Asset Management of Railway Tracks Using Stochastic Petri Nets

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Maintenance Engineering, master's level (120 credits)
2019

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Acknowledgements

The past six months will always be remembered as the time I learned to do research. The greatest learning that I extracted is that, it’s never complete. The deeper I go, the more it expands. I tried my best to do justice to the limited span of time I had for my master’s thesis. Overall, it was a challenging, sometimes overwhelming but a very enriching experience.

I would thank Prof. Uday Kumar, the head of the Division of Operation and Maintenance, for giving me the opportunity to work within the field of Asset Management and providing me with constant encouragement and guidance. Prof. Alireza Ahmadi, my examiner, redefined the role of an examiner in a master’s thesis. I cannot thank him enough for his expert insights that caught me off-handed at times, but without them, my project would lack a lot of direction. I would like to thank Johan Odelius, for his guidance with the process of doing a master’s thesis. He took care of all the administrative hurdles seamlessly.

My journey would not be the same without my supervisor Dr. Adithya Thaduri. He always set high objectives for me and guided me through the entire process towards completion. Apart from sharing his technical expertise in modelling, data processing and railways, he has also provided constant guidance, in the processes, structures and methodologies of compiling, and presenting my work. In between endless sessions with him, I somewhere completed my thesis successfully and, got numerous lessons for my future in research.

An incidental encounter with Prof. Pierre Dersin at the eMAintenance Conference was an important milestone in my project. His suggestion on Petri Net tools proved to be very useful for me. At this point, I also owe a vote of thanks to Prof. Ramin Karim and Miguel Castano, for giving me the opportunity to present my thesis at the eMaintenance Conference.

There are a lot of people who are not on the record, but without their support it wouldn’t have been possible. My sincere thanks to Iman Soleimanmeigouni, Hamid Khajehei and Praneeth Chandran, PhD students from the Division of Operation and Maintenance without whom I would never have been able to solve the mystery of data to any extent! Ignacio Gutierrez, a classmate, a friend and also the opponent to my master’s thesis deserves a thank you for sharing this journey together! Each person in the Division of Operation and Maintenance has helped or inspired my work in one way or another. It was great to be the part of such a wonderful group.

In the end I would thank my parents, my husband Nishant and my children, Ansh and Risha, for making me the person I am and for believing in me every day. They are responsible for every ounce of effort that comes from me!

I hope you enjoy reading this thesis. In case of comments or questions, please feel free to contact jaya.elec@gmail.com
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Abstract

Railways are one of the most important transport systems. It is crucial to have a rail network that is safe, reliable and available. Asset Management for railways involves the optimization of the maintenance activities based on asset condition, life cycle cost and availability of equipment. Irregularities in the track cause the wear of rail resulting in passenger discomfort, speed restrictions and line closures. The track is inspected for these irregularities and corrected using a tamping vehicle. The degradation behavior of the track can be modelled to predict the future degradation. This prediction forms the basis of the maintenance planning based on the expected track condition. A petri net model can be used to simulate the track degradation, inspection and maintenance process over a period of 20 years, and the outputs of the model are used for LCC analysis. Further, the cost is optimized with the safety risk to suggest maintenance threshold levels and Inspection Interval. The proposed methodology will assist the maintenance decision system for Asset Management of Railway track, which is strategic and cost effective. This methodology is demonstrated using a case study of a Line 414 in Sweden, by modelling the track behavior with Standard Deviation of Longitudinal Level. It can be further expanded and adapted for maintenance planning for similar assets within railways.

1 Introduction

Engineering Asset Management is a field, developed to integrate the established concepts in technology and management and adapt them for efficient management of engineering assets. It is a combination of science, engineering and technology to manage the life cycle of physical assets. The scope of Engineering Asset Management (EAM) is wide and complex, therefore it is important to adopt an interdisciplinary approach. It has a broader perspective and though Maintenance planning and management is a major part of Asset Management, it is not limited to this.

The two main pillars in the field of EAM have been the development of Information and Communication Technology (ICT),(1) to acquire, manage and analyze data from Assets i.e. Condition Monitoring of assets to detect early failures, and (2) to integrate the different Asset Management systems for decision making (Prescott, Andrews, 2013). However, this concept of short-term focus on profit is observing a paradigm shift. EAM is now seen as a communication channel between business requirements and practical engineering.

Engineering assets for e.g. manufacturing equipment, land, infrastructure etc. form the foundation of a business structure. All other assets like shares, insurance policies, etc. in the business are generated from the engineering assets. The value of an asset can be expressed in terms of its operating capacity and in terms of its financial value (Prescott, Andrews, 2013). These two value indices are however, interrelated. The financial value of an asset can be calculated only by the profit it generates, which in turn is a derivative of the operating capacity of physical assets.
The emerging concept of EAM is broader in terms of both, the types of assets, and the management goals. It encompasses all types of physical assets, including manpower, it includes short term operational plans and long-term business strategies and the qualitative as well as quantitative analysis of assets. The management goal can vary across organization from maximizing profit to reducing safety risks and/or mitigating environmental damage.

Any technical, administrative or management action taken to ensure the defined functioning of an asset is termed as maintenance (Tzanakakis, 2013). Maintenance can be carried out at pre-determined intervals, called preventive maintenance, or after a fault has occurred, known as corrective maintenance. Sometimes maintenance is also done to improve the productivity or life of an asset, known as Improvement maintenance.

The status of maintenance in an organization can be tracked down with pre-determined Key Performance Indicators (KPIs) like number of unplanned breakdowns, inventory management, equipment downtime, resource allocation etc., depending on the prioritization of the KPI within the organization. These KPIs help manage the maintenance by evaluation, analysis, comparison, identification and decision strategy formation. The Maintenance Management system follows specific standards like NP13460, EN13306 (Tzanakakis, 2013) which are defined by basic maintenance concepts, technical documentation and the formulae for the KPIs.

