steel that is being processed on ETL13 comes from DKG11. The production schedule at ETL13 accounts for the oil pollution of process rolls in the entry section due to steel from DKG11 by alternating between steel coils from DKG and other cold rolling production lines. Slip is identified as failure predictor.

### 6.5 Worn tracks in the body

The second function of the EB roll’s body is to transport the steel strip without deforming or damaging the steel strip. The functional failure in this case is the production of wavy edges\(^{20}\) on the steel strip. See Figure 19 for an illustration of this so-called *flatness defect*.

![Figure 19: Wavy edges of steel strip (Molleda, Usamentiaga, García, & Bulnes, 2010).](image)

Wavy edges occur when there are worn tracks in one or both ends of a process roll’s body. The worn tracks are caused by wear and tear as the edges of the steel strip cause the resilience of the rubber body to decrease. Figure 20 and Figure 21 illustrate what worn tracks in a process roll’s body look like. A photo is made of worn tracks from a different process roll type (type P) since no EB rolls with worn tracks were present during this project.

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\(^{19}\) DKG11 is a double-cold-rolling production line at TSP.

\(^{20}\) At TSP, the Dutch term *golfranden* is used for wavy edges.
Generally, wavy edges higher than 1.5 millimeters are considered a quality issue and for that reason the produced tinplate can be rejected. As soon as tinplate gets rejected, the process roll(s) causing wavy edges need(s) to be replaced by performing corrective maintenance. The difficulty lies in the fact that usually a combination of process rolls with worn tracks causes wavy edges in the steel strip. The four ETLs at TSP ETL11, ETL12, ETL13, and ETL14, contain 300, 316, 265, and 222 process rolls, respectively. When wavy edges occur, it is always a challenge to replace the right process roll(s). Employees need to search the process roll(s) that create the wavy edges by performing an inspection and replace the suspected process roll(s). In some cases, wavy edges reoccur in the steel strip after the corrective replacement of process rolls that were identified to be causing the wavy edges.

It is possible to postpone corrective replacements until the next revision. This can be achieved by producing production orders of which the steel strip is small enough to stay in the middle of two worn tracks on a process roll. However, this rarely occurs in practice since the planning horizon is short.

The worn tracks can be detected visually during inspections. The characteristics of these tracks can also be measured. See Figure 22. A combination of the values for $x$, $y$, and $z$ expresses the size of the worn tracks. These measurements will be called *track measurements*. $z$ can be determined by comparing the diameter of the worn track by the diameter of the body right next to the worn track.
6.6 Overheating of bearings

Process rolls are rotating components. To rotate, a process roll has one bearing on each side of the roll. The function of these bearings is to allow a process roll to rotate at the required speed with low rolling resistance. For the EB rolls, bearings lose their function when the process roll rotates with high rolling resistance or does not rotate at all. The latter one is a rare occasion. The failure mode that corresponds to this failure is the overheating of bearings. When the temperature of a bearing exceeds a certain threshold, the material of the ring and rollers can anneal and lose its hardness. This loss of hardness reduces the bearing capacity and therefore causes early failure. Deformation of a bearing’s ring and rollers takes place in extreme cases of overheating.

Bearings contain lubricant which is essential for the performance and lifetime of bearings. The main function of this lubricant is (1) to separate parts moving relative to one another to minimize friction and prevent wear and (2) to dissipate frictional heat and thus prevent overheating of the bearing (AST Bearings LLC, 2010). The causes for overheating can be that (1) too much or too little lubricant is applied or (2) that the wrong type of lubricant is used or (3) that the clearance in the bearing house is too high.

When bearings are overheated, the process roll cannot rotate at the required speed with the desirable amount of rolling resistance. In this case, a corrective replacement needs to be performed. In general, overheated bearings are both detectable and measureable. Failure can be detected by observing noise and/or sparks. The most common predictor to measure deterioration are temperature and vibrations of a bearing. A third predictor is the electric power that the electromotor uses. When rolling resistance of the bearings increases, it is likely that the electromotor uses more power to rotate at the required speed.

6.7 Shaft breakage

The shaft is the part that connects the bearings with the body. Its main function is to transfer the torque that is generated by the electromotor to the body of the process roll. The shaft only fails when it breaks. Therefore, the failure mode is shaft breakage. The cause is metal fatigue of the shaft and this process in influenced by the load that is put on the process roll. Unfortunately, the shaft can only be inspected during repair of the process roll when the maintenance decision has already been made and the process roll has already been replaced. During repair, a visual check of the shaft is performed followed by measuring micro-cracks if the repairman suspects a poor condition of the shaft. The effect of shaft breakage is that the steel strip is likely to break, the structure and other equipment close to the process roll can be damaged, and a corrective replacement is necessary. Shaft breakage occurs rarely or not at all, since the shaft is overdesigned.

6.8 Excluded failure modes

6.8.1 Driver and drive coupling

The tension differential in steel strip can also not be achieved when the electromotor fails or when the coupling that transfers the torque from the electromotor to the EB roll fails. However, these components are not considered for analysis because they are generally not part of process rolls.

6.8.2 Misalignment

Little literature exists concerning process rolls. Mobley (2002) describes process rolls in a broad sense: from applications in conveyer belts to applications in the paper industry. When it comes to which parameters to monitor to estimate the condition with regard to failure, Mobley focusses mainly on the bearings, load distribution, and misalignment. Misalignment is a common problem for process rolls at Tata Steel, but not for EB rolls. The housing in which the bearings (together with the EB roll)
are placed during a replacement has a fixed position in the ETL, allowing employees to install a new EB roll without realigning it. Therefore, there is no problem such as misalignment of EB rolls. For other process roll types, misalignment can be detected using vibration measurements (Mobley, 2002).

6.9 Prioritizing failure modes

In the previous paragraphs, the failure modes of EB rolls have been discussed. Table 16 shows an overview of the failure modes of EB rolls that are included and excluded in this research project.

<table>
<thead>
<tr>
<th>Included failure modes</th>
<th>Excluded failure modes</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Coefficient of friction is too low</td>
<td></td>
</tr>
<tr>
<td>• Worn tracks</td>
<td></td>
</tr>
<tr>
<td>• Overheating of bearings</td>
<td></td>
</tr>
<tr>
<td>• Shaft breakage</td>
<td></td>
</tr>
<tr>
<td>• Defect driver</td>
<td></td>
</tr>
<tr>
<td>• Defect drive coupling</td>
<td></td>
</tr>
<tr>
<td>• Misalignment</td>
<td></td>
</tr>
</tbody>
</table>

Table 16: Overview of failure modes.

The four relevant failure modes are coefficient of friction is too low, worn tracks, overheating of bearings, and shaft breakage. Prioritizing these failure modes based on their impact is important to gain insight in what is causing most problems and thus which failure modes have the highest priority for analysis. The failure modes are prioritized based on the costs made due to failures of each failure mode. These costs consist of corrective maintenance costs and costs of unplanned downtime. Again, the FLC is used to find the relevant maintenance orders and downtime notifications in SAP. This time, the FLC of the bridle sections are used instead of the individual EB roll positions. This will result in all maintenance orders and downtime notifications for the entire bridle sections including those not related to EB rolls. All maintenance orders and downtime notifications are analyzed manually to maximize the probability that all maintenance orders and downtime notifications related to the failure modes of EB rolls are included. The analysis of costs per failure mode is performed for every EB roll position in ETL13 for the time interval of which replacement data is known (1-1-2008 until 1-9-2016). All costs made due to failure modes of the past are excluded in this analysis. This includes the problems with oil in the excluded bridle sections. The results are shown in Figure 23 and Table 17. The failure modes coefficient of friction is too low and worn tracks are the failure modes with the largest impact on costs. Overheating of bearings occurred only once with a minor effect on costs. Shaft breakage never occurred. This is because the shaft is overdesigned.

![Figure 23: The operating costs of the failure modes of EB rolls.](image-url)
Table 17: Occurrences and operating costs of relevant failure modes for EB rolls in the period from 1-1-2008 until 1-9-2016.

<table>
<thead>
<tr>
<th>Failure mode</th>
<th>Occurrence</th>
<th>Operating costs (€)</th>
<th>Average costs per failure (€)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coefficient of friction is too low</td>
<td>16</td>
<td>187,850</td>
<td>11,741</td>
</tr>
<tr>
<td>Worn tracks</td>
<td>11</td>
<td>137,252</td>
<td>12,477</td>
</tr>
<tr>
<td>Overheating of bearings</td>
<td>1</td>
<td>2,980</td>
<td>2,980</td>
</tr>
<tr>
<td>Shaft breakage</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

After the analysis (Figure 23) it is decided to exclude the failure mode shaft breakage from further research because failure did not occur due to over dimensioning of the shaft and because micro-cracks can only be assessed during repair activities.

This project only focused on bridle section 1, 2, and 3, as discussed in paragraph 4.2. The costs per failure mode for EB rolls are calculated for every bridle section individually. For bridle sections 1, 2, and 3, the majority of the costs are caused by the failure mode coefficient of friction is too low.

Figure 24: Cost per failure mode per bridle section.

6.10 Chapter conclusion
The outcomes of the failure mode and failure predictor analysis for EB rolls, as well as the answer to the second research question, are given in Table 18.

<table>
<thead>
<tr>
<th>Failure mode</th>
<th>Operating costs (€)</th>
<th>Failure predictors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coefficient of friction is too low</td>
<td>187,850</td>
<td>• Roughness of body</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• The amount of slip</td>
</tr>
<tr>
<td>Worn tracks</td>
<td>137,252</td>
<td>• Track measurements</td>
</tr>
<tr>
<td>Overheating of bearings</td>
<td>2,980</td>
<td>• Temperature of bearings</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Vibrations</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Used power electromotor</td>
</tr>
</tbody>
</table>

Table 18: An overview of the failure modes, operating costs, and failure predictors for EB rolls in the period from 1-1-2008 until 1-9-2016.
Part III – Degradation modelling

The previous part ended with an overview of failure modes and failure predictors for EB rolls. The goal of part III is to explore the opportunities to predict failure of EB rolls with failure predictors by modelling the relations between these failure predictors and the failure mode. The only requirement is the availability of data of these predictors and thus data for each of the predictors must be collected. This is discussed in chapter 7.

Currently, data is only available for the predictors roughness and slip which both correspond to the failure mode coefficient of friction is too low. Therefore, the third research question is only answered for that failure mode:

| What are the relations between the failure predictors and degradation of the selected process roll type? |

Chapter 8 discusses degradation modelling with slip and chapter 9 discusses this for roughness. If relations exist between these failure predictors and failure, they can be used to predict failure of EB rolls and thus aid in maintenance decision-making.
7 Data of failure predictors

The previous chapter described how the failure predictors for EB rolls have been identified. The next step is to collect data of each of these failure predictors. In this chapter, a description of the potential data sources at TSP is given, followed by whether data of the failure predictors for EB rolls are found.

7.1 Data sources

The data sources in which data of failure predictors is found are RWB, IBA, and HTD Trillingsmeetgroep. Each of these sources are described in the next paragraphs. Which data source contains data of which failure predictor is shown in Table 19. There are no data available for the failure predictors track measurements and temperature of bearings and thus the relation between these predictors and failure cannot be modeled in this research project.

<table>
<thead>
<tr>
<th>Failure mode</th>
<th>Failure predictors</th>
<th>Data source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coefficient of friction is too low</td>
<td>• Roughness of body</td>
<td>RWB</td>
</tr>
<tr>
<td></td>
<td>• The amount of slip</td>
<td>IBA</td>
</tr>
<tr>
<td>Worn tracks</td>
<td>• Track measurements</td>
<td>No data available</td>
</tr>
<tr>
<td>Overheating of bearings</td>
<td>• Temperature of bearings</td>
<td>No data available</td>
</tr>
<tr>
<td></td>
<td>• Vibrations</td>
<td>HTD Trillingsmeetgroep</td>
</tr>
<tr>
<td></td>
<td>• Used power electromotor</td>
<td>No data available</td>
</tr>
</tbody>
</table>

Table 19: Data sources per failure predictor.

7.2 Process roll replacement file (RWB)

An Excel spreadsheet which is called process roll replacement file²¹ (RWB) keeps track of data about the usage and lifetime of process rolls. Input for the RWB are process roll replacement forms which are filled when a process roll in being replaced and enters the repair process. This form subsequently keeps track of the process roll until repair is finished. An example of such a form is shown in Appendix E. It captures the roughness, hardness, and diameter of the process roll’s body before and after repair. Furthermore, the RWB keeps track of when a process roll gets installed in which position of which ETL and subsequently what the reason is why it has been replaced. Table 20 shows an example of these variables in the RWB. A complete overview of the variables can be found in Appendix F.

<table>
<thead>
<tr>
<th>Process roll type</th>
<th>Process roll ID</th>
<th>Production line</th>
<th>Position in production line</th>
<th>Date in (start of use)</th>
<th>Date out (end of use)</th>
<th>Reason of replacement</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC</td>
<td>5</td>
<td>ETL11</td>
<td>1377</td>
<td>9-4-2016</td>
<td>29-4-2016</td>
<td>Bearing failed</td>
</tr>
</tbody>
</table>

Table 20: Variables in RWB.

The RWB keeps track of the roughness of every EB roll’s body at the start of its use and at the end of its use. An interesting finding is that the RWB spreadsheet includes 9 columns that are called roughness measurements during revisions (1 column per revision). This sounds promising, but all the columns are empty for the more than 6000 recorded process roll replacements.

7.3 IBA

ETL13 is equipped with an operating and control system that controls and monitors the processes performed on that line. This system consists of one or multiple programmable logic controllers (PLC). These PLCs include parameters which are controlled by the process (for example, speed of the steel strip and tension in the steel strip) and parameters that explain the process (for example, width of the steel strip that is being processed). The parameters in the PLC are called process parameters. IBA is

²¹ Process roll replacement file is derived from the Dutch word rol wissel bestand (RWB) which is used by TSP.
the system that collects data of process parameters from the PLC, allows online real time monitoring, and stores data in data files. These data files are accessible via IBA Analyzer.

The advantage of using process data for modelling degradation of equipment is described by Veldman et al. (2011). The major advantage is the usage of existing (process control) tools, measurement equipment, IT infrastructure, and data. This saves a significant amount of money that would else be needed to invest in measurement equipment, IT infrastructure, and so forth. This is a major advantage of IBA.

Data of the failure predictor slip is found indirectly in the IBA data files. Indirectly means that no data for slip itself were found, but that data of a set of other parameters are found with which slip can be calculated. These parameters are speed of the steel strip and peripheral speed of the EB roll which the PLC calculates using the radius of the EB rolls and angular velocity of the EB rolls. See Appendix G for an overview of the IBA parameters that are used to calculate slip.

The electrical current that the electromotor of an EB roll is using is a parameter that is in the PLC and can be monitored in real time. However, IBA does not store data of this parameter in the data files. This parameter can be added to the list of parameters of which IBA stores data. An indirect form of usage of electromotors is found in IBA, which is torque that the electromotor delivered. However, values for torque are expressed in percentages and within Tata Steel, the knowledge to interpret these percentages is not found. During the study on how a bridle roll works and how it is operated, knowledge is gained about the electrical power that an electromotor uses and the amount of torque that it needs to deliver given the tension differential and strip speed. Even though no data is found of the failure predictor used power electromotor, this knowledge is summarized in Appendix H. This Appendix describes the opportunities to use these electromotor characteristic for maintenance purposes.

The process of collecting data from the IBA data files is discussed in Appendix I.

7.4 HTD Trillingsmeetgroep
Tata Steel has a central department called HTD Trillingsmeetgroep that collects and analyses vibration data for various production lines. The goal of this department is to minimize the amount of unplanned downtime due to failure of equipment by planning maintenance when it is needed. Unfortunately, ETL13 is not one of the production lines of which vibration data is being collected and analyzed and thus no vibration data for EB rolls are available. It is worth notifying that these data are available for ETL14.

7.5 Data of failure predictors for EB rolls
The availability of data of failure predictors of EB rolls is summarized in Table 21. Data is only found for the two failure predictors of the failure mode coefficient of friction is too low.