Engineering Asset Management in current scenario is based on meeting specified business requirements by using condition monitoring and predictive maintenance strategies. With the development in ICT and expert decision modelling, it is evident that this field is under transition from a reactive to a proactive approach where it predicts, optimizes and enhances the asset productivity and suggests business improvement measures to the user. This paper starts to understand the basic concept of Asset Management and Maintenance Management. It goes on to explore the trends in technology and management that can have direct impact on Engineering Asset Management framework.

It can be challenging to try to distinguish MM and EAM with concrete and separate definitions. Based on business needs and cost models, one gradually expands or contracts into the other. Service providing is a cutting-edge business factor in today’s economy. A supplier of an engineering asset, with a lifetime management assurance, owing full responsibility from the stage of installation to Disposal creates a sense of security and trust build up in the user. On the other hand, a provider with only a maintenance support contract on failures, reflects uncertainty in business. This kind of service is suitable only for short term business models with high cost constraints. Although maintenance is the key service that is provided, in both the scenarios, the differentiating factor is in the way it is handled. The computerized maintenance management system (CMMS) approach or the EAM can be a superset or an expansion of traditional maintenance management. It uses the concepts of condition monitoring and condition-based maintenance to improvise on the design, maintainability, reliability, planning, operability and profitable disposal of the Asset.

Maintenance Planning for railway track geometry is a complex process that needs to consider an optimized combination of maintenance threshold levels, inspection intervals, maintenance intervals and renewal time. Swedish railway network is used for the transportation of passengers...
and goods. It is a complex system that must consider passenger’s safety, cost constraints and the impact on the environment. As the volume of traffic increases, it is important that the infrastructure is maintained effectively to ensure high performance and low risk in terms of safety and cost. The performance of the Railway Infrastructure is dependent on the decisions taken regrading maintenance and renewal throughout the life cycle. The Life cycle Cost (LCC) and Reliability, Availability, Maintainability and Safety (RAMS) need to be considered while making the decisions in the operation and maintenance phase. Asset Management is a term that is important for a sector such as railways with a huge network of infrastructure, where the cost and performance have a nationwide impact. Asset Management for railways focusses on

1) Optimizing and scheduling maintenance and renewal activities based on asset condition, life cycle cost and availability of assets.
2) Integrating the operational, organizational and the strategic levels.
3) Studying the degradation and failure of assets for informed decision making.

Asset management ensures planned maintenance which reduces the effort and minimizes the total Life Cycle cost. According to Lasting Infrastructure cost Benchmarks (LICB), the railway infrastructure consists of Ground Area, Track, track bed, bridges and tunnels, level crossings, the superstructure, access ways, signaling systems, lighting installations and power plant (Grzanka, September 2010).

This thesis proposes a maintenance plan methodology for Railway Track using petri nets by discussing a case study of line 414 in Sweden. This study assumes exponential degradation of the track geometry with time and models the inspection and maintenance response processes using stochastic petri nets. The states in the Petri Net model represent different stages of track degradation, the stages of track inspection and the stages of maintenance intervention. The transition times are the times spent in each of these stages which can be expressed either by a time distribution or by a constant value.

The model parameter considered to represent the track degradation is Standard deviation of longitudinal level alignment of the railway track; a track geometry parameter which has considerable impact on track degradation. The only maintenance action considered here is the tamping process, which measures the track geometry and corrects it by packing the ballast under the sleepers. Each tamping action also damages the ballast to some extent, consecutively increasing the degradation rate after each tamping, however, tamping effectiveness is not included in the model in terms of number of tamping actions at this stage. The tamping process is assumed to improve the ballast condition but not to as good as new.

The input to the model is transition times between threshold levels, which is varied in different runs by varying the threshold levels. Another variable input to the model is the inspection interval which is a constant time value. The maintenance response times are assumed to be constant in different runs of the model. The output of the model is the total number of interventions required over the simulation period, (60 years in this case) which is the sum of number of tamping actions, number of speed restrictions and number of line closures. The Life Cycle Cost of the asset is calculated based on these output values, based on specified cost
parameters. It provides the input in terms of multiple combinations of threshold levels and Inspection Interval, which can be used as input for maintenance planning.

1.1 Research problem
A safe, comfortable and reliable railway infrastructure is the requirement for traffic operators. To achieve this, the railway infrastructure needs to be continuously monitored, improved and maintained. With prolonged usage, the track geometry degrades, because of ageing, dynamic loading, weather conditions, moisture in ballast etc. The irregularities in track due to degradation, causes discomfort in riding and in extreme cases, it can also lead to derailment. This creates the need for a cost-effective maintenance decision support model for the infrastructure. The main maintenance decision includes, how often does the infrastructure need to be monitored, when does the infrastructure need maintenance, how and when the maintenance action will be carried out, when has the infrastructure reached a point when it needs to be renewed and cannot be maintained further. The LCC analysis of these decisions leads to suggestion of a strategic and cost-effective model for the infrastructure. For ballasted track, geometry degradation is the main ageing factor which calls for periodic intervention, to restore the initial or best possible track geometry. These interventions might include tamping or stone blowing which incur a certain cost and are dependent on availability of the vehicle as well as the track to be maintained. Therefore, this needs to be planned months in advance. Suggesting an optimum preventive maintenance strategy for the railway track has huge benefits in terms of cost effective and improved maintenance decisions.

1.2 Research Objectives
The purpose of this thesis is to develop a methodology for the Asset Management of Railway Infrastructure, considering the Life Cycle Cost.

The research objective is to optimize a cost-based maintenance plans for Railway Track considering, maintenance thresholds, Inspection Intervals and Renewal period.

1.3 Research Questions
Based on the literature survey in the field of Asset Management for railways, the research questions considered in this thesis were

1) How can varying the maintenance threshold levels affect the maintenance cost?
2) How can varying the inspection interval affect the maintenance cost?

1.4 Scope and Limitations
1.4.1 Scope
1. The methodology is developed on the data for Track Section 414 in Sweden.
2. The methodology is developed for the Asset Management of railway track only.
3. The effect of drainage on ballast conditions are not considered
4. Only normal degradation of the track is considered, the effect of isolated defects on track geometry parameters is not considered.
1.4.2 Limitations

1. Standard Deviation of Longitudinal Level (SDL) is the parameter considered to monitor the condition of track geometry, because the increase in SDL best indicates the need to improve the track geometry.

2. Degradation Model is not developed in this study. Based on literature survey, the track is assumed to degrade linearly.

3. Tamping is the only maintenance action considered in this study as it is the most commonly used automatic maintenance equipment for railway track.

4. The degradation of the track after first tamping follows the same trend as the degradation of the track after any number of tamping actions in this study.
2 Concepts and Background

2.1 Railway Track

The main function of the railway track is to guide the train. The components of a ballasted track structure are rails, sleepers, fasteners and ballast as the superstructure and sub ballast and subgrade as the sub structure (Figure 1).

The Rails are steel parts which distribute the concentrated load from the wheel to the sleepers and guide the wheels of the train. Sleepers connect the two rails and transfer the load received from the rails to the ballast. The ballast is the crushed stone layer that provides support to the sleepers. It transfers the load to the sub structure levels, provides a drainage structure and can be restructured for maintenance purposes.

2.2 Track degradation

Irregularities, in the track structure or track geometry, create imbalance in the dynamic forces which leads to wear of the rail. This is transferred from fasteners to ballast to the substructure, disrupting the entire track system. The main causes of track deterioration are static and dynamic forces by the load, the influence of climatic temperature, ice and water and faults in the system design (Tzanakakis, 2013). The deterioration of the rail happens by a complex interaction between the load and characteristics of the running vehicle, the contact between the wheel and the rail, and other external factors. The degradation can happen in terms of wear and cracks on the surface of the rail, wear of fasteners, ballast settlements and sub grade degradation. The fasteners and sleepers degrade because of the acting forces and moments on them. The restructuring of the ballast, due to the vehicle load on rails, or due to maintenance actions by a tamping or stone blowing machine, deteriorates the ballast condition. This adversely affects the drainage condition of the ballast, weakening the sub-grade. The settlements in the sub-grade are realized as irregularities in the track geometry, causing passenger discomfort and safety risk.

Figure 1: A Typical Structure of Railway Track
2.3 Track Geometry
The condition of the track can be represented in terms of the track structure and the track geometry. Track geometry refers to the 3-dimensional geometry of the track. The 5 parameters to measure the track geometry are (Soleimanmeigouni, Ahmadi & Kumar, 2018)

- longitudinal level- the track center line projected on the longitudinal vertical plane.
- alignment- the track center line projected on the longitudinal horizontal plane.
- gauge-the distance between the inner part of one rail to the inner part of another rail at a point.
- Cant -the distance between the elevations of the top surfaces of two rails at a point.
- twist- twist is the numerical difference between cant at two different points, which is expressed as the changing value between two different points.

The longitudinal level, cant and twist are vertical measures of the track, while alignment and gauge are horizontal measures. Every rail network has specified acceptable limits for these track geometry parameters. The track condition is measured against these threshold values. The threshold values are generally dependent upon the permissible speed of the train for that line. The higher the speed, the lower is the acceptable limit of deviation. The standard deviation of the short wavelength(3-25m) longitudinal level, is the main degradation parameter in this report.

![Track Geometry Parameters](Figure 2:Track Geometry Parameters: (Sadeghi, Heydari & Doloei, 2017))

2.4 Inspection and Maintenance
The inspection of the railway track is done by a measuring train. The measuring train moves along the network, recording the track geometry conditions. For each track, the measuring frequency might depend on the availability of the track and the measuring vehicle. Generally, measuring frequency is schedule during the maintenance planning.

The irregularities in the track geometry appear due to the degradation and settlements in the ballast. The easiest way to correct the track geometry is to repack the ballast structure under the
sleepers. This is done by processes like tamping, stone blowing and manual interventions for localized irregularities. A stone blowing machine measures the track irregularities and lifts the track to the desired position. It inserts small pieces of rock from the stone blower, to fill the void in the ballast and hold the track in that position that doesn’t damage the ballast. (Prescott, Andrews, 2015)

A tamping machine also measures irregularities and required adjustments in the track. It lifts the track and squeezes the ballast inside the sleepers by using its vibrating tines and provides support to the track after it is released. The desired track geometry is attained in this manner. However, the tamping process damages the ballast to some extent while applying pressure to the ballast. This weakens the closed packed structure of the ballast and induces drainage problems in the system, increasing the degradation rate of the track in the long run. A track which has been maintained by stone blowing once, cannot be tamped. The small stones injected in stone blowing might move down to the sub ballast layer while tamping, thus damaging the entire structure.

2.5 Research Methodology
The research methodology is shown in Figure 3. The Research consists of primarily two areas. In the initial phase, literature survey and background concepts on Asset Management, Railways, Track Geometry and related concepts was established. In the second phase a methodology for Asset Management was suggested with the help of a case study.

![Figure 3: Research Methodology](image)
3 Case Study

3.1 The Line Information

The maintenance model has been built for the data from Line 414, between Katrineholm and Järna central stations (Figure 4). This line is the part of the Western Main Line is Sweden (Västra Stambanan), which runs between two major cities, Stockholm and Gothenburg. The train speed on the Western Main Line is limited to 200km/hr. The Line 414 is 82 kms long. The standard deviation of longitudinal level is measured over around 200 m track segment of the line. The length of the track section varies based on the type of the track. The sections can sometimes be smaller like 110m or larger like 210m depends on the type of object such as Switches and crossing, curve, transition curve, etc. They are not only segregated by a specific length, but also since each track segment should logically be an individual entity.