<table>
<thead>
<tr>
<th>Failure mode</th>
<th>Failure predictors</th>
<th>Data available</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coefficient of friction is too low</td>
<td>• Roughness of body</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>• The amount of slip</td>
<td>Yes</td>
</tr>
<tr>
<td>Worn tracks</td>
<td>• Track measurements</td>
<td>No</td>
</tr>
<tr>
<td>Overheating of bearings</td>
<td>• Temperature of bearings</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>• Vibration</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>• Used power electromotor</td>
<td>No</td>
</tr>
</tbody>
</table>

Table 21: Failure predictors for modelling degradation of EB rolls.
8 Degradation modelling with slip

First, the relation between the failure predictor slip and degradation of EB rolls is analyzed.

8.1 The relation between roughness and slip

Roughness is a variable that directly indicates the condition of the EB roll’s rubber body regarding the failure mode coefficient of friction is too low. Thus, roughness is a condition parameter. The other failure predictor, slip, describes the performance of the EB roll; it is a performance characteristic. It is calculated using the process parameters speed of the steel strip and angular velocity of the EB roll. This paragraph describes the use of process data for degradation modelling and the relation between roughness and slip.

8.1.1 Requirements for using process data for modelling degradation

Veldman et. al (2011) identify several advantages and requirements for modelling degradation with process parameters. The two most important requirements will be explained into more detail. First, it is important to establish a clear relationship between the process parameters and the failure modes of the process roll. This is important because in comparison to a condition parameter, a process parameter does not have to be directly related to degradation or failure of equipment. The second important requirement regards to knowledge about the relevant processes that are described and controlled by process parameters. This knowledge is necessary because deviations in output of process parameters needs to be related to either normal behavior, change in environmental conditions, or failure of the component (Veldman, Wortmann, & Klingenberg, 2011). Integration of this process knowledge and maintenance engineering knowledge is important in the maintenance decision-making process. A lack of understanding of the process or a lack of understanding of the failure of process rolls makes it hard to make good maintenance decisions. The requirements and advantages are summarized in Table 22.

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Provides insight into the different processes</td>
<td>Process parameters need to be representative of the condition of process rolls</td>
</tr>
<tr>
<td>Many possibilities for analysis</td>
<td>Sufficient knowledge of the process (through process control engineering)</td>
</tr>
<tr>
<td>Usage of existing (process control) tools</td>
<td>Maintenance engineering knowledge</td>
</tr>
<tr>
<td>Parameters can be continuously monitored online already</td>
<td>Integration of process control engineering and maintenance engineering</td>
</tr>
</tbody>
</table>

Table 22: Advantages and requirements for modelling with process data, based on Veldman et al. (2011).

8.1.2 Determining factors of performance of EB rolls

When looking at the function of the EB roll’s body to provide friction between the EB roll and the steel strip, the performance of the EB roll is generally determined by the roughness of the body and the load that is put on the EB roll. The load is determined by the production order that is being produced. Production orders determine among others how much tension is required in every section of the ETL and thus how big the tension differentials are that bridle sections need to generate. The cross-sectional area of steel strip that is being produced on ETL13 varies from 120 to 525 mm². The bigger the cross-sectional area, the higher the absolute amount of required tension becomes and thus the higher the load that is put on EB rolls. Figure 25 shows an overview of the monthly amount of steel strip (in kilometers) for that has been produced on ETL13 for 9 categories of cross-sectional area. Based on this graph and an interview with the production manager of ETL13, it is assumed that the production schedule is constant over time, even though the it includes a wide variety of steel strip.
That means that every type of steel strip is produced in constant proportions for every period and therefore that the load put on bridle sections is constant.

![Production on ETL13 in financial year 2016.](image)

Figure 25: Monthly production in kilometers and cross-sectional area for ETL13 in financial year 2016.

Since a bridle section contains 2 or more bridle rolls (EB rolls), the total load is balanced between the EB rolls. An explanation of load balancing (not to confuse with load sharing) can be found in Appendix J. A result of load balancing is that every EB roll in one bridle section has a proportion of the total load that is based on the angle of wrap.

Next to roughness and production orders, other external and environmental factors can play a role in the performance of EB rolls. An example that applies for EB rolls can be an oily strip. An oily strip does not influence the roughness nor the load, but it does influence the coefficient of friction in a way that the performance of the EB roll can decrease temporarily due to loss of friction. Failure of the electromotor, gearbox, and drive coupling are also other factors that influence the performance of slip. See Figure 26.

![Diagram showing the relation between roughness and slip](image)

Figure 26: A schematic representation of the relation between roughness and slip.

### 8.2 The calculation of slip

Slip is expressed as the difference between the peripheral speed of a bridle roll and the strip speed at this bridle roll, relative to this strip speed. It is chosen to express the difference in speed relative to the strip speed to correct for different strip speeds (production speeds). The thought behind this
decision is that the absolute difference between the peripheral speed and the strip speed is larger at higher production speeds. The formula for slip is shown in equation (5). It should be noted that the strip is not being stretched by bridle sections.\footnote{The only part in an ETL where steel is being stretched is at the multi-roll leveler which is not in the scope of this project.}

\[ s_t^{(i,j)} = \frac{v_t^{(i,j)} - v_t^{\text{strip}(i)}}{v_t^{\text{strip}(i)}} \cdot 100\% \]  

(5)

Where;

- \(s_t^{(i,j)}\): The difference between the peripheral speed of bridle roll \((i, j)\) and the speed of the strip at time \(t\) (in % of the strip speed).
- \(v_t^{(i,j)}\): The peripheral speed of EB roll \(j\) in bridle section \(i\) (in m/s) at time \(t\).
- \(v_t^{\text{strip}(i)}\): The speed of the strip at bridle section \(i\) at time \(t\) (in m/s). The speed of the strip is defined per bridle section, because the strip speed can vary in different parts of the production line due to increasing and decreasing buffers in the entry and exit loop (see Figure 6 on page 8).

In the current situation, \(v_t^{\text{strip}(i)}\) is measured directly, but \(v_t^{(i,j)}\) is not measured directly but instead is calculated by the operating and control system. This calculation is shown in equation (6).\footnote{\(v_t^{(i,j)}\) can be found in the IBA database with variable name V_ACT. The name V_ACT suggest that the variable is represents the actual speed, but the values for V_ACT in IBA are calculated using the radius and the rotational speed as described in equation (6).}

\[ v_t^{(i,j)} = \frac{\pi \cdot r^{(i,j)} \cdot n_t^{(i,j)}}{30 \cdot g^{(i,j)}} \]  

(6)

Where;

- \(n_t^{(i,j)}\): The rotational speed of the electromotor of bridle roll \(j\) in bridle section \(i\) (in rpm).
- \(g^{(i,j)}\): The gear ratio of bridle roll \(j\) in bridle section \(i\).
- \(r^{(i,j)}\): The radius of EB roll \(j\) in bridle section \(i\) (in m).

For every EB roll in ETL13, \(n_t^{(i,j)}\) is measured continuously with a tachometer and \(g^{(i,j)}\) is fixed. The radius \(r^{(i,j)}\) is not measured continuously. The radius is measured accurately right before an EB roll gets installed. This measurement serves as an input variable for the operating and control system which needs the radius to determine how to operate the EB roll.\footnote{How the radius is used by the operating and control system is discussed in Appendix H.} This is only done once; the radius never gets re-measured and updated in the system during the lifetime of an EB roll. The system assumes that the radius of EB rolls stay constant over time. It is questioned whether this is a reasonable assumption, since any variation in radius causes the calculation of the peripheral speed \(v_t^{(i,j)}\) and subsequently slip \(s_t^{(i,j)}\) unreliable.

Two questions are asked; (1) how does the radius of an EB roll change during its lifetime and (2) how does a change in diameter influence the calculated peripheral speed and slip?

**Question 1:** how does the radius of an EB roll change during its lifetime
Remember that the RWB consists the variables diameter in and diameter out (see Appendix F). There are 15 combinations of diameters before and after known for bridle section 1, 2, and 3 according to the RWB. These data can be found in Appendix L. Even if the assumption is made that the measurement instruments were always perfectly calibrated and operated, then these data are still considered unreliable for the following reasons:

- The diameter of the EB roll (and process rolls in general) varies from one end of the body to the other. The process roll maintenance specialist cannot guarantee that the measurements were always performed in the middle of the EB roll’s body.
- It is unclear if the diameters were measured during the same circumstances (for example, at the same temperature).

According to the process roll maintenance specialist at TSP, the diameter can both increase and decrease during its usage, depending on the situation. The diameter is likely to increase at bridle section 1 due to a polluted strip from previous production lines where pollution can accumulate on the EB roll’s body. In other instances, the diameter is likely to decrease because the EB’s body is made of rubber which will lose its resilience (the rubber will get compressed during usage). Even if these before and after measurements were reliable and valid and the absolute change is known, it would remain unknown how the radius develops over time (for example, linear or exponential). In conclusion, there is no concrete answer to the first question of how a radius changes during the lifetime of an EB roll. But, the assumption that the radius does during the lifetime seems unreasonable.

**Question 2: how does a change in diameter influence the calculated peripheral speed, \( v_t^{(i,j)} \)?**

There are three scenarios; the radius remains constant over the lifetime, the radius increases over the lifetime, and the radius decreases over the lifetime. To ease the interpretation of what changes in radius of an EB roll will do to the calculation of \( s_t^{(i,j)} \), Table 23 is constructed. The input that is needed to use this table is the calculation of \( s_t^{(i,j)} \) (with fixed \( r^{(i,j)} \) of the operating and control system) according to equations (5) and (6). The value for \( s_t^{(i,j)} \) determines in which column to look. Then, the three scenarios for the actual \( r^{(i,j)} \) are described in the rows. The change in radius over time is denoted with \( \Delta r^{(i,j)} \) where, for example, an increase in radius during the lifetime equals \( \Delta r^{(i,j)} > 0 \). Which scenario is most likely must be determined by analyzing the environment and context of the EB roll being analyzed.

Two types of slip are distinguished:

- \( v_t^{(i,j)} > v_{\text{strip}}^{(i)} \) \textit{Accelerating slip}. In this case, the EB roll pulls the steel strip in the direction of the speed of the steel strip. When the EB roll loses its grip, it will rotate faster than the speed of the strip.
- \( v_t^{(i,j)} < v_{\text{strip}}^{(i)} \) \textit{Braking slip}. In this case, the EB roll holds back the strip for the subsequent section. The EB roll increases the starting tension.

---

25 See section 6.5 for examples on how the diameter can vary for one process roll (convexity and worn tracks).
\[ s_{t}^{(i,j)} = 0 \quad s_{t}^{(i,j)} > 0 \quad s_{t}^{(i,j)} < 0 \]

| \( \Delta r^{(i,j)} = 0 \) | No slip. | Accelerating slip as calculated. | Breaking slip as calculated. |
| \( \Delta r^{(i,j)} > 0 \) | There is accelerating slip. | The actual slip is higher than the calculated slip. | The calculated braking slip decreases towards the moment of no slip as \( \Delta r_{i,j} \) increases and can even turn into accelerating slip. There is a turning point. |
| \( \Delta r^{(i,j)} < 0 \) | There is braking slip. | The accelerated slip decreases towards the moment of no slip as negative \( \Delta r_{i,j} \) increases and can even turn into braking slip. There is a turning point. | The actual breaking slip is higher than the calculated slip. |

Table 23: Interpreting the development of slip by comparing slip with possible changes in body radius.

8.3 Discussion of the results
Equation (6) is used to calculate slip using the collected data for bridle sections 1, 2, and 3. An extensive description of the data collection process is given in Appendix I. The two most important things regarding the data collection is the time window for which data is available (from 5-10-2014 until 8-11-2016, see Figure 27) and the fact that only data are used that are collected during stable production processes. The results for each bridle section will be discussed separately.

Figure 27: The replacement (blue crosses) of EB rolls of bridle sections 1, 2, and 3, compared to the available process data in IBA.

8.3.1 Bridle section 1
Bridle section 1 contains three EB rolls. For every observation in the dataset and for each of the three EB rolls, \( s_{t}^{(1,j)} \) is calculated and the results are shown in Figure 28. The first two notable things are the increasing, decreasing, and constant development of \( s_{t}^{(i,j)} \) and the drop to approximately 0% in September 2015. All three EB rolls in bridle section 1 were replaced preventively on September 9, 2015, which immediately explains the drop to approximately 0%. Now, the question is; is the development of \( s_{t}^{(i,j)} \) before and after the replacement on September 9, 2015 the real amount of slip, an underlying change in radius, or a combination of both?
Without knowing the changes in radius, this question remains unanswered. Yet, there are still remarkable things to discuss. First, a better understanding of the control system of bridle section 1 is required. Bridle section 1 is the Speed Master of the entry section of ETL13. This means that this bridle section controls the speed and not the tension for the entry section of ETL13. The speed set-point (or reference, or target) for bridle section 1 is determined by the speed of the steel strip in the process section of the ETL plus the movement of the entry loop buffer. Since data is collected during stable processes where the entry loop is filled and stationary, the strip speed at the entry section is equal to the strip speed at the process section. The set-points (or targets) for the peripheral speed of EB rolls are equal to the speed of the strip. This accounts for each of the three EB rolls. The collected data confirm this. However, the calculated peripheral speeds (based on $n_{(i,j)}$) in the operating and control system differ from the set-point. One would expect that when the operating and control system thinks the radius stays constant over time, it would not regulate a different rotational speed, $n_{(i,j)}$, other than the one that the system calculates to match the set-point speed.

The EB roll that is installed in position (1,1) shows a decrease in $s_{(1,1)}$ after the replacement in September 2015 while the previous EB roll in that position showed a minor increase. A reason for this difference is that the EB roll that is currently installed in position (1,1) is a repaired EB roll that faced oil problems in its previous usage. See Figure 29. The rubber body is still affected by the oil even though the entire process roll has been repaired by IJssel Technologie. The body of the EB rolls in the exit sections which faced this oil swelled and thus increased in radius. It is possible that the rubber of the EB roll in (1,1) is still reacting to the oil that penetrated the rubber body. If that is true, it can explain the decrease in $s_{(1,1)}$ because a larger radius requires a lower rotational speed to achieve the same peripheral speed.

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$A$ set-point is the value of a control parameter that must be achieved in order to operate properly. In case of the peripheral speed of an EB roll, the set-point is a value of speed which the electromotor must generate. This set-point is determined based on the speed of the strip.
8.3.2 Bridle section 2

Bridle section 2 contains 2 EB rolls. For every observation in the dataset, $s_{t}^{(2,j)}$ is calculated and the results are shown in Figure 30. For this graph, the two notable things are the increasing values for $s_{t}^{(i,j)}$, and the drop of approximately 0.2% for both EB rolls in September 9, 2015.