The measurement data on the line is collected between 2008 to 2018 by OPTRAM. OPTRAM is the Swedish Measurement Administration system which is responsible for studying and analyzing periodic measurements for railway tracks. The measurement vehicles used were Strix, IMV100S, IMV100M, IMV100N and IMV200 as shown in Table 1. The measurements are available in both directions of the line.

Table 1: Use of measurement vehicle by OPTRAM

<table>
<thead>
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<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Choice 1</td>
<td>Unknown</td>
<td>Strix</td>
<td></td>
<td></td>
<td></td>
<td>IMV200</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Choice 2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>IMV100S, IMV100N, IMV100M</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

3.2 Data Pre-Processing

The measurement data obtained by OPTRAM contains the measurements of the track geometry parameters sorted by a Segment ID for each track segment of varied lengths. Details about the track segment, like the track start and end, the type of track, measurement date, measurement direction, measuring vehicle etc. are specified. The data pre-processing for this report was limited to the value of Standard Deviation of Longitudinal Level (SDL). Since, the data contains values in up as well as down measuring directions, and from different measuring vehicles, it is difficult to extract a trend from the data. After the data is filtered to consider only one measurement vehicle for a specific amount of time as shown in Figure 5, the trendline becomes
smooth. There are certain values in the measurement that seem to be outliers. For example, in the data sample, Table 2, the degradation in SDL value is following a trend except for the 4th value, which jumps and drops back to the trendline. These kinds of values do not have any clear explanation. They may be considered as measurement error for the ease of processing, however there are other physical conditions on a track, like a missing fastener which can explain such values. The decision to consider or omit the outlier values depends on the robustness and flexibility of the degradation model.

Table 2: Sample of fluctuating SDL values

<table>
<thead>
<tr>
<th>S.No.</th>
<th>SDL</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.41415</td>
<td>5/4/2010</td>
</tr>
<tr>
<td>2</td>
<td>0.43272</td>
<td>6/15/2010</td>
</tr>
<tr>
<td>3</td>
<td>0.4173</td>
<td>8/17/2010</td>
</tr>
<tr>
<td>4</td>
<td>0.63821</td>
<td>3/9/2011</td>
</tr>
<tr>
<td>5</td>
<td>0.52817</td>
<td>6/21/2011</td>
</tr>
<tr>
<td>6</td>
<td>0.49832</td>
<td>9/1/2011</td>
</tr>
<tr>
<td>7</td>
<td>0.53833</td>
<td>11/17/2011</td>
</tr>
<tr>
<td>8</td>
<td>0.54497</td>
<td>3/4/2012</td>
</tr>
<tr>
<td>9</td>
<td>0.55925</td>
<td>6/25/2012</td>
</tr>
</tbody>
</table>

The thesis aims to derive a maintenance plan based on an available degradation model. Therefore, it does not explore the degradation process in detail with comparisons between the goodness of various models. Based on previous research and the observed trend in the given data, it was considered that the track follows a linear degradation. The linear regression model was used, with the time of measurement as the predictor variable X and the corresponding SDH value as the response variable Y.

After comparing the data with the recorded dates of Tamping action in a different dataset, it was observed that each tamping reduced the SDL value to a minimum of 80 percent of the value before tamping. Therefore, the tamping ratio was assumed to be 0.8 as shown in Equation 1.
**Equation 1: The Tamping Ratio**

\[
\frac{\text{SDL value after tamping}}{\text{SDL value before tamping}} \leq 0.8 \text{ (Tamping Ratio)}
\]

### 3.3 Extraction of Degradation Rate

For each track segment, the tamping interval was found based on the above criteria Figure 6. Each tamping cycle is a separate degradation cycle; therefore, each tamping cycle has a different degradation rate. This, in a way also accounts for the tamping effectiveness, as the degradation rates for each cycle are calculated from actual variations in the SDL over time.

![Figure 6: A plot of Standard Deviation of Longitudinal Level vs time in years, highlighting tamping intervals and depicting the rate of degradation](image)

### 3.4 Maintenance Modelling Techniques

This aim of this study is to develop a data-driven preventive maintenance strategy for the railway track. Preventive maintenance is carried out to ensure better operation with optimized cost. The preventive maintenance for the railway track can either be scheduled or condition based. In scheduled preventive maintenance, the maintenance activity, which in context of this paper is tamping, is carried out in fixed time intervals to restore the track to its original good state. Condition based preventive maintenance is done based on the track condition after each inspection (Sharma et al., 2018).

Corrective Maintenance is done when a fault is detected in specific points of the track after inspection. The maintenance activity in this case aims at restoring the track to the point to which it can perform the required function. Proposing an optimized maintenance strategy for preventive maintenance activities, helps prevent the risks of accidents, discomfort and derailments while also controlling the cost spent on maintenance of the track.

This thesis suggests a maintenance model for the railway track, based on degradation of the track in terms of the SDL value. The models discussed below are based on various stages of
degradation of the track that are defined based on the speed restrictions and safety thresholds for the track segment.

3.4.1 Cost Model for Maintenance
The cost model suggested by (Letot et al., 2016), assumes that the degradation model is known for a given track segment. It defines three threshold values for the SDL for the track.

1) Comfort Level
2) Speed Reduction
3) Line Closure

The costs in the model include

1) Cost of comfort level per unit time
2) Cost of speed reduction per unit time
3) Corrective maintenance cost for line closure
4) Preventive maintenance cost for tamping
5) The One-time cost for tamping machine usage

The analytical cost model calculates the total life cycle cost for preventive maintenance after fixed time intervals, by estimating the probability of being in the states of speed restriction and line closures using a Weiner Process. The limitation of this model is that, it does not take into consideration the inspection cost or the effect of varying the inspection time on the probability to reach degraded states without being detected.

3.4.2 Cost effective model for Inspection Interval
This model combines degradation, shock and recovery model of the track to predict the track geometry behavior in the long term (Soleimanmeigouni et al., 2016). It considers two threshold levels for the SDL of the track segment.

1) The limit for Corrective maintenance with a penalty cost
2) The limit for corrective maintenance with a larger penalty cost

The cost function considers

1) The tamping cost
2) The Inspection cost
3) The penalty cost for threshold 1
4) The penalty cost for threshold 2

It compares 4 inspection intervals based on the Total Cost Function output for each interval. However, it does not consider the factors like maintenance response times and the possibility of the track to degrade even after an Inspection before maintenance has taken place.

3.4.3 Markov Model
A Markov model consists of states and transition. The states are linked to each other with the transition paths. The different degraded conditions of the track can be the states of the Markov model, and the degradation model parameters to move from one condition to another can be the
The output of the model is the probability of being in a good state or other degraded states.

The Markov model proposed by (Prescott, Andrews, 2013) considers the fact that the degradation rate of the railway track is increased after each tamping action.

The model input parameters that were varied in this model were

1) The maintenance threshold limits
2) The Inspection Interval
3) The Renewal Time
4) The Maintenance Response Times

The Model Outputs were

1) Expected time in good state
2) Expected Time in Comfort Level State
3) Expected Time in Speed Restriction State
4) Expected Time in Line Closure State
5) Probability to perform a specific maintenance action

However, there are certain limitations of using a Markov Model for track degradation

1) The transition time distribution between states is limited to an exponential distribution
2) The probability to reach a state only depends on the previous state, and not how that state was reached.
3) A Markov chain for a process does not represent the structure of the design effectively, for any addition in the feature of the model, it needs to be revised completely.

3.4.4 Petri Net Modelling

Petri Nets are tools that can be used to a number describe several systems that are asynchronous, distributed, parallel, stochastic and non-deterministic. It is a graphical as well as a mathematical tool. As a graphical tool, it describes the structural flow chart of a system depicting different components and their interconnections. As a mathematical tool, it defines the flow of information between different components governed by an underlying mathematical equation.

It can be used to model a system both methodically and realistically for research as well as industrial purposes.

Petri Net originated from Carl Adam Petri’s dissertation in the year 1962 (Murata, 1989). Among other applications like industrial control systems, neural networks, concurrent and parallel systems etc. Petri Nets are also well suited for decision models.

To plan maintenance considering the track degradation, inspection and maintenance action, the time for degradation was extracted using a Weibull distribution in Andrews et al (Andrews, 2013). This distribution was used to substitute the transition time in the Petri Net model. The Inspection Interval and the threshold values were input variables. The output of this model was the percentage of times spent in different states and the number of interventions during the period of simulation. This thesis uses Petri Net modelling technique to suggest a maintenance model for the railway track.
3.4.4.1 Components of a Petri Net

A Petri Net is a bipartite graph that has places and transitions which are called nodes, connected by arcs. (Figure 7)

1) Places – A place represents the condition of a system. It is graphically represented as a circle.
2) Transitions – Transitions describe the event of movement of the system from one state to another. They are governed by underlying mathematical equations used to describe the type of transition. On the drawing area, it is graphically represented by a square.
3) Tokens – The presence of token in a state means that the system is in that state at a given time. The flow of token describes the movement of the system between states.
4) Arcs – They are the arrows connecting a place and a transition. They define the flow of tokens in the model. An arc never connects two nodes of the same type, i.e. a place to place or a transition to transition.

Arcs are of three types
1) Regular - Enables the flow of token from a place to a transition or a transition to a place in only one direction.
2) Bi directional- Enables the flow of tokens in both directions
3) Inhibitor- Inhibits the flow of tokens.

![Figure 7: A basic Petri Net Depicting places, transitions and tokens](image)

3.4.4.2 Enabling and Firing of Transitions

The enabling and firing of transitions in a Petri Net model, is the foundation of Petri Net theory. Each transition is an event that is connected to certain input and output places. The presence of token in a place can be interpreted in two ways, 1) the logical state of being in that place, 2) the number of tokens in a state represent the number of resources in that place. For the application in this thesis, the token represents the logical true or false of being or not being in a state.

The behavior of a system can be described as the states and the change in states of that system based on the following firing rules:

1) A transition is enabled only if all the input places have the minimum number of tokens specified by the weight of the arc connecting the respective place to the transition.
2) An enabled transition will fire only when the time condition on the transition is met
For example
- A transition with 0 time, will fire immediately as soon as the condition in (1) is met
- A transition with a constant time of 10 units will fire after 10 time-units of meeting the condition (1).
- A transition time with a normal distribution of time with a mean of 10 time-units may fire after any time between 1 to 10 units, after meeting condition (1).

3) When an enabled transition is fired, it moves token from each input place to each output place.

Some conditions for the flow of tokens are depicted in Figure 8, Figure 9 and Figure 10.

**Figure 8: flow of tokens 1**

**Figure 9: flow of tokens 2**

**Figure 10: flow of tokens 3**

### 3.4.4.3 Petri Nets Based on Firing Delays

**Untimed Petri Nets** – All the transitions fire one by one based on their occurrences. Only one transition fires at a time. In case of conflicting transitions, Figure 11 i.e. multiple transitions attached to the same input state, the transition fires based on the probability or priority that can be pre-assigned to them.
**T-Timed Petri Nets** – These are transition timed petri nets with minimum firing delays specified for the transitions. After a transition is enabled, it fires only after the delay. Transitions with no firing delays in a timed petri net are immediate transitions. In case of a conflicting transition, the transition with the lowest firing delay takes precedence.

### 3.4.4.4 Stochastic Petri Nets

The petri net model used for this thesis, is the Stochastic Petri Net, which can be understood as an extension of the T timed Petri Nets. The concept of time delay was introduced in Petri Nets to depict time dependent applications. The time delay was earlier only deterministic. Later in (Molloy, 1982), stochastic petri nets were introduced with exponential time distributions assigned to transitions. They were isomorphic to the Markov process which also uses exponential time distributions for transition between states. Followed by that, many evolved types of Petri Nets have been proposed for system analysis, which are generalized stochastic petri nets, extended stochastic petri nets, and the stochastic and deterministic petri nets (Ferreira et al., 2018). The working of Stochastic Petri Nets is the same as basic petri nets. The added feature is that it accommodates random time distributions for the time between the enabling and firing of a transition. The stochastic petri net used in this study, uses deterministic, immediate, normal and Weibull time distributions for the firing of transitions.