Remember that for bridle section 2, none of its 2 EB rolls have been replaced during the observed period. The last replacement for both EB rolls took place on 22-8-2012. Then, what explains the drop of 0.2%? Based on the rotational speed and the peripheral speed of every observation in the dataset, the radius is calculated. The outcome is that for both EB rolls the radius stayed constant for all observations. Since the radius did not affect the drop of $s_{t}^{(i,j)}$, the cause can only be actual slip that dropped. See Figure 26. Since the roughness of the two EB rolls in bridle section 2 did not increase during the drop and no other factors that could possibly cause such a drop were found, only a difference in load could have caused this drop. There were no exceptional changes in strip characteristics that could have changed the load. Then what did change the load? The moment when the slip dropped is in the exact moment at which the EB rolls of bridle section 1 were replaced by new ones. Before the replacement of EB rolls in bridle section 1, the EB rolls in bridle section 2 experienced a higher load that causes these rolls to slip more. Thus, when EB rolls in bridle section 1 deteriorate, the load on EB rolls in bridle section 2 increases. This is the most important finding:

| The load on - and performance of - the two EB rolls in bridle section 2 depend on the performance of the EB rolls in bridle section 1. |

In the period right before September 9 2015, at least 0.2% slip, $s_{t}^{(i,j)}$, can be explained by the actual slipping of the EB rolls.
8.3.3 Bridle section 3

Bridle section 3 contains 3 EB rolls. For every observation in the dataset, $s_{t}^{(3,j)}$ is calculated and the results are shown in Figure 31. Remember that for bridle section 3, none of its 3 EB rolls have been replaced during the period shown in Figure 31. The radius stayed constant over time. Several drops in $s_{t}^{(i,j)}$ (marked with blue lines) can be observed in Figure 31. For the dates around these drops, all maintenance orders for ETL13 have been investigated. It turns out that all three EB rolls in bridle section 4 have been replaced 4 times in total in the period from 5-10-2014 to 8-11-2016 (the period in the graph below). These four replacements are performed on each of the blue lines in Figure 31. There are no other notable maintenance actions performed around these four dates, nor did the roughness of EB rolls in bridle section 3 change. Therefore, the performance and condition of EB rolls in bridle section 4 influence the load on EB rolls in bridle section 3. In between bridle section 3 and 4 there is another bridle section with 4 EB rolls, called bridle section 3A. The EB rolls in 3A have been replaced 3 times in the period of the graph below, but do not seem to influence $s_{t}^{(i,j)}$ for EB rolls in bridle section 3.
8.3.4 Sensitivity analysis of $s_t^{(i,j)}$

To gain insight in how a change in radius influences the calculated $s_t^{(i,j)}$, a sensitivity analysis is performed. EB roll (2,2) is used as an example to calculate $s_t^{(2,2)}$ when its diameter (which is twice the radius) increases or decreases with 1 mm. The results are shown in Figure 32. Even though the data about EB roll diameters before and after usage (Appendix L) are unreliable, these data indicates changes not bigger than 3 mm. Figure 32 gives an indication of the impact of a change in diameter on the calculated values of $s_t^{(2,2)}$.
8.4 Dependence between bridle sections

The previous paragraph proved dependence between bridle section 2 and bridle section 1, and bridle section 3 and bridle section 4. In total, there are 6 bridle sections. What are the dependencies between all bridle sections?

A multi-roll leveler is placed in the section in-between bridle sections 2 and 3. The function of this multi roll leveler is to eliminate all flatness defects (such as wavy edges and wavy center) in the steel strip by bending the strip while it is being stretched. To do this, the multi-roll leveler is equipped with two special 4-roll bridle sets (with non-EB rolls) that put enough tension on the strip to stretch it. Because of the local tension control in the multi-roll leveler, there is no dependency observed between bridle sections 1 and 2 and bridle sections 3, 3A, 4, and 5. These cells are colored red in Table 24. A green cell means that dependence is found and a question mark means that it is unknown if dependence between these bridle sections exist.

<table>
<thead>
<tr>
<th>Bridle section</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>3A</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3A</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 24: Dependence between bridle sections in ETL13. Read horizontally; bridle section 2 depends on bridle section 1.

No data was collected for bridle sections 3A, 4, and 5, because they are excluded in this research project (see paragraph 4.2) and thus the dependence for these bridle sections is unknown.

8.5 Dependence between EB rolls in one bridle section

Now that degradation-based dependence between bridle sections is proven to exist, the question rises if there is the same kind of dependence between EB rolls in the same bridle section. Since all three EB rolls of bridle section 1 were replaced simultaneously during the period of which data is available, this cannot be proved based on data, yet. It is known that the load is balanced between EB rolls in one section, dependent on the angle of wrap that the strip makes with the EB roll (see Appendix J). But, this does not automatically mean that there is degradation-based dependence between these EB rolls.

EB rolls in one bridle section cooperate to achieve the goal of the bridle section, which is to control the tension in the steel strip in the neighboring production line sections. When one EB roll performs poorly, the load that is put on the others should increase to reach bridle section’s goal. The operating and control system controls the entire bridle section and thus must share the load between EB rolls when one or more EB rolls perform poorly. There are two tension control principles used for bridle sections of ETL13; master-slave and torque limiting. An attempt was made to understand the control system of those two principles, but it remains unclear how EB rolls react to degradation of other EB rolls in the same bridle section.
8.6 Degradation model for slip

In the previous paragraph, the development of calculated slip, $s_t^{(i,j)}$, over time has been analyzed for EB rolls in bridle sections 1, 2, and 3. The lack of intermediate radius measurements makes the interpretation of $s_t^{(i,j)}$ difficult, as values for $s_t^{(i,j)}$ can be explained by both slip or a change in radius, or a combination of both.

The degradation of performance (the increase in slip) can be modelled using degradation models. A degradation model describes how a certain characteristic of equipment degrades over its lifetime. Degradation models are required in order to estimate the remaining useful life of EB rolls at any given point in time, given that EB rolls fail when the degradation level (amount of slip) reaches a specified failure threshold. Degradation is a stochastic process; therefore, it could be modeled in several approaches (Gorjian, Ma, Mittinty, Yarlagadda, & Sun, 2009). Generally, two approaches exist for modeling degradation. One approach assumes a continuous degradation process while the other approach assumes a degradation process that follows a discrete number of states. The preferred model depends on the characteristics of the data and the operating context. In case of slip, a continuous degradation model is preferred because of the gradual deterioration and the ability to monitor slip continuously.

The type of dependence that is found for EB rolls is stochastic dependence. Stochastic dependence means that the degradation processes of components are (partially) dependent (Olde Keizer, Flapper, & Teunter, 2017). Olde Keizer et al. (2017) distinguish failure-based load sharing and degradation-based load sharing. In the case of EB rolls, degradation-based load sharing is proved to exist among EB rolls of different bridle sections. Rasmekomen et al. (2015) and Do et al. (2015) conclude that stochastic dependence should be included in the degradation model, as this can have significant positive impact on the condition-based maintenance policy.

Modelling degradation with degradation-based load sharing is a complex task. Rasmekomen et al. (2015) develop a degradation model in two steps that includes stochastic dependence. First, they developed an independent degradation model that is used to understand the underlying independent degradation of components in the system. This model does not include any dependence between components. Second, this degradation model forms a basis to develop the degradation model that includes the stochastic dependence between components.

Modeling degradation of EB rolls require information about the independent degradation process of an EB rolls, which is not available and difficult to obtain. Besides, no full degradation path (from the start of an EB roll until the moment of failure) is observed in the data. In the current situation and with the currently available data, it is not possible to formally model degradation of EB rolls that includes degradation-based load sharing.

Do et al. (2015) describe a two-component system with dependence between the components. The degradation model used in their paper is used to describe how a degradation model can look like for an EB roll in bridle section 2, assuming that EB rolls (2,1) and (2,2) are degrading independently of each other. Remember that there is degradation-based load sharing between bridle sections 1 and 2.

Denote:

$X_{t}^{(i,j)}$  The random variable describing the degradation level (slip) of EB roll $(i, j)$ at time $t$.

$\Delta X_{t}^{(i,j)}$  The increase in the degradation process (slip) for EB roll $(i, j)$ in time interval $(t, t + 1)$.

$f\left(X_{t}^{(k,l)}\right)$  This is a function of the degradation level of EB roll $(k, l)$ at time $t$ and represents the impact of this EB roll on the degradation speed of EB roll $(i, j)$, where $k \neq i$. 

Then the degradation model for EB roll (2,1) becomes:

$$X_{t+1}^{(2,1)} = X_t^{(2,1)} + f\left(X_t^{(1,1)}\right) + f\left(X_t^{(1,2)}\right) + f\left(X_t^{(1,3)}\right) + \Delta X^{(2,1)}$$  \hfill (7)

The following characteristics are unknown and make it impossible to formally model degradation of EB rolls for slip:

- The functions $f(\cdot)$ that impact the degradation speed.  
- The probability density function of $\Delta X^{(i,j)}$ and its parameters. This is because only a part of the degradation curve are observed and because the actual value for the radius during the observations is unknown.  
- The failure thresholds are unknown.

These unknown characteristics are visualized in Figure 33 for EB roll (2,1), where the blue line represents the values of $s_t^{(2,1)}$ as shown in Figure 30 and the unknown curves depend on the impact functions $f\left(X_t^{(1,j)}\right)$, and the increments of the individual degradation process of EB roll (2,1), $\Delta X^{(2,1)}$.

**Figure 33:** Visualization of unknown characteristics of the degradation model of EB roll (2,1).

### 8.7 Chapter conclusions

It is showed that slip is a failure predictor for EB rolls. It takes the operating conditions into account, as well as the performance of other bridle sections for which there is degradation-based load sharing. There is degradation-based load sharing between EB rolls of bridle sections 1 and 2 and bridle sections 3 and 4. It is not known if there also exists degradation-based load sharing among EB rolls of the same bridle section. Formal degradation modelling is not possible based on the currently available data. Individual degradation information is unavailable for each of the EB rolls and the impact of one EB roll’s performance on another EB roll’s performance is unknown. Also, no failure threshold is determined because no failure is observed in the available data.

The advantage of using process data to calculate slip is that measurement equipment, IT infrastructure, and data is already present. The unavailability of information about the change of the radius of EB roll’s bodies over time causes that the calculated values of $s_t^{(i,j)}$ cannot be fully explained by actual slipping of EB rolls. In order to fully interpret values of $s_t^{(i,j)}$, the radius needs to be measured during the usage of EB rolls or the peripheral speed needs to be measured differently.
9 Degradation modelling with roughness

The previous chapter showed degradation-based dependence between EB rolls of different bridle sections. Knowing this dependence, the use of roughness as a failure predictor for EB rolls is re-evaluated. This chapter discusses the question how and if roughness can be used as a failure predictor for EB rolls.

9.1 The use of roughness as failure predictor

The use of roughness as a failure predictor is discussed by using an EB roll of bridle section 2 as an example. The performance of EB rolls in bridle section 2 depends on the performance of EB rolls in bridle section 1, the production order, the roughness of the EB roll’s body, and possible other factors. See Figure 34 for a schematic view of these factors.

![Figure 34: A schematic representation of the factors that determine the performance of EB roll (2, j).](image)

Roughness describes the ability of a single EB roll’s body to perform its function. A degradation model for roughness will describe how roughness degrades over the lifetime of an EB roll until it fails. An EB roll’s body can fail to perform its function in two ways and thus a corrective replacement can be triggered by two events.

**Failure 1: Tension issues are the trigger**
1. The tension in a certain section of the ETL is too low. Tension is being measured continuously with the use of tension-measurement rolls and the operating and control system controls the bridle sections based on these measurements. When the tension is too low, the operator is notified immediately.
2. The bridle section that controls the tension in the section fails.
3. One or more EB rolls of that bridle section fail.
4. The EB roll slips too much.
5. Perform a corrective replacement.

**Failure 2: Quality issues are the trigger**
1. Scratches on the tinned steel strip are discovered by quality inspection equipment at the end of the ETL. This equipment inspects the steel strip on a continuous base.
2. The ETL gets stopped. Employees start with inspecting the steel strip for scratches in the exit section of the ETL and work towards the entry section until they found the process roll(s) that scratch the strip.

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27 See Figure 16 on page 24 for an example of the positioning of tension-measurement rolls in ETL13.
3. If the scratches are caused by one or more EB rolls in the bridle section, it means that these EB rolls were slipping excessively due to insufficient friction.

4. Perform a corrective replacement.

In both situations, slip is the direct measure of failure. Roughness can be a cause of slip, but it is not the only cause of slip as the production order, the performance of bridle section 1, and possibly other factors can also influence the amount of slip. Thus, roughness of an EB roll’s body is not a direct indication of failure. In other words, no matter how low the roughness of the EB roll, if the EB roll does not slip to the extent that it causes scratches or does not reach the tension requirement, it does not matter. Figure 35 shows two EB rolls to illustrate this. The EB roll on the left has a relatively rough body surface and the one on the right with a relatively low body surface; both EB rolls function properly.

![Figure 35: Two EB rolls that are installed in ETL13. One with a rough body (left) and one with a relatively smooth body (right) (photos made during the annual revision of ETL13 on 26-10-2016 by A.P.J. Avontuur).](image)

Where slip takes the degradation-based dependence between bridle sections and operating conditions into account, roughness does not. For EB rolls in bridle section 2, roughness of these rolls can only be used as a failure predictor when the roughness of EB rolls in bridle section 1 are taken into account too. This also means that the failure threshold for roughness is not fixed but depends on the roughness of EB rolls from section 1: the roughness threshold of EB roll \((2,j)\) becomes lower (roughness decreases and a low threshold means a small value for roughness) when the roughness of EB rolls in bridle section 1 are relatively high and the roughness threshold of EB roll \((2,j)\) becomes higher when the roughness of EB rolls in bridle section 1 are relatively low. A high threshold means a high value for roughness. When measuring the roughness of all EB rolls, it remains a complex task to construct the contribution of each EB roll’s roughness to the failure threshold of another EB roll. To compare with slip, the slip threshold is much more straightforward as slip takes all the other factors into account and slip determines directly what failure is.
9.2 Roughness data

Even though slip is the preferred failure predictor for EB rolls, the opportunities to use available data of roughness for the prediction of failure are investigated. To develop a degradation model for roughness that includes degradation-based load sharing, the individual degradation process of roughness of the EB roll and the impact of the degradation of other EB rolls are required.

The roughness data that is available only describes the roughness of EB rolls at the beginning of their lifetime and at the end of their used lifetime. In other words, roughness of an EB roll is measured before it is installed in an ETL and after it has been used in an ETL. There are no data available of roughness of EB rolls during their used lifetime. All roughness data is shown in Table 25, where roughness is expressed in micrometers (μm). The roughness of an EB roll that is “as good as new” lies between 15 and 20 μm. Notice that there is no roughness data for EB rolls in bridle section 3.

<table>
<thead>
<tr>
<th>Bridle section</th>
<th>Date replacement</th>
<th>EB roll</th>
<th>Time until replacement (days)</th>
<th>Roughness before (μm)</th>
<th>Roughness after (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bridle section 1</td>
<td>5-5-2011</td>
<td>EB roll (1,1)</td>
<td>84</td>
<td>16.55</td>
<td>17.89</td>
</tr>
<tr>
<td></td>
<td></td>
<td>EB roll (1,2)</td>
<td>84</td>
<td>17.23</td>
<td>17.49</td>
</tr>
<tr>
<td></td>
<td></td>
<td>EB roll (1,3)</td>
<td>84</td>
<td>16.7</td>
<td>14.72</td>
</tr>
<tr>
<td>Bridle section 2</td>
<td>28-9-2011</td>
<td>EB roll (2,1)</td>
<td>726</td>
<td>Unknown</td>
<td>14.01</td>
</tr>
<tr>
<td></td>
<td></td>
<td>EB roll (2,2)</td>
<td>726</td>
<td>Unknown</td>
<td>2.7</td>
</tr>
<tr>
<td>Bridle section 1</td>
<td>14-5-2014</td>
<td>EB roll (1,1)</td>
<td>632</td>
<td>18.39</td>
<td>1.27</td>
</tr>
<tr>
<td></td>
<td></td>
<td>EB roll (1,2)</td>
<td>632</td>
<td>15.24</td>
<td>3.51</td>
</tr>
<tr>
<td></td>
<td></td>
<td>EB roll (1,3)</td>
<td>632</td>
<td>15.2</td>
<td>6.17</td>
</tr>
<tr>
<td>Bridle section 1</td>
<td>9-9-2015</td>
<td>EB roll (1,1)</td>
<td>483</td>
<td>16.2</td>
<td>1.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>EB roll (1,2)</td>
<td>483</td>
<td>16.82</td>
<td>6.18</td>
</tr>
<tr>
<td></td>
<td></td>
<td>EB roll (1,3)</td>
<td>483</td>
<td>20</td>
<td>5.43</td>
</tr>
</tbody>
</table>

Table 25: Roughness data for EB rolls in bridle sections 1, 2, and 3.

For all EB rolls, both the individual degradation process of roughness and the impact of degradation of EB rolls in other bridle sections are unknown, and a degradation model for roughness cannot be developed based on the currently available data.