### 3.4.4.5 Petri Net Toolboxes

During this study, two toolboxes were used for implementing the Railway track maintenance model. The observation features and review of the toolboxes based on experience is shared below.

**MATLAB toolbox Petri net 2.4 features (Mahulea, Matcovschi & Pastravanu, 2018.)**

1) The PN toolbox can be integrated with MATLAB version R2015 and R2016.
2) The toolbox has a graphical user interface that is easy to follow (see Figure 12).
3) It is inbuilt with online help and demos.
4) Immediate, Deterministic and Stochastic transitions can be implemented with five types of Petri Nets, 1) Untimed 2) P-timed 3) T-timed 4) Stochastic 5) Generalized Stochastic.
5) The inhibitor and bidirectional properties of the arcs can be implemented.
6) The simulations can be run fast, run slow and run in steps for graphical analysis.
7) The simulation results can be recorded in a log file.
8) After a simulation, the place and transition performance indices are available for analysis.
Limitation of PetriNet2.4

1) Reset functionality cannot be implemented in the toolbox
2) Conflicting transitions do not work as per the theoretical functioning described for Petri Nets.

The above limitations can be overcome by customizing the toolbox with a specific code for the system in hand. However, for analytical purposes, it is more desirable to use a toolbox which is pre-programmed with all the basic features and can be plugged and played with the input variables.

Grif 2011-Petri Nets (GRaphiques Interactifs pour la Fiabilite)

The second toolbox used during this thesis was the Grif 2011 Petri Net (see Figure 13). The maintenance modelling in this report is implemented using Grif Petri Nets.

This was chosen because of the following features.

1) Easy to implement Graphical Design Interface.
2) Flexibility with multiple options in terms of time distributions for transition firing delays.
3) Effective firing of Conflicting transitions based on the shortest time.
4) Easy to edit, update and modify an existing model.
5) The ability to duplicate transition times at separate places.
6) Step and Fast simulations.
7) Running large number (~10000) of Simulations in seconds.
8) Effecting log creation and analytical tools
9) The ability to input Model Parameters in a database and retrieve directly for simulations.
10) A comprehensive display of results.
3.5 Track Model

3.5.1 The Degradation Process

The degradation process for the railway track is shown in Figure 14. It shows four states P1, P2, P3 and P4 which represent the different conditions of the track. T1, T2 and T3 are the transitions between the places.

Figure 14: Petri Net of the track degradation process

P1 - The good state, immediately after the renewal of the ballast. In this thesis, the good state is represented by SDL=0.6, based on the available data.

P2 – This is a degraded state needing maintenance. The threshold for SDL value for this state is defined as Alert Level (AL). The transition time distribution to reach the AL are expressed using Weibull parameters β1 and η1. These parameters describe the transition time t1.

P3 – This is a further degraded state needing speed restriction. This state is reached if the track is not maintained at the state P2. The transition time distribution for this state is expressed using
Weibull parameters $\beta_2$ and $\eta_2$. These parameters describe the transition time $t_2$. $T_2$ is a convolution transition as time distribution to reach this state is estimated based on the fact, that the track is already in condition $P_2$.

$P_4$ – This is the degraded state needing line closure. This state is reached if the track is not maintained at the state $P_3$. The transition time distribution for this state is expressed using Weibull parameters $\beta_3$ and $\eta_3$. These parameters describe the transition time $t_3$. $T_3$ is a convolution transition as time distribution to reach this state is estimated based on the fact, that the track is already in condition $P_3$.

![The distribution of SDL values at the beginning of the Life cycle](image)

**Figure 15:** A histogram showing the mean value of SDL after renewal for different track segments of the line 414

### 3.5.2 The Inspection Process

The degraded state of a track can be detected only when the measurement train runs on the track. The measurement train runs after a fixed time interval $I$. This recurrent running of the measurement train over the Life Cycle of the track is shown in Figure 16.

![The Inspection Process for Railway track](image)

**Figure 16:** The Inspection Process for Railway track

The place $P_5$ is shown to have a token. This means that at the beginning of the cycle, there is no section inspection in progress. The transition $t_4$ is enabled as there is token in the state $P_5$, but it will fire only after the specified interval $I$, which is the planned inspection interval for the railway track. After the transition $t_4$ is fired, a token is moved from the state $P_4$ and placed into
the state P6. The state P6 is connected to the states P2, P3 and P4 in the degradation process. When there is a token in any of the degraded states, at the same time when there is a token in P6, the degraded state is identified. After the degraded state gets identified, the token moves back to the state P5 and waits for the next section inspection cycle.

3.5.3 The Maintenance Process
The Maintenance Process for the railway track is shown in Figure 17. A token in the state P2 means that the track is in a degraded state needing maintenance. The transition t6 is an immediate transition. It is enabled when there is a token in the state P2 and the state P6 from the Inspection process, meaning that while the track is in a degraded state, there is a section inspection in progress. T6 fires immediately and places a token in the state P7, which means that the degraded state needing maintenance has been identified. The transition time t9 is the maintenance response time for the state P2. It is expressed by a normal distribution of expected response time for that state, based on the severity of the impact. The state P10 is the improved state of the track section after tamping. The section does not move to as good as new state after tamping, but to another state P10. The transition time t14 is expressed by the Weibull parameters b4 and n4 which describe the transition time distribution. As shown in Figure 19, the mean of the SDL values for different track sections is accumulated around 0.6-0.9. Therefore, the state P10 of improved section condition is assumed to be at SDL=0.8 mm for calculating the transition time distribution for t14. As tamping effectiveness is not considered directly in this study, the improved condition after any number of tamping can be assumed to be the same.

3.5.4 The Renewal Process
The renewal of the ballast happens when the ballast has completely exhausted its lifetime. The condition for renewal can either be a fixed lifetime ‘L’ or it can be based on number of tamping actions done on the track. In that case the ballast should be renewed after N tamping. In this study, the condition for renewal is a fixed lifetime ‘L’. At the beginning of the degradation process, there is a token in the good state P1, Figure 18.
The transition t16 is an immediate transition which fires as soon as token is placed in the state P1. The bi-directional arrows connecting P1 and t16 places a token each in the state P13 and back in P1. The inhibitor arc between P13 and t16 keeps the transition t16 from firing till there is a token in the state P13. The token in P1 goes through the degradation and maintenance process while the token in P13 goes through the renewal process. After a lifetime ‘L’ the transition t17 fires and places a token in the state P12 which initiates the renewal process. At this stage, the immediate transition t15 fires and places a token back in the good state P1, restarting the entire track life cycle again. The renewal process also resets the tokens in the model to start the process again with one token in P1 for degradation and maintenance process, one token in P13 for the renewal process and one token in the place P5 for the inspection process.

3.5.5 The Petri Net Model for a Track Segment
All the individual processes are combined to get the Petri Net model for a track segment in Figure 20. The transition times in the model are listed in the Table 6. Apart from the immediate
transitions, there are deterministic transitions with a constant time, like the Inspection and Renewal cycle transitions, and stochastic transitions with normal distributions for the Maintenance Response Times and Weibull Distributions for transition between different states of degradation. This is a basic model to simulate the degradation, inspection and maintenance process on a track. T12 and t13 are two additional transitions in the model that allow the track to degrade while it is in the state of waiting for maintenance. This model can be enhanced in several ways to get better and more lifelike simulations. A few of them are listed below.

1) The Renewal cycle can be dependent on the number of tamping, or ballast condition, instead of a fixed lifetime. Additionally, renewal can also be further classified into ballast cleaning or ballast replacement.
2) A reset transition can be programmed and implemented for renewal, which resets the model immediately after renewal.
3) The tamping effectiveness can be considered in the model by implementing a conditional transition based on the number of tamping actions on the track.
4) This study only considers SDL as the parameter for track geometry degradation. Other parameters can also be integrated in the model.
5) The degradation model can be improvised for accurate results.
6) Other maintenance actions than tamping can be considered in the model.
7) The effect of failure of other components of the railway track infrastructure on the track geometry can be considered in the model.

Figure 20: The Petri Net Model for the track section
3.5.6 Petri Net Model for the Line

In Andrews et al (Andrews, 2013) the extension of the model for a track segment to a Line model is discussed. This is done to enable opportunistic maintenance on the line. It is a very complex model which connects the individual track segments models for the line through the inspections cycle.

In this study, the Maintenance Model for a line has been suggested following a different approach than above. First, the track segments are filtered using the track type, for the given Line 414. Second, all consecutive track segments of the same Object Type were treated as one cluster. The degradation rates for all these track segments were used collectively to find the Weibull parameters for transition time between states. This will become more explicit in the next section where the calculation of transition times is discussed in detail.

3.6 Preparation of Inputs to the Model

3.6.1 Transition Time Between Degraded States

In this study four stages of track geometry degradation in terms of threshold for the SDL value are considered (Figure 21):

1. AL - Alert Limit
2. IL - Intervention Limit (The limit for speed restriction)
3. IAL – Immediate Action Limit (The limit for line closure)
4. Critical limit

The transition times t1, t2 and t3 are the distribution of times to from P1 to P2, P2 to P3 and P3 to P4 respectively.

![Figure 21: The threshold levels of SDL in mm for Maintenance](image)

3.6.2 Calculation of Transition Time Distribution Parameters

Before calculating the transition times for the Petri Net model, the following steps need to be performed on the pre-processed data.

1) Get the measurement data for Line 414, with the columns - Segment ID, SDL in mm, Start Date, Object Type
2) Identify the tamping dates for each track segment based on the theory in section 3.1 of this report
3) Treating each tamping cycle as a separate cycle, fit the SDL values to a linear model, to get the degradation rate for each cycle. A sample of calculated degradation rates is shown in Table 4.

4) Filter the data with Object Type. Select one Object Type at a time from Table 3.

5) Select a cluster of consecutive Segment IDs of the same Object Type.

### Table 3: Types of track in the Line 414

<table>
<thead>
<tr>
<th>Object Type Number</th>
<th>Object Type in Swedish</th>
<th>Object Type in English</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Plain</td>
<td>Plain</td>
</tr>
<tr>
<td>1</td>
<td>Bfri</td>
<td>Ballast free</td>
</tr>
<tr>
<td>2</td>
<td>BfriÖg</td>
<td>Ballast free transition</td>
</tr>
<tr>
<td>3</td>
<td>Cirkurv</td>
<td>Circular</td>
</tr>
<tr>
<td>4</td>
<td>Plk</td>
<td>Level crossing</td>
</tr>
<tr>
<td>5</td>
<td>Vxl</td>
<td>Switch</td>
</tr>
<tr>
<td>6</td>
<td>Ögkurv</td>
<td>Transition Curve</td>
</tr>
</tbody>
</table>

### Table 4: A sample of linear degradation rates for each track segment: NOTE that each segment has multiple degradation rates. These are the rates for each tamping cycle