9.3 Chapter conclusion

Where slip takes the production order, performance of other dependent EB rolls, and possible other factors into account, roughness does not. Roughness of EB rolls cannot be considered independently of each other. The roughness of all EB dependent EB rolls need to be taken into account when using roughness for maintenance decision-making. Based on the available data, no relation between roughness of EB rolls and failure of EB rolls can be established. In this project, only slip is used as a failure predictor for EB rolls.
Part IV - Maintenance optimization

The goal of Part IV is to use the found relations of Part III to optimize maintenance. First, the appropriate maintenance policies need to be selected. The different maintenance policies and how the appropriate maintenance policies can be selected for a given process roll type are discussed in chapter 10.

For EB rolls, a condition-based maintenance policy is selected. Chapter 11 proposes a condition-based maintenance policy for EB rolls. At the end of chapter 11, the fourth research question is answered:

*What is the optimal maintenance policy, based on the found relations between predictors and failure?*

After Part IV, the implementation of the developed method is discussed in chapter 12, followed by the conclusions and recommendations of this research project in chapter 13.
10 Maintenance policy selection

10.1 Maintenance policy categorization
A maintenance policy is a rule that describes when a maintenance activity should be executed. Bakker (2015) performed a literature review on maintenance policy categorization and summarized the findings into one categorization. The maintenance categorization for this research project is based on the one developed by Bakker (2015). See Figure 36. The two main categories are preventive maintenance (perform maintenance before failure occurs) and corrective maintenance (perform maintenance upon or after failure). A main objective of preventive maintenance is to reduce the amount of failures of equipment (Ahmad & Kamaruddin, 2012). That explains why the key characteristic for a preventive maintenance policy is that it aims to plan and perform maintenance before failure. When considering process rolls, preventive maintenance can be initiated based on elapsed time, their usage, or their condition which can be detected or measured.

![Figure 36: Categorization of maintenance policies.](image)

10.1.1 Corrective maintenance policy
Under a corrective maintenance policy, all maintenance actions are performed after failure of equipment. As soon as equipment fails, maintenance needs to be executed (maintenance is urgent) before continuing the operations on the production line. There is instant need for components, manpower, and materials/tools. Since corrective maintenance is always unplanned, the availability of these resources can cause a delay in the maintenance process. The need for corrective maintenance actions in a production environment causes issues with the production planning and delivery times of produced products.

10.1.2 Time-based maintenance policy
Using a time-based maintenance policy, preventive maintenance is triggered by a fixed periodic maintenance interval or by failure if failure occurs before this interval. The time interval is based on calendar time and not production time (production time would be usage-based maintenance). The periodic maintenance interval can be optimized by minimizing the expected costs using the probabilistic failure characteristics (failure time distribution).

10.1.3 Usage-based maintenance policy
For usage-based maintenance policies, the same story as for time-based maintenance applies, but instead of calendar time a parameter that expresses usage is used. For process rolls, examples of usage are kilometers and weight of processed steel. An example of a usage-based maintenance policy is to replace process roll \(i\) preventively after it processed 1,000 kilometers of steel strip. Lubbers (2016) conducted research regarding maintenance optimization of the pickling production line at TSP and developed a usage-based maintenance policy. See Lubbers (2016) for the optimization of a usage-based and time-based maintenance policy.
### 10.1.4 Detection-based maintenance

Both detection-based maintenance policies and a condition-based maintenance policies trigger preventive maintenance actions based on the condition or performance of equipment. A detection-based maintenance policy differs from a condition-based maintenance policy by the fact that a change in condition or performance is only be detected. Detecting means that any irregularity (for example, increased temperature of bearing houses) is detected by, for example, the senses of employees or quality control camera’s. These irregularities must describe a potential failure in the near future.

### 10.1.5 Condition-based maintenance policy

When using a condition-based maintenance (CBM) policy, maintenance actions of a component are triggered based upon that component’s condition in relation to failure. Information about the condition can generally be obtained in two ways; periodically by performing inspections or continuously by condition monitoring. A CBM policy attempts to reduce unnecessary maintenance actions by only performing maintenance “just-in-time”. It differs from detection-based maintenance policies as in this case, deterioration is not only detected but multiple states of degradation are measured.

**Continuous monitoring**

Continuous monitoring means that the condition of components can be monitored in real time. A continuous flow of parameter value data is generated by measurement equipment. The advantage of continuous monitoring is that whenever a threshold value of a condition parameter is exceeded, this can be notified immediately and thus a decision regarding maintenance actions can be planned directly. It often requires an investment in measurement equipment for every component to monitor and an IT infrastructure to manage and analyze the data.

**Periodic inspections**

Periodic inspections are planned inspections during which the values of condition parameters of components are measured and analyzed in order to come to the decision to maintain the component, to replace the component, or to perform minimal repair. Periodic inspections require less measurement equipment than continuous monitoring, since the same piece of measurement equipment can be used for measuring parameter values of multiple components during one inspection. The downside is that incipient failure and subsequently actual failure can arise in-between two successively periodic inspections. Therefore, the optimization problem using periodic inspections is to find the optimal inspection interval and preventive threshold value in such a way that incipient failure can be detected before actual failure arises while minimizing the total cost.

### 10.2 Selection

Now that a general categorization of maintenance policies has been discussed, the following question arises: how to select potential maintenance policy/policies for a given type of process rolls? The first requirement for a preventive maintenance policy to be beneficial over a corrective maintenance policy is that the costs of performing a preventive maintenance action are lower than the costs of performing a corrective maintenance action. This is further explained in the next paragraph.

Bakker (2015) developed a decision tree with criteria that are based on technical aspects of equipment. This decision tree is shown in Figure 37 and the three criteria are:

1. The failure rate of equipment.
2. Detectable deterioration of equipment.
3. Measureable deterioration of equipment.

Each of the criteria are discussed in the following paragraphs.
10.3 Costs of a corrective and preventive maintenance action
It only makes sense to choose a preventive maintenance policy over a corrective maintenance policy when the costs of a preventive maintenance action are lower than the costs of corrective maintenance action. Because preventive maintenance takes place before failure of equipment (and thus before corrective maintenance), the time between successive preventive maintenance actions is less than the time between successive corrective maintenance actions. Thus, there will be more preventive maintenance actions per unit time than corrective maintenance actions. For preventive maintenance to be financially beneficial, the costs per preventive maintenance action must be lower than the costs per corrective maintenance action. For process rolls, costs of downtime are only accounted for when replacements are corrective and costs of labor are only accounted for when replacements are preventive. The hourly downtime costs for the ETLs range from €4,000 to €6,000 and the hourly labor costs are €100 for two workers. Therefore, the costs of a preventive replacement is lower than the costs of a corrective replacement. A detailed calculation of these two types of costs for process rolls is given in Appendix M.

10.4 Failure rate
The failure rate (also called hazard rate) at time $t$ describes the likeliness that equipment will fail in the next small time interval, relative to the length of that time interval (instantaneous expected number of failures per unit time). The mathematical formula of the failure rate and other failure distributions are discussed in Appendix N. In this paragraph, only the importance of the failure rate for maintenance policy selection is discussed. A failure rate can either be an increasing function of time (increasing failure rate (IFR)), decreasing function of time (decreasing failure rate (DFR)), or a constant function of time (constant failure rate (CFR)).

- When the failure rate is IFR it means that equipment degrades over time; it wears out. When performing preventive maintenance to equipment which has an IFR, the reliability of that piece of equipment will be increased.
- When the failure rate is DFR it means that equipment becomes more reliable over time. For example, electronic components during the burn-in period. When performing preventive maintenance to equipment which has a DFR, the reliability of that piece of equipment will decrease, which is never the desired in maintenance.
- When the failure rate is CFR it means that equipment does not degrade, but also does not become more reliable over time. For example, electronic components after their burn-in period because electronic components do not wear out. When performing preventive maintenance to equipment which has a CFR, the reliability of that piece of equipment will not increase or decrease but will stay constant.
10.5 Detectable deterioration
An example that accounts for the situation with process rolls at TSP is the detection of increased heat of the bearing houses. During an inspection, a maintenance expert can feel the temperature of the bearing houses of a process roll and even compare it with other similar process rolls. To be able to detect deterioration for a process roll; parameters must be identified of which the state can be detected and which indicate a possible failure in the near future.

10.6 Measureable deterioration
Measureable deterioration means that deterioration can be determined by measuring a parameter. In this project, these parameters are called failure predictors. The measurement can be performed through continuous monitoring or through manual inspections.

10.7 EB rolls
The relation between predictor slip and failure mode coefficient of friction is too low is proved to exist and slip describes the degrading performance of EB rolls. This means that the body of the EB roll wears out and thus has an increasing failure rate. Slip is both detectable and measureable; a CBM policy is selected for the failure mode coefficient of friction is too low. Other failure modes are ignored for bridle sections 1, 2, and 3 because costs due to other failure modes are negligible (see Figure 24).

Minor costs were made due to the failure mode worn tracks for the EB rolls in bridle sections 1, 2, and 3. The multi-roll leveler is placed in the section in-between bridle sections 2 and 3. The function of this multi roll leveler is to eliminate all flatness defects (such as wavy edges and wavy center) in the steel strip by bending the strip while it is being stretched. This means that when EB rolls in bridle sections 1 and 2 fail with failure mode worn tracks which causes wavy edges, these wavy edges are being removed in the multi-roll leveler. A corrective replacement of EB rolls in bridle sections 1 and 2 due to worn tracks is therefore unlikely. Furthermore, no data is available to model degradation of these worn tracks. The best alternative would be to use a detection-based maintenance policy or policy for the failure mode worn tracks. This would result in a combined maintenance policy in which preventive maintenance of EB rolls is either triggered by the level of slip that reached or exceeded the preventive threshold or by the periodic or usage replacement interval, whatever occurs first.
11 Condition-based maintenance policy

11.1 The current situation
In the current situation, for both preventive and corrective maintenance actions of bridle sections all EB rolls of that section get replaced. When not all EB rolls of the bridle section have failed, the non-failing EB rolls are being replaced too. This is called opportunistic maintenance.

11.1.1 Preventive maintenance actions
In the current situation, preventive maintenance actions for EB rolls are triggered by a periodic interval. But, the time-until-replacement data for EB rolls tells that preventive replacements are rarely performed at this interval. As discussed in chapter 1, for certain process roll types experts at TSP perform an inspection right before the periodic replacement to decide if the preventive replacement can be postponed. EB rolls are among these process roll types. During an inspection for EB rolls, experts measure the roughness of the body. However, no threshold value of roughness is determined and thus the preventive maintenance decision is based on intuition. All preventive maintenance actions for ETLs are clustered in 8-weekly revisions.

11.1.2 Corrective maintenance actions
A corrective replacement of an EB roll can be triggered in two ways; the required tension level is not reached or the EB roll scratches the surface of the steel strip that causes rejection of the strip because of quality issues. For both failures, the steps from trigger to a corrective replacement of EB rolls were described in paragraph 9.1. When an EB roll fails, there is immediate loss of production and a corrective replacement cannot be postponed until the next preventive maintenance opportunity. A corrective replacement incurs downtime costs and costs.

11.2 Proposed maintenance policy
In the proposed maintenance policy for EB rolls, slip is the only failure predictor. No complete degradation models are established for slip, but there are some things to be said about the degradation process of slip; the amount of slip is increasing over time and there is stochastic dependence between EB rolls of different bridle sections. The type of stochastic dependence is degradation-based load sharing and this shown for 2 out of 3 studies bridle sections. Slip is a measurement of performance that takes the degradation-based load sharing into account, along with the operating conditions and other environmental factors. No failure threshold is observed in the available data.

In the next paragraphs, first a formal description of the system that represents the current situation is given. Then, the condition-based maintenance policy is described, followed by how to optimize this policy. The last paragraph describes the costs and potential savings.

11.3 Formal description of the current system
Figure 38 shows the part of ETL13 that has been studied in this research project and the system that represents these parts. The system consists of three subsystems where each subsystem represents a bridle section. Each subsystem consists of 2 or 3 components which are the EB rolls. The EB rolls and subsystems are connected in series. This means that each component is critical for the performance of the system. When one EB roll fails, the entire system is down. Minimal repair of EB rolls is not possible. If an EB roll fails, it must be replaced instantly. Preventive maintenance opportunities (revisions) occur periodically with interval $\Delta T^R$. For ETL13, $\Delta T^R$ is 56 days (or 8 weeks). This is a given and not a decision variable. Preventive maintenance can only be performed during these revisions on times $T_k^R = k\Delta T^R = k \cdot 56$ (in days) where $k = 1, 2, ...$. It is assumed that after the replacement of an EB roll (both corrective and preventive), the installed EB roll is “as good as new”; the deterioration
level of the new EB roll is assumed to be zero.

There is positive economic dependence between EB rolls in the same bridle section. This means that combining the replacement of multiple EB rolls is less expensive than replacing each EB roll separately on different times. The costs related to a certain maintenance policy can be influenced by the degree of economic dependence (Olde Keizer, Flapper, & Teunter, 2017). This is generally the case when there are set-up costs for performing maintenance which are only paid for once, independent of the number of maintained components. For EB rolls within the same bridle section, it can be the case that parts of the ETL need to be removed before an EB roll can be replaced. Also, to replace one EB roll, other EB rolls that are placed for example on top of it might need to be disassembled first. The shared set-up costs for replacing EB rolls of different bridle sections simultaneously is downtime costs in case of corrective maintenance.

11.3.1 Deterioration of EB rolls
Slip is being continuously measured through online monitoring of the process parameters strip speed and angular velocity of the electromotor. When using angular velocity of the electromotor to calculate the peripheral speed of an EB roll, the radius of this EB roll needs to be measured during its used lifetime to ensure valid calculations of slip. Next to using the angular velocity of the electromotor and the radius of EB rolls, other methods can be used too to measure the peripheral speed of EB rolls such as measuring the peripheral speed of EB rolls directly.

The degradation models for slip take into account the degradation-based load sharing between EB rolls according to Table 24. EB roll \((i, j)\) fails if slip reaches the failure threshold \(m_f^{(i,j)}\). The measured degradation level, slip, at time \(t\) is \(s_t^{(i,j)}\) for EB roll \(j\) in bridle section \(i\).
11.4 Maintenance policy
A condition-based maintenance policy is developed in which preventive maintenance and opportunistic maintenance rules select an EB roll or group of EB rolls within the same bridle section to be replaced.

Individual corrective replacement
If EB roll \((i,j)\) fails at time \(t\) and \(T_{k-1}^R < t < T_k^R\), then a corrective maintenance action is performed at time \(t\). EB roll \((i,j)\) fails when the monitored slip reaches the failure threshold \(m_f^{(i,j)}\).

Individual preventive replacement
If the monitored slip of EB roll \((i,j)\) reaches or exceeds the fixed preventive threshold level \(m_p^{(i,j)}\), \(s_t^{(i,j)} \geq m_p^{(i,j)}\) and \(m_p^{(i,j)} < m_f^{(i,j)}\), at time \(t\) where \(T_{k-1}^R < t \leq T_k^R\), then a preventive maintenance action is planned and performed at time \(T_k^R\). The preventive threshold level of EB roll \((i,j)\), \(m_p^{(i,j)}\), is a decision parameter that needs to be optimized.

Opportunistic replacements at sub-system level (bridle section)
Given that an EB roll is decided to be preventively or correctively replaced based on the individual corrective and preventive replacement rules, an opportunity arises to replace other EB rolls preventively. Given the decision to replace EB roll \((i,k)\) at time \(t\), if the monitored slip of EB roll \((i,j)\), \(j \neq k\), reaches or exceeds the opportunistic threshold level \(m_o^{(i,j)}\), \(s_t^{(i,j)} \geq m_o^{(i,j)}\), where \(0 < m_o^{(i,j)} < m_p^{(i,j)}\), then EB roll \((i,j)\) is replaced preventively together with EB roll \((i,k)\). \(m_o^{(i,j)}\) is a decision parameter that needs to be optimized.

11.5 Stochastic dependence between EB rolls in the same bridle section
Since no stochastic dependence between EB rolls in the same bridle section is proved, but also not disproved, two scenarios with regards to opportunistic maintenance are described below.

11.5.1 No stochastic dependence between EB rolls in the same bridle section
Consider a bridle section with 2 EB rolls, labeled EB roll 1 and EB roll 2. Figure 39 shows an example of the degradation process of these two EB rolls. When EB roll 1 is replaced at time \(t\), an opportunity arises to replace EB roll 2 preventively. Since no stochastic dependence exists between the two EB rolls, the degradation level of EB roll 2 is not affected by the replacement of EB roll 1. In case of opportunistic replacement of EB roll 2 at time \(t\), the degradation level of EB roll 2, \(s_t^2\), can be compared directly to its opportunistic threshold \(m_o^2\).

![Figure 39: An example of degradation of two EB rolls in one bridle section without stochastic dependence between them.](image)
11.5.2 Stochastic dependence between EB rolls in the same bridle section

Consider the same example as used in the previous paragraph. When EB roll 1 is replaced (preventively or correctively), an opportunity to preventively replace EB roll 2 preventively occurs. But, the level of slip of EB roll 2 depends on the performance of EB roll 1. When EB roll 1 is replaced, the monitored slip of EB roll 2, \( s^2_t \), will drop (less slip) by an amount that is equal to the impact that the performance of the old EB roll 1 had on EB roll 2. In other words, when \( s^2_t \geq m^2_o \) right before the replacement of EB roll 1, it can be the case that replacing EB roll 1 will already cause \( s^2_t \) to become less than \( m^2_o \). This is what happens at time \( T^R_4 \) of the example in Figure 40. To know the impact of the performance of the old EB roll 1 on \( s^2_t \), a degradation model that includes the stochastic dependence between the two EB rolls needs to be developed.

![Figure 40: An example of degradation of two EB rolls in one bridle section with stochastic dependence between them.](image)

11.6 Optimization of the proposed maintenance policy

The goal of optimizing the CBM policy is to minimize the operating costs of EB rolls. Thresholds \( m^{(i,j)}_o \) and \( m^{(i,j)}_p \) are the decision parameters that must be optimized taken the revision interval, \( \Delta T^R \), of 8 weeks into account. The requirement for optimizing the CBM policy is the degradation model for slip of every EB roll, which remains unknown in the current situation. When the degradation models for slip are known, the optimal preventive threshold is based on the required reaction time. Reaction time is defined as the time between the moment that the degradation reaches the preventive threshold and the moment that a preventive maintenance action can be performed. The maximum reaction time equals the time between two revisions, which is 8 weeks. Figure 41 shows an example of the optimal preventive threshold given a degradation model and fixed revision interval.

![Figure 41: The optimal preventive threshold of an EB roll with a revision occurring every \( T^R \).](image)
11.7 How to continue
Since the complete degradation models for slip that are required to optimize the preventive and opportunistic threshold are not developed, how can Tata Steel decide when to perform preventive maintenance?

One option is to start with closely monitoring the development of slip for every EB roll and compare these developments to the measured tensions in the ETLs and scratches on the steel strip. The idea behind monitoring these parameters is to detect if any irregularities arise and to be able to act on those irregularities in time. However, this can take a significant amount of time before the degradation models are developed. For this research project, data for a period of 2 years are used and these data were insufficient to model the complete degradation models for EB rolls. What other options are there to estimate the degradation models? Two other options are:

- Extrapolation of the observed degradation paths. However, this is an unreliable option since it is unclear how the EB roll degrades outside of the range of observed data.
- Consult the experience and knowledge of experts who can estimate the degradation of the performance of EB rolls, based on the observed degradation paths from the available data. Such a specialist can be one who is specialized in the used rubber for EB rolls of a specialist of bridle rolls and bridle sections in general. The difficulty lies in the fact that every EB roll is installed in a unique position in different sections of a production line and that the degradation process for one EB roll can differ from the degradation process of another EB roll.

11.8 Potential costs savings
The advantage of using slip as a failure predictor is that most measurement equipment and the IT infrastructure already exist and it is relatively easy to add other measurement equipment, for example for measuring the radius. No significant additional costs have to be made to implement the condition-based maintenance policy with failure predictor slip. Costs can be saved by reducing the number of corrective replacements and unnecessary preventive replacements by performing maintenance “just-in-time”. Based on the calculated costs for the failure mode coefficient of friction is too low as given in Figure 24 on page 31, approximately in total €13,750 can be saved per year for EB rolls in bridle sections 1, 2, and 3.
12 Implementation of the developed methodology

One of the deliverables of this research project is a methodology that enables Tata Steel to predict failure of process rolls in order to improve maintenance decision-making. This methodology is described throughout Part I to IV of this report. A summary of the methodology is shown in Figure 42. Each step contains the paragraph or chapter number in which the step is discussed. For degradation modelling and maintenance optimization, the steps in this research project are mainly described for the case study.

![Figure 42: A summary of the developed methodology.](image)

To facilitate the calculation of operating costs of process rolls, a tool is developed in Microsoft Excel. The manual of the tool is provided in Appendix C. Besides the operating costs tool, two other means have been transferred to Tata Steel. The first one is a blanc version of the Excel table that is used to define failure modes and identify failure predictors during the group session that is held with experts. The second one is the presentation that is given at the beginning of the group session in order to create understanding and commitment of the experts can use as example for future group sessions for other process roll types.
13 Conclusions and recommendations

13.1 Conclusions
At the beginning of this research project, the goal of the research project and the research questions were defined. The main research question is:

\[
\text{How can Tata Steel increase the predictability of failure of process rolls?}
\]

The answer to the main research question is captured in the developed methodology. This methodology is developed with the help of a case study and was tested to be successful for the case study. The goal of the research project is:

\[
\text{Develop (and implement as much as possible) a methodology to predict failure of process rolls in order to improve maintenance decision-making.}
\]

It can be concluded that the goal of the research project has been achieved, as a methodology to predict failure of process rolls in order to improve maintenance decision-making is developed and implemented as much as possible given the available time for this research project. This report consisted of four parts where each part answered a research question. The conclusions for each part regarding the methodology are given below, followed by the conclusion of the case study.

Part I
To select a process roll type for research, a type with high potential costs savings is preferred. Therefore, the operating costs for every process roll type are calculated using an Excel tool. This is an important step as 11 out of 185 process roll types together caused 50% of all operating costs. Process roll types that have recently been modified or are about to be modified are excluded for this research project.

Part II
An approach has been developed to identify failure predictors for a given process roll type. First, the failure modes are defined, followed by identifying possible failure predictors for each failure mode. This can be done with information from literature, maintenance orders and downtime notifications in SAP, the original equipment manufacturer, and most important the experience of experts at Tata Steel. The experience of experts at Tata Steel is consulted by organizing a group session in which experts from different disciplines participated. Finally, the failure modes are ranked based on their impact on operating costs to determine which failure modes and failure predictors deserve the highest priority.

Part III
Since the modelling of degradation of process rolls in this research project relied on the availability of data, all potential data sources are checked to find data regarding the identified failure predictors. When no data is available, Tata Steel can decide to install measurement equipment if the potential costs savings outdo to costs of installing measurement equipment. The main source for condition monitoring data is IBA, which contains mostly data of process parameters. Degradation models are required to estimate the remaining useful life of process rolls, which is a key requirement for a condition-based maintenance policy. The preferred degradation model depends on the characteristics of the data and the operating context. The degradation models that are tried to develop in this report apply to the case study only.

Part IV
An overview of maintenance policies is provided together with a decision tree to select the
appropriate maintenance policies given a process roll type and its characteristics. Of the selected maintenance policies, the optimal values for the decision parameters need to be determined, followed by selecting the optimal maintenance policy.

**Case study**

For the case study of this research project and to test the developed methodology, the bridle rolls (type EB) of bridle sections 1, 2, and 3 of ETL13 are used. The dominant failure mode of these rolls is that the coefficient of friction is too low to control the tension in the steel strip without damaging the strip and the failure predictor that is used for this failure mode is slip, which is defined as the difference in speed of the strip and peripheral speed of the bridle roll, as percentage of the strip speed. For slip, there is degradation-based load sharing among EB rolls and based on the available data it was not possible to develop the degradation models. However, based on the found relations between slip and degradation of EB rolls a condition-based maintenance policy is proposed. This policy could not be optimized since it requires the degradation models of EB rolls.

**13.2 Recommendations**

**Part I – Process roll selection**

For the calculation of operating costs, maintenance orders and downtime notifications in SAP are used. For every process roll type, the maintenance orders and downtime notifications are selected based on the functional location code (FLC) of these orders and notifications that match the process roll. The use of correct FLCs is important for accurate calculations of operating costs. It turns out that not all maintenance orders and downtime notifications that concern process rolls contain the appropriate FLC and thus these orders and notifications cannot be selected based on the FLC. Seen the high number of maintenance orders and downtime notifications, it is a very time consuming task to select all of them for every process roll. It is recommended to instruct employees who create and manage maintenance orders and downtime notifications in SAP to use the appropriate FLCs. This is not only beneficial for the calculation of operating costs for process rolls, but also for every other kind of maintained equipment.

**Part II – Degradation modelling**

In the current situation, there are some downsides for using IBA for which recommendations are made:

- There are parameters in IBA for which the unit of these parameters are uninterpretable. In this project, motor torque is expressed in percentages and it remained unclear what these percentages mean. This should be checked with for example the supplier of the operating and control system.
- Collecting data can only be done by extracting hourly data files out of the database which is a time-consuming task. At the hot-rolling plant of Tata Steel, employees integrated IBA with another piece of software that automatically creates an overview of all data per component. It is recommended that when IBA is going to be used more often, the manual data extraction gets automated.
- Data of only two years is available. For equipment which lifetime is longer than 2 years you might want to data for a longer period. The only requirement for this is to install a hard disk with more memory.

Another recommendation regarding data is the data logging of inspections. There was no data available from measurements that are performed during inspections of process rolls, even though inspections are performed for certain process roll types.
The case study: EB rolls
The only pitfall of using slip as a failure predictor is that the change in radius remains unknown in the current situation and since the calculation of slip is among others based on the radius, this radius should be measured during the use of EB rolls to ensure valid calculations of slip. Another advantage of measuring the radius is that updated information about the radius can also be used by the operating and control system to control EB rolls properly. An example of an alternative of calculating slip is to measure the peripheral speed of EB rolls directly.

To gain a better understanding in the use of slip as a failure predictor of bridle rolls, it can be interesting to model slip of other bridle rolls in other production lines. Note that for a new type of bridle roll, for example the failure modes and failure predictors can differ so this should be analyzed first using the developed methodology.

Based on the currently available data, it was not possible to observe degradation-based load sharing between EB rolls of the same bridle section. This could for example be investigated by replacing only one EB roll of a bridle section and to observe the change in performance of the remaining EB rolls.
References


Research, [unknown], [unknown].


## Appendix A Stakeholders of the project

<table>
<thead>
<tr>
<th>Name</th>
<th>Company/division - Function</th>
<th>Relation to the project</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Project group</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tom Avontuur</td>
<td>TUE – Student</td>
<td>Executing master thesis project</td>
</tr>
<tr>
<td>Simme Douwe Flapper</td>
<td>TUE – Assistant professor</td>
<td>First supervisor</td>
</tr>
<tr>
<td>Gero Walter</td>
<td>TUE – Researcher</td>
<td>Second supervisor</td>
</tr>
<tr>
<td>Andre Nooij</td>
<td>TSP – Maintenance Manager Infrastructure</td>
<td>Project owner/company supervisor</td>
</tr>
<tr>
<td>Joop Slootweg</td>
<td>TSP – Specialist Process Roll Maintenance</td>
<td>Daily supervisor</td>
</tr>
<tr>
<td>Nico van Kessel</td>
<td>TSE – Tata Steel Europe Asset Management</td>
<td>Project coach</td>
</tr>
<tr>
<td>C. S.</td>
<td>AMD – Contract Manager IJssel Technologie</td>
<td>Supervisor AMD (informative)</td>
</tr>
<tr>
<td>W.G.</td>
<td>IJT – Region Manager IJssel Technologie</td>
<td>Contract partner IJssel Technologie</td>
</tr>
<tr>
<td><strong>Directly involved stakeholders</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F. S.</td>
<td>TSP – Production Line Manager work-area 4</td>
<td>Manager of ETL13</td>
</tr>
<tr>
<td>P. W.</td>
<td>TSP – Maintenance manager work-area 4</td>
<td>Owner of process rolls ETL13</td>
</tr>
<tr>
<td>T. K.</td>
<td>TSP – Production manager work-area 4</td>
<td>Production manager ETL13</td>
</tr>
<tr>
<td>C. B.</td>
<td>TSP – Maintenance Engineer work-area 4</td>
<td>Maintenance engineer ETL13</td>
</tr>
<tr>
<td>P. L.</td>
<td>TSP – Manager Maintenance Engineers TSP</td>
<td>Maintenance engineer TSP</td>
</tr>
<tr>
<td>H. S.</td>
<td>TSP – Former process roll specialist work-area 4</td>
<td>Process rolls</td>
</tr>
<tr>
<td>A. H.</td>
<td>TSP – Former process roll specialist work-area 4</td>
<td>Process rolls</td>
</tr>
<tr>
<td>G. B.</td>
<td>TSP – Process roll specialist work-area 4</td>
<td>Process rolls</td>
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<td><strong>Other consulted experts/specialists</strong></td>
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<tr>
<td>R. A.</td>
<td>TSP – Former Technical Assistant</td>
<td>Process data: IBA</td>
</tr>
<tr>
<td>A. B.</td>
<td>TSP – Technical Specialist work-area 4</td>
<td>Process data: IBA</td>
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<tr>
<td>R. H.</td>
<td>AMD – Expert Condition Monitoring and Lubrication</td>
<td>Vibration measurements</td>
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<tr>
<td>N. N.</td>
<td>AMD – Consultant Maintenance Engineer</td>
<td>Optimizer+</td>
</tr>
<tr>
<td>P. T.</td>
<td>TSP – Maintenance Engineer</td>
<td>Maintenance order structure in SAP</td>
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<tr>
<td>L. M.</td>
<td>TSP – Maintenance Engineer</td>
<td>Logbook data (downtime and production)</td>
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<tr>
<td><strong>Advisory board</strong></td>
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<tr>
<td>B. vd M.</td>
<td>MLE – Chief Engineering MLE</td>
<td>Sponsor</td>
</tr>
<tr>
<td>H. D.</td>
<td>OSF2 – Works Engineer OSF2</td>
<td>Sponsor</td>
</tr>
<tr>
<td>M. S.</td>
<td>TSP – Works Engineer TSP</td>
<td>Senior user</td>
</tr>
<tr>
<td>H. S.</td>
<td>AMD – Chef CAMF Knowledge &amp; Innovation</td>
<td>Support</td>
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<tr>
<td>J. F.</td>
<td>AMD – Chef Contract &amp; Shutdown Management</td>
<td>Support</td>
</tr>
<tr>
<td>J. H.</td>
<td>TSE – Manager Maintenance Improvement</td>
<td>Board member WCM</td>
</tr>
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<td><strong>Visited as reference</strong></td>
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</tr>
<tr>
<td>A. v B.</td>
<td>Fujifilm Tilburg</td>
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</tr>
<tr>
<td>J. A.</td>
<td>SKF Bearings Nieuwegein</td>
<td></td>
</tr>
<tr>
<td>P. vd A.</td>
<td>Hot rolling plant (Tata Steel IJmuiden)</td>
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**Table 26: Stakeholders of Tata Steel and IJssel Technologie in relation to this project.**

**Abbreviations:**

- AMD: Asset Management Development (Tata Steel)
- IJT: IJssel Technologie
- MLE: Tata Steel Mainland Europe
- OSF2: Oxygen steelmaking-plant 2 (Tata Steel)
- TSE: Tata Steel Europe
- TSP: Tata Steel Packaging
- TUE: Eindhoven University of Technology
Appendix B  Tension control in production lines using bridle rolls

This appendix discusses how tension rises unintendedly and how a bridle section can control tension.

The unintended rise of tension

When steel strip is being processed on an ETL, the strip faces several sources of friction throughout the different sections of an ETL. This friction tends to slow down the strip, as it is a force in the opposite direction of the strip’s speed. With every source of friction that the strip encounters, the tension will increase. This accumulation of tension can be explained with the help of a simple example. See Figure 43. In this example, four discrete sources of friction represented by blocks are put on the steel strip, each with a force of 10 N. No other friction or resistance is caused by the unwinder and rewinder. The steel strip flows with an arbitrary constant speed from the unwinder to the rewinder. Because of the resistance in the first block, a reaction force with equal size (10 N) manifests in the steel strip which is tension. Subsequently, when the steel strip encounters the second block the total friction becomes 20 N (the sum of the friction of the first two blocks) and thus the reaction force in the strip becomes 20 N. At the end of the production line, there is 40 N of tension in the strip. This means that the rewinder needs to pull the strip with a force of exactly 40 N to maintain the speed of the strip.

In practice, common sources of friction are rolling resistance of bearings of process rolls, entrainment (drag) of liquid when steel strip enters and leaves tanks (for example, pickling and tinning tanks), and pressing rolls which press the steel strip against another process roll. Some of the friction caused by pressing rolls and entrainment of liquid are compensated by driven process rolls in these production line sections.

Tension control using a bridle section

When considering an ETL, the tension is being controlled by the unwinder and rewinder, bridle sections, and the entry and exit loop. See Figure 6 on page 8 for an example of these sections in an ETL. If two successive sections in a production line require different tension levels, a bridle section is placed in-between these sections, where a bridle section consists of two or more bridle rolls. A bridle section’s function is to control the tension in the steel strip at the required strip speed. It can either increase or decrease the tension in the steel strip. Decreasing tension with a bridle section will be illustrated by an extension of the example showed in Figure 43. In this example, the tension throughout the production line is not allowed to be higher than 25 N. Therefore, a bridle section is
used that pulls the steel strip with a force of 15 N. Thus, the tension after the bridle section is reduced to 5 N. In the new situation, the tension at the rewinder equals 25 N and thus the rewinder must pull the strip with a force equal to 25 N instead of 40 N.

Figure 44: Simplified example of how a bridle section can influence the tension in the steel strip.
Appendix C  Excel tool to calculate operating costs for process rolls

The tool that is developed to calculate the operating costs of process rolls of the four ETLs consists of 8 sheets. Brief descriptions of these sheets are given in Table 27. The core of the tool is the Start sheet, which includes the manual. This sheet and thus the manual of the tool are shown in Figure 45.

<table>
<thead>
<tr>
<th>Name of the sheet</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Start</td>
<td>See Figure 45. This sheet is the core of the tool. It describes all the steps that must be executed to calculate the operating costs for process rolls. These steps are: Step 1 – Erase results of previous analysis Step 2 – Erase input data of previous analysis Step 3 – Start of a new analysis Step 4 – Downtime costs parameters Step 5 – M1 notifications Step 6 – PM20 orders Step 7 – M2 notifications Step 8 – PM10 orders Step 9 – Construct the results on the Result sheet.</td>
</tr>
<tr>
<td>Result</td>
<td>See Figure 46. The Result sheet contains the results of the analysis. Per process roll type, the number of PM20 and PM10 orders, the total costs of these maintenance orders, the downtime costs, and the operating costs are given. The results are sorted in a descending order. A graph shows the 50 process roll types with the highest operating costs and the cumulative percentage.</td>
</tr>
<tr>
<td>PO Plannen</td>
<td>The PO Plannen sheet contains all the periodic maintenance plans from SAP and is used to select preventive maintenance orders.</td>
</tr>
<tr>
<td>Functieplaatsen</td>
<td>The Functieplaatsen sheet contains all the FLCs for process rolls for the four ETLs. This sheet is used to select notifications and maintenance orders of every process roll position in each of the four ETLs.</td>
</tr>
<tr>
<td>M1</td>
<td>The M1 sheet is where the data of M1 notifications from sap need to be imported. The columns from A to H are: Meldingssoort, Melding, Order, Omschrijving, Meldingsdatum, Omschrijving, Functieplaats, Uitvalduur. The exported data from SAP must match each of these columns.</td>
</tr>
<tr>
<td>PM20</td>
<td>The PM20 sheet is where the data of PM20 maintenance orders from sap need to be imported. The columns from A to H are: Order, Ordersoort, Basisstartterm., Korte tekst, Functieplaats, Omschrijving, Melding, Werk. totaal. The exported data from SAP must match each of these columns.</td>
</tr>
<tr>
<td>M2</td>
<td>The M2 sheet is where the data of M2 notifications from sap need to be imported. The columns A to H are: Meldingssoort, Melding, Order, Omschrijving, Begin storing, Omschrijving, Functieplaats, Uitvalduur. The exported data from SAP must match each of these columns.</td>
</tr>
<tr>
<td>PM10</td>
<td>The M1 sheet is where the data of PM10 maintenance orders from sap need to be imported. The columns A to H are: Order, Ordersoort, Basisstartterm., Korte tekst, Functieplaats, Omschrijving, Melding, Werk. totaal. The exported data from SAP must match each of these columns.</td>
</tr>
</tbody>
</table>

Table 27: Descriptions of the sheets of the operating costs tool.
Figure 45: The Start sheet of the operating costs tool.

1. **Erase results of previous analysis**
   Before a new analysis of operating costs can be performed, the previous analysis must be erased. This is done in two steps. This first step is to erase the results of the previous analysis by clicking the button "Erase results" on the right.

2. **Erase input data of previous analysis**
   The second step is to erase all the input data on the following sheets: PM20, M1, PM10, and M2. This is done by clicking the button "Erase input data" on the right.

3. **Start of a new analysis**
   There are four important things to do when starting a new analysis. (1) Define the period and ETLs for which you want to run the analysis. For example, analyze the operating costs of process rolls that are used in ETL14 for the period from 1-1-2016 to 1-1-2017. (2) When searching maintenance orders and notifications from SAP, make sure to select the defined time window and to use the following filter criteria: 353\(\ast\) for ETL11, 255\(\ast\) and 255\(\ast\) for ETL12, 255\(\ast\) for ETL13, and 255\(\ast\) for ETL14. (3) Select the columns in SAP that correspond to the columns in the sheets "PM20", "M1", "PM10", and "M2" in this tool. (4) Do not change any columns in this tool that have a red header and do not make any changes to the red sheets "Result", "PO Planen", and "Funktionsplanen".

4. **Downtime costs parameters**
   In case that the variable and/or fixed downtime costs for one or more ETLs change, these costs must be updated before starting a new analysis of operating costs. These costs can be updated by changing the costs in the grey cells below (as this tool uses the costs in the grey cells).
   - ETL11 downtime costs: € 4,000 Per hour € 1,000 Per stop
   - ETL12 downtime costs: € 5,000 Per hour € 1,000 Per stop
   - ETL13 downtime costs: € 6,000 Per hour € 1,000 Per stop
   - ETL14 downtime costs: € 7,000 Per hour € 1,000 Per stop

5. **M1 notifications**
   Import the M1 notifications from SAP in sheet "M1". Make sure that the columns of the extracted dataset from SAP matches each of the columns A to H of sheet "M1". M1 notifications are only used to process PM20 orders. Therefore, processing M1 notifications is done at step 6.

6. **PM20 orders**
   Import the PM20 orders from SAP in sheet "PM20". Make sure that the columns of the extracted dataset from SAP matches each of the columns A to H of sheet "PM20". When the M1 and PM20 data are imported in the corresponding sheets, click on the button "Process PM20 orders" on the right.

7. **M2 notifications**
   Import the M2 notifications from SAP in sheet "M2". Make sure that the columns of the extracted dataset from SAP matches each of the columns A to H of sheet "M2". Check the imported M2 notifications for outliers. This can be done with the help of the process roll maintenance specialist who can spot outliers. For example, 20 hours of downtime can be an outlier for a process roll that is usually replaced in two hours but 20 hours of downtime cannot be an outlier for a process roll that is usually replaced in 20 hours. When the downtime costs parameters in step 4 and the M2 notifications are updated, click on the button "Process M2 notifications" on the right.

8. **PM10 orders**
   Import the PM10 orders from SAP in sheet "PM10". Make sure that the columns of the extracted dataset from SAP matches each of the columns A to H of sheet "PM10". When the M2 and PM10 data are imported in the corresponding sheets, click on the button "Process PM10 orders" on the right.

9. **Construct results on the Result sheet**
   When steps 1 to 8 are performed, it is time to generate the results of the analysis on the "Result" sheet. This is done by clicking on the "Summarize results" button on the right.
Figure 46: The Result sheet of the operating costs tool.

<table>
<thead>
<tr>
<th>Type</th>
<th>PM09 (amount)</th>
<th>PM09 total (€)</th>
<th>PM10 (amount)</th>
<th>PM10 total (€)</th>
<th>Downtime costs (€)</th>
<th>Operating costs (€)</th>
<th>Cumulative (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>MB</td>
<td>20</td>
<td>153,401</td>
<td>40</td>
<td>€ 244,002</td>
<td>€ 634,750</td>
<td>1,232,764</td>
</tr>
<tr>
<td>2</td>
<td>AF</td>
<td>13</td>
<td>55,184</td>
<td>18</td>
<td>€ 71,155</td>
<td>€ 1,028,560</td>
<td>1,170,859</td>
</tr>
<tr>
<td>3</td>
<td>P</td>
<td>32</td>
<td>65,212</td>
<td>36</td>
<td>€ 90,662</td>
<td>€ 385,960</td>
<td>877,880</td>
</tr>
<tr>
<td>4</td>
<td>AA</td>
<td>38</td>
<td>146,150</td>
<td>37</td>
<td>€ 220,301</td>
<td>€ 514,010</td>
<td>894,661</td>
</tr>
<tr>
<td>5</td>
<td>S</td>
<td>37</td>
<td>116,711</td>
<td>34</td>
<td>€ 208,377</td>
<td>€ 536,870</td>
<td>1,075,668</td>
</tr>
<tr>
<td>6</td>
<td>EG</td>
<td>35</td>
<td>83,432</td>
<td>49</td>
<td>€ 157,148</td>
<td>€ 380,040</td>
<td>641,250</td>
</tr>
<tr>
<td>7</td>
<td>MA</td>
<td>30</td>
<td>17,545</td>
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<td>€ 49,680</td>
<td>€ 111,895</td>
<td>259,875</td>
</tr>
<tr>
<td>8</td>
<td>MIC</td>
<td>2</td>
<td>17,320</td>
<td>19</td>
<td>€ 145,120</td>
<td>€ 320,310</td>
<td>453,600</td>
</tr>
<tr>
<td>9</td>
<td>ME</td>
<td>10</td>
<td>16,171</td>
<td>15</td>
<td>€ 128,500</td>
<td>€ 265,900</td>
<td>439,431</td>
</tr>
<tr>
<td>10</td>
<td>LH</td>
<td>15</td>
<td>16,972</td>
<td>16</td>
<td>€ 20,979</td>
<td>€ 381,080</td>
<td>425,031</td>
</tr>
<tr>
<td>11</td>
<td>LB</td>
<td>20</td>
<td>35,451</td>
<td>13</td>
<td>€ 40,907</td>
<td>€ 277,690</td>
<td>357,148</td>
</tr>
<tr>
<td>12</td>
<td>EV</td>
<td>31</td>
<td>31,407</td>
<td>37</td>
<td>€ 128,493</td>
<td>€ 177,320</td>
<td>337,219</td>
</tr>
<tr>
<td>13</td>
<td>Y</td>
<td>2</td>
<td>11,949</td>
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<td>€ 40,551</td>
<td>€ 257,920</td>
<td>310,420</td>
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<td>14</td>
<td>KN-A</td>
<td>17</td>
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<td>10</td>
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<td>€ 215,700</td>
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<td>15</td>
<td>RG</td>
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<td>€ 45,759</td>
<td>€ 219,420</td>
<td>300,801</td>
</tr>
<tr>
<td>17</td>
<td>KG-C</td>
<td>37</td>
<td>28,000</td>
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<td>€ 93,246</td>
<td>€ 123,870</td>
<td>245,116</td>
</tr>
<tr>
<td>18</td>
<td>N</td>
<td>16</td>
<td>13,565</td>
<td>3</td>
<td>€ 39,676</td>
<td>€ 65,020</td>
<td>245,061</td>
</tr>
<tr>
<td>19</td>
<td>T</td>
<td>30</td>
<td>56,294</td>
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<td>€ 67,719</td>
<td>€ 121,020</td>
<td>244,273</td>
</tr>
<tr>
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<td>RF</td>
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<td>€ 44,955</td>
<td>€ 156,800</td>
<td>243,012</td>
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<td>21</td>
<td>KT</td>
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<td>68,880</td>
<td>22</td>
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<td>€ 98,580</td>
<td>240,547</td>
</tr>
<tr>
<td>22</td>
<td>AC</td>
<td>52</td>
<td>52,219</td>
<td>22</td>
<td>€ 57,030</td>
<td>€ 71,500</td>
<td>191,069</td>
</tr>
<tr>
<td>23</td>
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<td>€ 128,760</td>
<td>181,025</td>
</tr>
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<td>€ 14,616</td>
<td>€ 170,300</td>
<td>179,284</td>
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<td>25</td>
<td>KK</td>
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<td>12,061</td>
<td>18</td>
<td>€ 39,270</td>
<td>€ 121,640</td>
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<tr>
<td>26</td>
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<td>1,093</td>
<td>0</td>
<td>€ 1,433,750</td>
<td>€ 1,44,845</td>
<td>76.56%</td>
</tr>
<tr>
<td>27</td>
<td>AM</td>
<td>10</td>
<td>10,277</td>
<td>9</td>
<td>€ 34,992</td>
<td>€ 97,520</td>
<td>142,765</td>
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<td>28</td>
<td>MD</td>
<td>11</td>
<td>19,926</td>
<td>5</td>
<td>€ 22,081</td>
<td>€ 95,490</td>
<td>136,478</td>
</tr>
<tr>
<td>29</td>
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<td>16,775</td>
<td>12</td>
<td>€ 35,414</td>
<td>€ 84,160</td>
<td>136,349</td>
</tr>
<tr>
<td>30</td>
<td>EU</td>
<td>3</td>
<td>2,961</td>
<td>14</td>
<td>€ 49,104</td>
<td>€ 78,360</td>
<td>131,425</td>
</tr>
<tr>
<td>31</td>
<td>LP</td>
<td>1</td>
<td>3,333</td>
<td>5</td>
<td>€ 15,817</td>
<td>€ 100,440</td>
<td>119,590</td>
</tr>
<tr>
<td>32</td>
<td>BS</td>
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<td>4</td>
<td>€ 11,997</td>
<td>€ 100,490</td>
<td>117,439</td>
</tr>
<tr>
<td>33</td>
<td>AF-nat</td>
<td>4</td>
<td>103,770</td>
<td></td>
<td>€ 179,284</td>
<td>€ 379,040</td>
<td>530,570</td>
</tr>
<tr>
<td>34</td>
<td>ZZ</td>
<td>14</td>
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<td>€ 20,580</td>
<td>€ 94,888</td>
<td>94,158</td>
</tr>
<tr>
<td>35</td>
<td>D</td>
<td>28</td>
<td>92,655</td>
<td>8</td>
<td>€ 8,759</td>
<td>€ 9,710</td>
<td>94,235</td>
</tr>
<tr>
<td>36</td>
<td>PO</td>
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<td>11</td>
<td>€ 62,000</td>
<td>€ 90,983</td>
<td>181,083</td>
</tr>
<tr>
<td>37</td>
<td>RP</td>
<td>5</td>
<td>30,692</td>
<td>4</td>
<td>€ 15,482</td>
<td>€ 42,450</td>
<td>88,559</td>
</tr>
<tr>
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<td>11,989</td>
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<td>€ 8,342</td>
<td>€ 63,130</td>
<td>83,461</td>
</tr>
<tr>
<td>39</td>
<td>Co</td>
<td>6</td>
<td>2,969</td>
<td>7</td>
<td>€ 11,590</td>
<td>€ 68,200</td>
<td>93,069</td>
</tr>
<tr>
<td>40</td>
<td>AE</td>
<td>10</td>
<td>20,470</td>
<td>5</td>
<td>€ 5,549</td>
<td>€ 64,730</td>
<td>80,750</td>
</tr>
<tr>
<td>41</td>
<td>KG</td>
<td>15</td>
<td>51,699</td>
<td>3</td>
<td>€ 5,345</td>
<td>€ 19,590</td>
<td>76,544</td>
</tr>
</tbody>
</table>

Graph

Top 50 process roll types with regard to operating costs
### Appendix D  Failure modes and failure predictors for EB rolls

<table>
<thead>
<tr>
<th>Sub-component</th>
<th>Function</th>
<th>Functional failure</th>
<th>Failure mode</th>
<th>Effect</th>
<th>Cause</th>
<th>Detectable</th>
<th>Measurable</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Body</strong></td>
<td>To provide friction between process roll and steel strip without damaging the steel strip</td>
<td>The required level of friction cannot be achieved</td>
<td>Coefficient of friction is too low</td>
<td>Slipping strip. Dropping tension (can be compensated by other bridles but then speed losses). Scratches in the surface of the steel strip (quality rejection). Possible corrective replacement.</td>
<td>Wear and tear</td>
<td>Wear and tear</td>
<td>Yes (Slip (effect): indirect when speed of strip differs substantially with RPM and when torque drops)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>To transport the steel strip, without deforming or damaging the steel strip and without steering the steel strip other than the centerline</td>
<td>Causes flatness defects: wavy edges</td>
<td>Worn tracks at one or both ends of the body</td>
<td>When waves larger than 1.5mm: quality issues. Corrective replacement. Replacement can be postponed by changing to orders with a smaller strip.</td>
<td>Wear and tear</td>
<td>Yes</td>
<td>Track measurement</td>
</tr>
<tr>
<td><strong>Bearings</strong></td>
<td>Allow the process roll to rotate at the required speed with low rolling resistance.</td>
<td>Process roll rotates with high rolling resistance or does not rotate at all.</td>
<td>Overheating of bearings</td>
<td>Lubricant: too much, too little, and wrong type of lubricant.</td>
<td>Yes (sparks, noise)</td>
<td>Wear and tear</td>
<td>Temperature. Vibrations. Electrical power (more power needed when rolling resistance increases)</td>
</tr>
<tr>
<td><strong>Shaft</strong></td>
<td>Transfer torque from driver to body.</td>
<td>Not able to transfer torque from driver to body.</td>
<td>Shaft breakage. Damage to the production line. Corrective replacement.</td>
<td>Metal fatigue</td>
<td>Yes (during repair)</td>
<td>Wear traces.</td>
<td>Micro-cracks</td>
</tr>
</tbody>
</table>

*Table 28: Results of the failure mode and failure predictor analysis for EB rolls.*
Appendix E  An example of a process roll replacement form

Figure 47: An example of a process roll replacement form.
Appendix F  Variables in RWB

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>The type of process roll</td>
<td>EB</td>
</tr>
<tr>
<td>Roll no.</td>
<td>The unique ID number</td>
<td>4</td>
</tr>
<tr>
<td>Diameter in</td>
<td>The diameter of the body before usage of the process roll</td>
<td>760.00 mm</td>
</tr>
<tr>
<td>Hardness in</td>
<td>The hardness of the body before usage of the process roll</td>
<td>70.0 °shore A</td>
</tr>
<tr>
<td>Roughness in</td>
<td>The roughness of the body before usage of the process roll</td>
<td>19.0 µ</td>
</tr>
<tr>
<td>Firma</td>
<td>The company that repaired the process roll that is being installed</td>
<td>IJssel</td>
</tr>
<tr>
<td>Order no. in</td>
<td>The order number of repair of the process roll before it got installed</td>
<td>4502371730</td>
</tr>
<tr>
<td>Line</td>
<td>The production line in which the process roll is installed</td>
<td>ETL13</td>
</tr>
<tr>
<td>Position</td>
<td>The position in the production line in which the process roll is installed</td>
<td>1514</td>
</tr>
<tr>
<td>Date in</td>
<td>The date that the process roll got installed in the production line</td>
<td>1-1-2015</td>
</tr>
<tr>
<td>Date out</td>
<td>The date that the process roll got replaced</td>
<td>1-1-2016</td>
</tr>
<tr>
<td>Reason replacement</td>
<td>The reason why the process roll has been replaced. Either periodic or the failure mode/problem is stated here.</td>
<td>Periodic</td>
</tr>
<tr>
<td>Comments</td>
<td>Room for comments</td>
<td>-</td>
</tr>
<tr>
<td>Diameter out</td>
<td>The diameter of the body after usage of the process roll</td>
<td>759.00 mm</td>
</tr>
<tr>
<td>Hardness out</td>
<td>The hardness of the body after usage of the process roll</td>
<td>71.0 °shore A</td>
</tr>
<tr>
<td>Roughness out</td>
<td>The roughness of the body after usage of the process roll</td>
<td>5.0 µ</td>
</tr>
<tr>
<td>Order no. out</td>
<td>The order number of repair of the process roll after it has been replaced</td>
<td>4502576826</td>
</tr>
<tr>
<td>Date repair finished</td>
<td>The data on which the repair process has finished</td>
<td>1-4-2016</td>
</tr>
</tbody>
</table>

*Table 29: An overview of the variables that are used in the RWB, including a description and example.*
Appendix G  Used IBA parameters for calculating slip

The variables used in Table 30 are described in paragraph 8.2.

<table>
<thead>
<tr>
<th>Variable</th>
<th>IBA parameter name</th>
<th>Unit</th>
<th>IBA Code</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strip 60 \cdot v_{\text{strip}}^{i} \ (i \in {1,2})</td>
<td>V_ACT_Intree snelheid</td>
<td>m/min</td>
<td>[0:18]</td>
</tr>
<tr>
<td>60 \cdot v_{\text{strip}}^{i} \ (i \in {3})</td>
<td>Proces Actual linespeed [m/min]</td>
<td>m/min</td>
<td>[25:12]</td>
</tr>
<tr>
<td>Bridle section 1  \nu^{(1,1)}_t</td>
<td>N_DRV03_BR11_V_ACT_DBDB804</td>
<td>m/s</td>
<td>[5:20]</td>
</tr>
<tr>
<td>\nu^{(1,2)}_t</td>
<td>N_DRV04_BR12_V_ACT_DBDB804</td>
<td>m/s</td>
<td>[6:4]</td>
</tr>
<tr>
<td>\nu^{(1,3)}_t</td>
<td>N_DRV05_BR13_V_ACT_DBDB804</td>
<td>m/s</td>
<td>[6:12]</td>
</tr>
<tr>
<td>\nu^{(1,3)}_t</td>
<td>N_DRV05_BR13_N_ACT_DBDB816</td>
<td>rpm</td>
<td>[6:13]</td>
</tr>
<tr>
<td>Bridle section 2  \nu^{(1,2)}_t</td>
<td>N_DRV07_BR21_V_ACT_DBDB804</td>
<td>m/s</td>
<td>[7:4]</td>
</tr>
<tr>
<td>\nu^{(2,1)}_t</td>
<td>N_DRV07_BR21_N_ACT_DBDB816</td>
<td>rpm</td>
<td>[7:5]</td>
</tr>
<tr>
<td>\nu^{(2,2)}_t</td>
<td>N_DRV08_BR22_V_ACT_DBDB804</td>
<td>m/s</td>
<td>[7:12]</td>
</tr>
<tr>
<td>\nu^{(2,2)}_t</td>
<td>N_DRV08_BR22_N_ACT_DBDB816</td>
<td>rpm</td>
<td>[7:13]</td>
</tr>
<tr>
<td>Bridle section 3  \nu^{(3,1)}_t</td>
<td>P_DRV02_BR31_V_ACT_DBDB804</td>
<td>m/s</td>
<td>[11:12]</td>
</tr>
<tr>
<td>\nu^{(3,1)}_t</td>
<td>P_DRV02_BR31_N_ACT_DBDB816</td>
<td>rpm</td>
<td>[11:13]</td>
</tr>
<tr>
<td>\nu^{(3,2)}_t</td>
<td>P_DRV03_BR32_V_ACT_DBDB804</td>
<td>m/s</td>
<td>[11:20]</td>
</tr>
<tr>
<td>\nu^{(3,2)}_t</td>
<td>P_DRV03_BR32_N_ACT_DBDB816</td>
<td>rpm</td>
<td>[11:21]</td>
</tr>
<tr>
<td>\nu^{(3,3)}_t</td>
<td>P_DRV04_BR33_V_ACT_DBDB804</td>
<td>m/s</td>
<td>[12:4]</td>
</tr>
<tr>
<td>\nu^{(3,3)}_t</td>
<td>P_DRV04_BR33_N_ACT_DBDB816</td>
<td>rpm</td>
<td>[12:5]</td>
</tr>
</tbody>
</table>

Table 30: IBA parameters and their names which are used to calculate slip.
Appendix H  Using the electromotor for fault detection

Fault detection
A relationship needs to be established between failure modes of EB rolls that are being monitored and signs of malfunctioning in the process data. In other words, are the values of the measured process data sufficiently influenced by the most important types of failure? (Veldman, Wortmann, & Klingenberg, 2011). The use of parameters that describe the power usage of electromotors of EB rolls is based on the idea of fault detection methodologies. Isermann (2006), wrote the following about fault detection models:

“A straightforward way to detect process faults is to compare the process behavior with a process model describing the nominal, i.e. non-faulty behavior. The difference of signals between the process and the model are expressed by residuals. Therefore, residuals describe discrepancies between the process and the model.”

Thus, fault detection methods first consider a system operating in its normal condition (the model). They then use the relation between measured variables of the process to extract information on possible changes caused by faults (degradation). The appearance of a fault can have multiple reasons. The three most common reasons are wrong design, wrong operation, and wear during normal operation.

How an electromotor drives a bridle roll
The electromotor of a bridle roll uses an electric power to create a torque with a certain angular velocity. Torque, also called moment of force, is a force that is applied at a right angle to a lever. In the case of bridle rolls, the lever is the roll’s radius, r, and the force, F, is applied to the steel strip creating a tension differential that is equal to the force. See Figure 48. Thus, torque is the force that is needed to create a tension differential in the steel strip, it is generated by an electromotor, and transferred to the bridle roll via a gearbox with fixed gear (see Figure 14 on page 22 for the set-up of a bridle roll).

![Figure 48: Torque equals the force vector times the radius.](image)

Let \( TQ^{\text{roll}} \) denote the torque that needs to be put on the bridle roll (that is the torque after the gearbox) to create tension differential \( \Delta T_{1,2} \) in the steel strip. Then;

\[
TQ^{\text{roll}} = \Delta T_{1,2} \cdot r \tag{8}
\]
The gearbox that is placed between the electromotor and the bridle roll not only affects the speed, but also the torque. For bridle rolls, a gearbox reduces the angular velocity, but it increases the torque. Let \( TQ_{\text{motor}} \) denote the torque that an electromotor needs to deliver to create tension differential \( \Delta T_{1,2} \). When assuming the torque that is being delivered by the electromotor is transferred to the bridle roll without facing any resistance in the gearbox, equation (9) accounts. In this equation \( g \) is the gear ratio which is calculated in equation (10), where \( \omega_{\text{motor}} \) and \( \omega_{\text{roll}} \) are the angular velocities of the electromotor’s shaft and bridle roll in radians per second, respectively.

\[
TQ_{\text{motor}} = \frac{TQ_{\text{roll}}}{g}
\]  

(9)

\[
g = \frac{\omega_{\text{motor}}}{\omega_{\text{roll}}}
\]  

(10)

Let \( P_m^{\text{required}} \) denote the mechanical power (in Watt) that the electromotor delivers to create the required tension differential, \( \Delta T_{1,2} \), at strip speed \( v_{\text{strip}} \), assumed that the gearbox is free of resistance. For electromotors in general, equation (11) applies.

\[
P_m^{\text{required}} = TQ_{\text{motor}} \cdot \omega_{\text{motor}}
\]  

(11)

It should be noticed that the torque which is needed to create the required tension differential is independent of the speed of the steel strip (see equations (8) and (9)). The gearbox increases the torque and reduces the angular velocity. The law of energy conservation tells that there cannot be more energy after the gearbox than provided by the electromotor. Therefore, the power that the electromotor needs can also be calculated as shown in equation (12). In this equation, \( v_{\text{strip}} \) is the speed of the steel strip in m/s.

\[
P_m^{\text{required}} = TQ_{\text{motor}} \cdot \omega_{\text{motor}} = \Delta T_{1,2} \cdot v_{\text{strip}}
\]  

(12)

Since \( TQ_{\text{motor}} \) is usually not measured, it is most interesting to look to the electrical power of an electromotor which is being measured more easily. The electrical power of the electromotor is calculated according to equation (13), where an electromotor uses voltage, \( V \), in volts and current, \( I \), in ampere.

\[
P_e^{\text{required}} = V \cdot I
\]  

(13)

For a perfectly efficient electromotor; \( P_e^{\text{required}} = P_m^{\text{required}} \). In real life, electromotors are not perfectly efficient and thus; \( P_e^{\text{required}} > P_m^{\text{required}} \).

**Using electric power to detect faults**

Based on the required tension and speed of the strip, the required power, torque, and speed that the electromotor needs to deliver can be calculated as discussed in the previous paragraph. The main idea about using the electric power that the electromotor of an EB roll uses, is to model *residuals*. Residuals are the difference between the model and the actual process. The model describes what is required by the system based on the production characteristics. The actual process includes various losses or differences due to deterioration and faults of EB rolls.

The residuals that will be modelled are mostly the result of resistance in the set-up of a bridle roll. The amount of power that a bridle roll’s electromotor uses is greater than \( P_e^{\text{required}} \). Seen the set-up of an
EB roll, possible the sources that cause resistance are the bearings and the gearbox. Bearings deteriorate usually as the result of usage. When bearings deteriorate, the rolling resistance increases which causes more load for the electromotor to deliver the required speed and tension. Torque generated by the motor is lost to the increased rolling resistance in the bearings. The electromotor needs to compensate these losses. Besides the bearings, losses are generally made by the resistance in the gearbox.

Denote:

- $P_{e \text{actual}}$: The actual used power by the electromotor (in Watt).
- $\epsilon_{\text{bearings}}$: The residuals of power caused by rolling resistance of bearings.
- $\epsilon_{\text{gearbox}}$: The residuals of power caused by resistance in the gearbox.
- $\epsilon_{\text{slip}}$: The residuals of power caused by slip.

\[
P_{e \text{actual}} = P_{e \text{required}} + \epsilon_{\text{bearings}} + \epsilon_{\text{gearbox}} + \epsilon_{\text{slip}}
\]  
\[ (14) \]

Where $\epsilon_{\text{slip}}$ can be explained as:

\[
\epsilon_{\text{slip}} = \Delta T_{1,2} \cdot (v^{\text{roll}} - v^{\text{strip}})
\]  
\[ (15) \]

An assumption in the model is that the electromotor does not deteriorate. This assumption is made based on the knowledge of specialists at TSP.

The actual amount of power that the electromotor uses can be influenced by increasing rolling resistance in the bearings, by increasing resistance in the gearbox, and by slipping. At all three instances; the power will go up as resistances and slip increases. An exceptional high power usage of an electromotor (in comparison to its average values and the other bridle roll(s) in the same bridle section) can trigger an inspection in the next planned stop. Inspections can involve:

- Feeling or measuring the bearing-house temperature. Compare it to temperature of other bridle rolls’ bearing houses in the bridle section.
- Checking slip (as discussed in chapter 8).
- Inspecting the gearbox.
- Inspecting the electromotor.

Data

Unfortunately, no data of the electrical power, $P_{e \text{actual}}$, is available, but data from a derivative from $P_{e \text{actual}}$ is. The operating and control system expresses performance of electromotors in torque. Then, the model in equation (14) can be written as:

\[
TQ_{\text{actual}} = \frac{TQ^{\text{roll}}}{g} + \epsilon_{\text{bearings}} + \epsilon_{\text{gearbox}} + \epsilon_{\text{slip}}
\]  
\[ (16) \]

Equation (16) is based on equations (8) and (9), where $TQ^{\text{roll}} = \Delta T_{1,2} \cdot r$. The operating and control systems of the ETLs express the torque in percentages. After studying the Siemens control system books of ETL13 and interviewing employees with different expertise related to process control, process data, IBA, and tension control, it remained unclear what these percentages represent. Also, based on values of relevant parameters at one single point in time, it is tried to calculate the percentages by hand. See Figure 49. Torque (TQ) is displayed in Nm in the control screen, but is not logged as a parameter. First, the calculation of TQ_SET, TQ_ACT, and TQ_Strip must be known before the data can be used.
Figure 49: Screen of control system for EB roll 1 in bridle section 1, where I_ACT is the used electrical current in Ampère.
Appendix I  Data collection from IBA database

The time window of process data
For ETL13, process data is logged in hourly files. This means that for one day there are 24 separate data files. Whenever the storage capacity for data reaches its limit, the oldest data files are being deleted. In practice, this means that the time window for which data is logged is a rolling time window. For every new day of data that is being logged (the present day), the oldest day of data is removed. For ETL13 this time window is only approximately 2 years. Figure 50 shows an overview of the replacements of EB rolls of these bridle sections and the current availability of IBA data. A blue cross indicates the replacement of the EB rolls of the bridle section. Only the replacement of EB rolls of bridle section 1 are captured in the currently available data. No full used lifetime of an EB roll is captured in these data.

Data of process parameters is being logged every 0.02 seconds. Extracting data for every 0.02 seconds will result in 180,000 values per hour for every parameter. The amount of collected data is based on the amount of time it takes to extract data. The bottle neck (in sense of time) for the extraction of data turned out to be loading data files into IBA Analyzer. One hourly data file is approximately 140 megabytes large. With trial and error, it turned out that loading 24 data files at once (for one day) took at least 10 minutes, after which the not responding program was forced to quit. Loading 2 data files (2 hours of data) turned out to be feasible. For each day for which data needs to be collected, the data files need to be manually searched for, opened, exported, and saved. There was data for 770 days. However, it is chosen selects days with steps of four days (1/10/14, 5/10/14, 9/10/14, and so forth). Thus, for the sake of available time for this research project 2 hours of process data are collected once every four days. Furthermore, instead of extracting a value every 0.02 seconds it is decided to extract a value for once every minute, since the processing of coils can take from 10 minutes to over 30 minutes, depending on the size of the coil. IBA Analyzer automatically takes the average of all the 3,000 values that are measured in this minute when data is exported from IBA Analyzer.

Measuring in a stable system
When the steel strip accelerates or decelerates, tension in the strip is influenced by mass-inertia and of course the speed changes. When comparing different measurements of different production orders, it is important that all the values are measured in a stable system. The question is, what defines a stable system? A stable system is characterized by several things such as the entry loop (buffer) that needs to be full and the exit loop (buffer) needs to be empty. This will enable an equal strip speed

\[ \frac{60}{0.02} = 3,000 \]
throughout the entire ETL. When one of the buffers is moving, strip speed will differ between the entry-, process-, and exit section. It is decided that the most straightforward way to collect data of a steady system is to use measurements when a coil of steel is halfway processed. This is done by using Excel VBA.
Appendix J Load balancing principle

For every production order there are predefined values for the required tension and the preferred speed. Denote $T_i$ as the tension in the steel strip in production line section $i$ in N/mm$^2$. Then, the difference in tensions $T_i$ and $T_{i+1}$ is denoted with $\Delta T_{i,i+1}$, where:

$$\Delta T_{i,i+1} = |T_{i+1} - T_i|$$

A bridle section that is situated in-between sections $i$ and $i + 1$ needs to create a tension differential that is equal to $\Delta T_{i,i+1}$. The load balancing principle determines the tension differential each of the bridle rolls in the bridle section has to generate in order for the bridle section to create the total $\Delta T_{i,i+1}$.

From equation (4) on page 21; a bridle roll can maximally affect the tension with the factor $R = e^{\alpha \cdot \mu}$ where $\alpha$ is fixed for every bridle roll but can vary among different bridle rolls. Therefore, $R$ differs among bridle rolls. The load that is put on each of the bridle rolls (in the same bridle section) will have the same ratio as their $R$. This will be illustrated by a numerical example.

A bridle section consists of 2 bridle rolls, denoted with 1 and 2. The first bridle roll has $R_1 = 1.5$ and the second bridle roll has $R_2 = 2$. When the incoming tension $T_1$ is 500 N, this bridle section can create a maximum outgoing tension $T_2$ equal to $500 \cdot 1.5 \cdot 2 = 1,500$ N. Now, if the outgoing tension only needs to be 1,000 N, what is the tension differential (load) created by each of the two bridle rolls?

$$T_2 = T_1 \cdot R_1 \cdot R_2$$

$$1000 = 500 \cdot 1.5 \cdot 2x$$

$$x = \sqrt{\frac{1000}{1500}} = 0.816$$

Thus, bridle roll 1 multiplies the tension with $1.5 \cdot 0.816 = 1.225$ and bridle roll 2 multiplies the tension with $2 \cdot 0.816 = 1.633$. Check: $500 \cdot 1.225 \cdot 1.633 = 1000$. 

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Appendix K  The calculation of peripheral speed

As discussed in paragraph 8.2, the peripheral speed of EB $(i, j)$ at time $t$, $v_t^{(i,j)}$, is not being measured directly but instead is being calculated by the operating and control system. Input for this calculation are the rotational speed of the electromotor’s shaft which is being measured continuously, the gear ratio which is fixed, and the radius of the EB roll which is also fixed.

The input variables are denoted by:

- $n_t^{(i,j)}$  The rotational speed of the electromotor of bridle roll $j$ in bridle section $i$ at time $t$ (in rpm).
- $g^{(i,j)}$  The gear ratio of bridle roll $j$ in bridle section $i$, where $g = \frac{\text{rotational speed of electromotor}}{\text{rotational speed of EB roll}}$.
- $r^{(i,j)}$  The radius of EB roll $j$ in bridle section $i$ (in m).

To calculate the peripheral speed of an EB roll using these input variables, the periphery and the rotating speed of the EB roll’s shaft must be known. The periphery of EB roll $(i, j)$ is calculated according to equation (17).

$$ \text{periphery of EB roll } (i, j) = 2\pi r^{(i,j)} $$  \hspace{1cm} (17)

Since $v_t^{(i,j)}$ is expressed in meters per second, the rotational speed of the EB roll’s shaft must be expressed in seconds. Since the operating and control system measures the rotational speed of the electromotor in rounds per minute and the gearbox in-between the electromotor shaft and the EB roll’s shaft reduces the rotational speed, the rotational speed of the EB roll becomes:

$$ \text{rotational speed of EB roll } (i, j) \text{ at time } t = \frac{1}{60} \cdot \frac{n_t^{(i,j)}}{g^{(i,j)}} $$  \hspace{1cm} (18)

Now, $v_t^{(i,j)}$ can be calculated by multiplying the periphery with the rotational speed of the EB roll. See equation (19).

$$ v_t^{(i,j)} = 2\pi r^{(i,j)} \cdot \frac{1}{60} \cdot \frac{n_t^{(i,j)}}{g^{(i,j)}} = \frac{\pi \cdot r^{(i,j)} \cdot n_t^{(i,j)}}{30 \cdot g^{(i,j)}} $$  \hspace{1cm} (19)
## Appendix L  
Data of diameters of EB roll bodies before and after usage

<table>
<thead>
<tr>
<th>Bridle roll ( (i, j) )</th>
<th>Lifetime (days)</th>
<th>Diameter before usage (mm)</th>
<th>Diameter after usage (mm)</th>
<th>Difference (mm)</th>
<th>Difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1,1</td>
<td>514</td>
<td>746</td>
<td>747.25</td>
<td>-1.25</td>
<td>-0.17%</td>
</tr>
<tr>
<td>1,1</td>
<td>84</td>
<td>741.8</td>
<td>741.8</td>
<td>0</td>
<td>0.00%</td>
</tr>
<tr>
<td>1,1</td>
<td>1</td>
<td>739.55</td>
<td>739</td>
<td>0.55</td>
<td>0.07%</td>
</tr>
<tr>
<td>1,1</td>
<td>632</td>
<td>743.65</td>
<td>744.11</td>
<td>-0.46</td>
<td>-0.06%</td>
</tr>
<tr>
<td>1,1</td>
<td>483</td>
<td>755.94</td>
<td>759.7</td>
<td>-3.76</td>
<td>-0.50%</td>
</tr>
<tr>
<td>1,2</td>
<td>84</td>
<td>755.5</td>
<td>754.2</td>
<td>1.3</td>
<td>0.17%</td>
</tr>
<tr>
<td>1,2</td>
<td>632</td>
<td>748.55</td>
<td>749.12</td>
<td>-0.57</td>
<td>-0.08%</td>
</tr>
<tr>
<td>1,2</td>
<td>483</td>
<td>745.65</td>
<td>745.91</td>
<td>-0.26</td>
<td>-0.03%</td>
</tr>
<tr>
<td>1,3</td>
<td>84</td>
<td>744</td>
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<td>0.08</td>
<td>0.01%</td>
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<td>1,3</td>
<td>322</td>
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<td>761</td>
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<td>0.02%</td>
</tr>
<tr>
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<td>739</td>
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<td>0.02%</td>
</tr>
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<td>762.87</td>
<td>-0.57</td>
<td>-0.07%</td>
</tr>
<tr>
<td>1,3</td>
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<td>754.7</td>
<td>-1.87</td>
<td>-0.25%</td>
</tr>
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<td>749.21</td>
<td>2.59</td>
<td>0.34%</td>
</tr>
<tr>
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<td>726</td>
<td>746.1</td>
<td>745.45</td>
<td>0.65</td>
<td>0.09%</td>
</tr>
</tbody>
</table>

*Table 31: Data concerning the diameter of used EB rolls for bridle sections 1, 2, and 3.*

![Figure 51: The change of the diameter over the cycle time of EB rolls in bridle section 1.](image-url)
Appendix M  Costs of preventive and corrective maintenance actions

**Maintenance costs of process rolls in general**

When looking at maintenance of process rolls, three types of costs are distinguished; costs of repair, costs of labor, and downtime costs. These three types are discussed below for process rolls at TSP.

Denote $c_{r}^{\text{repair}}$ as the costs of repairing process roll type $r$. This includes transportation from and to the repair shop of IJssel Technologie. Common repair activities are replacing bearings and grinding, sending, or recoating the process roll’s body. Repair costs are incurred for both corrective and preventive maintenance actions.

Denote $c_{r}^{\text{labor}}$ as the labor costs of replacing process roll type $r$. These costs are only made when a process roll is replaced preventively. All preventive maintenance actions on a production line take place during revisions. Because of the temporary high need for workers, Tata Steel outsources the preventive replacements of process rolls to external companies and labor costs are made. When a process roll is being replaced correctively, it means that the replacement is not planned and employees of Tata Steel need to perform the replacement. Even though Tata Steel pays these employees on a monthly base, no labor costs are assigned to corrective maintenance actions of process rolls and the costs of these employees are considered as overhead costs at TSP.

Denote $c_{r}^{\text{downtime}}$ as the downtime costs for replacing process roll type $r$. Downtime costs are only accounted for when process rolls are being replaced correctly and consist of the hourly costs of being down and fixed costs for every stop due to steel strip that is rejected and is sold for a lower price or got scrapped. Preventive replacements are performed during revisions and in general, the duration of such a revision is fixed. This means that when more maintenance actions (of any kind) need to be performed in one revision, more external workers will be hired to perform these maintenance actions. The number of preventive process roll replacements to perform during one revision is assumed to not influence the duration of the revision and therefore no downtime costs are made directly for each preventive process roll replacement.

Denote $c_{r}^{\text{cr}}$ as the costs of a corrective replacement for process roll type $r$. Then:

$$c_{r}^{\text{cr}} = c_{r}^{\text{repair}} + c_{r}^{\text{downtime}}$$  \hspace{1cm} (20)

Denote $c_{r}^{\text{pr}}$ as the costs of a preventive replacement for process roll type $r$.

$$c_{r}^{\text{pr}} = c_{r}^{\text{repair}} + c_{r}^{\text{labor}}$$  \hspace{1cm} (21)

**Maintenance costs of EB rolls**

The average costs of repair for one EB roll, $c_{EB}^{\text{repair}}$, equals €3,370. The costs of labor, $c_{EB}^{\text{labor}}$, are based on 2 workers of each €50 per hour. $t_{EB}^{\text{replacement}}$ denotes the time (in hours) it takes to replace a process roll. Depending on where a bridle section is positioned in a production line, $t_{EB}^{\text{replacement}}$ can vary from 3 to 8 hours equaling €300 to €800 labor costs, respectively.

$$c_{EB}^{\text{labor}} = t_{EB}^{\text{replacement}} \cdot 100$$  \hspace{1cm} (22)

Downtime after failure takes at least 3 hours (including shutting down and starting up the production

\hspace{1cm}

30 Costs of material, such as the use of a crane, are not accounted for and are considered general overhead costs for TSP.
line). With an hourly downtime costs of €6,000 (for ETL13) and fixed downtime costs of €1,000, the minimum downtime costs are €19,000:

$$C_{EB}^{down} = t_{downtime} \cdot 6,000 + 1,000$$  \hspace{1cm} (23)

For every bridle section, all the EB rolls are always replaced at the same time. When replacing a set of EB rolls, $C_{EB}^{labor}$ and $C_{EB}^{downtime}$ are only made once for the entire set of EB rolls. In ETL13, the number of EB rolls per bridle section are either 2, 3, or 4. Denote $x_{EB}$ the number of EB rolls in a bridle section. Then, the estimated costs of replacing the EB rolls for that bridle section correctly and preventively are:

$$C_{EB}^{cr} = x_{EB} \cdot 3,370 + t_{downtime} \cdot 6,000 + 1,000$$  \hspace{1cm} (24)

$$C_{EB}^{pr} = x_{EB} \cdot 3,370 + t_{replacement} \cdot 100$$  \hspace{1cm} (25)

Remember that $t_{downtime}$ includes shutting down and starting up the production line for a corrective replacement and that $t_{replacement}$ only includes the actual replacement of the process roll while the ETL is already shut down. When assuming that the time it takes to perform the replacement of a set of EB rolls is the same for both corrective and preventive replacements;

$$t_{downtime} > t_{replacement}$$  \hspace{1cm} (26)

Combining the equations (24) and (25) with (26), it can be concluded that the costs of a preventive replacement are significantly lower than the costs of a corrective replacement.
Appendix N  Probabilistic failure characteristics

There exist four related probability functions to describe the failure process of equipment; the cumulative distribution function, the probability density function, the reliability function, and the failure rate function. The failure rate function is used to select maintenance policies. The other functions are for example used to calculate expected costs of maintenance policies and to optimize a TBM maintenance policy.

Denote continuous random variable $T$, with $T \geq 0$, as the time to failure of a component. For a component that has $n$ different independent failure modes, each failure mode can have a different time to failure distribution. The cumulative distribution function of $T$ is the probability that the component fails before time $t$, where:

$$F_T(t) = P(T \leq t) = \int_0^t f_T(x)dx$$  \hspace{1cm} (27)

The probability density function of $T$ is:

$$f_T(t) = \frac{dF_T(t)}{dt}$$  \hspace{1cm} (28)

The reliability at time $t$ is the probability the component survives beyond time $t$ (also called survival function):

$$R(t) = 1 - F_T(t) = \int_t^\infty f_T(x)dx$$  \hspace{1cm} (29)

Failure rate (also called hazard rate) at time $t$ describes the likeliness that the component will fail in the next small time interval, relative to the length of that time interval (instantaneous expected number of failures per unit time).

$$\lambda(t) = \frac{f_T(t)}{R(t)}$$  \hspace{1cm} (30)

An example of how these four functions relate to each other is shown in Figure 52. For this example, a Weibull distribution with shape parameter $\beta$ and scale parameter $\theta$ is used.

![Example of the four functions](image)

Figure 52: Example of how PDF, CDF, reliability, and failure rate are related.