<table>
<thead>
<tr>
<th>asset ID</th>
<th>Degradation Rate</th>
<th>SDH</th>
<th>SegmentID</th>
<th>ObjectType</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.0056</td>
<td>1.4168</td>
<td>2381738034</td>
<td>‘Ögkurv’</td>
</tr>
<tr>
<td>1</td>
<td>0.3216</td>
<td>1.3987</td>
<td>2381738034</td>
<td>‘Ögkurv’</td>
</tr>
<tr>
<td>1</td>
<td>0.0462</td>
<td>1.5350</td>
<td>2381738034</td>
<td>‘Ögkurv’</td>
</tr>
<tr>
<td>1</td>
<td>0.1485</td>
<td>1.0448</td>
<td>2381738034</td>
<td>‘Ögkurv’</td>
</tr>
<tr>
<td>2</td>
<td>0.0070</td>
<td>1.2101</td>
<td>2381737671</td>
<td>‘Cirkurv’</td>
</tr>
<tr>
<td>2</td>
<td>0.1849</td>
<td>1.1290</td>
<td>2381737671</td>
<td>‘Cirkurv’</td>
</tr>
<tr>
<td>2</td>
<td>0.1194</td>
<td>1.3113</td>
<td>2381737671</td>
<td>‘Cirkurv’</td>
</tr>
<tr>
<td>2</td>
<td>0.0900</td>
<td>0.6445</td>
<td>2381737671</td>
<td>‘Cirkurv’</td>
</tr>
<tr>
<td>3</td>
<td>0.0224</td>
<td>0.7702</td>
<td>2381737841</td>
<td>‘Ögkurv’</td>
</tr>
<tr>
<td>3</td>
<td>0.1064</td>
<td>0.7293</td>
<td>2381737841</td>
<td>‘Ögkurv’</td>
</tr>
<tr>
<td>3</td>
<td>0.0599</td>
<td>0.7512</td>
<td>2381737841</td>
<td>‘Ögkurv’</td>
</tr>
<tr>
<td>3</td>
<td>0.0806</td>
<td>0.7591</td>
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<td>‘Ögkurv’</td>
</tr>
<tr>
<td>3</td>
<td>0.0295</td>
<td>0.4634</td>
<td>2381737841</td>
<td>‘Ögkurv’</td>
</tr>
<tr>
<td>4</td>
<td>0.2312</td>
<td>2.1035</td>
<td>2381737842</td>
<td>‘Ögkurv’</td>
</tr>
<tr>
<td>4</td>
<td>0.2150</td>
<td>1.9188</td>
<td>2381737842</td>
<td>‘Ögkurv’</td>
</tr>
<tr>
<td>4</td>
<td>0.3983</td>
<td>1.4516</td>
<td>2381737842</td>
<td>‘Ögkurv’</td>
</tr>
<tr>
<td>4</td>
<td>0.2529</td>
<td>0.9345</td>
<td>2381737842</td>
<td>‘Ögkurv’</td>
</tr>
</tbody>
</table>

3.6.2.1 The Transition Time \( t_1 \)

The transition time \( t_1 \) is the distribution of time required to move from the good state to state needing maintenance. Since, it is the data after renewal, no tamping has been performed on the track in this period. Therefore, the distribution \( t_1 \) will only be calculated using the degradation rates for the first cycle for each track segment.
The formula for linear regression is

**Equation 2 linear degradation**

\[
SDL_{\text{final}} = SDL_{\text{initial}} + K \cdot t
\]

where, \(SDL_{\text{final}}\) is the predicted value of SDL
\(SDL_{\text{initial}}\) is the starting value of SDL
K is the linear degradation rate
t is the time in years (365 days)

For \(t1\),

\[
SDL_{\text{final}} = AL
\]
\[
SDL_{\text{initial}} = 0.4
\]
\(SDL_{\text{initial}}\) is the initial value of SDL at the beginning of the degradation cycle, based on the data trend in Figure 15.
K – degradation rate
t= \(t1\)

Putting these values in Equation 2, the transition time for each segment is calculated.

All the transition time \(t1\) for the first cycle of each segment of the same object type, are fit to a Weibull distribution to get the parameters \(\beta1\) and \(\eta1\).

3.6.2.2 **The Transition Time \(t2\)**
The transition time \(t2\) is the distribution of time required to move from state needing maintenance to the state needing speed restriction. This state can either be reached directly from renewal - P1 - P2- P3, or after any number of tamping from state P10- P2- P3 as can be seen in the petri net model in Figure 20. Therefore, all the degradation cycles for each track segment will be considered for the calculation of the transition time \(t2\).

For \(t2\),

\[
SDL_{\text{final}} = IL
\]
\[
SDL_{\text{initial}} = 0.6
\]
\(SDL_{\text{initial}}\) is the reduced value of SDL after tamping has been done, based on the data trend in Figure 19: The histogram showing the SDL value in mm after tamping.
K – degradation rate
t= \(t2\)
Putting these values in Equation 2 linear degradation the transition time for each cycle of each segment is calculated. The Weibull parameters $\beta_2$ and $\eta_2$ are estimated in a similar manner as for $t_1$.

3.6.2.3 The Transition Time $t_3$

The transition time $t_3$ is the distribution of time required to move from state needing speed restriction to the state needing line closure. This state can also be reached from renewal or after one or multiple tamping cycles. Therefore, the parameters $\beta_3$ and $\eta_3$ are calculated using the process as that for $t_2$.

For $t_3$,

\[ \text{SDL}_{\text{final}} = IAL \]
\[ \text{SDL}_{\text{initial}} = IL \]

$K$ – degradation rate

$t = t_3$

3.6.2.4 The Transition Time $t_{14}$

The transition time $t_3$ is the distribution of time required to move from the improved state after tamping to a degraded state P2. This transition can only be achieved after at least one tamping action on the track. Therefore, the degradation rates from the 2$^{nd}$, 3$^{rd}$, 4$^{th}$ etc. cycles for each track segment is used, except the 1$^{st}$ cycle where no tamping has happened. The calculations are like that of $t_1$, $t_2$ and $t_3$

For $t_3$,

\[ \text{SDL}_{\text{final}} = AL \text{ (the threshold level to reach state P2)} \]
\[ \text{SDL}_{\text{initial}} = 0.6 \text{ (based on the data observation in} \]

$K$ – degradation rate

$t = t_{14}$

The parameters $\beta_4$ and $\eta_4$ are estimated by fitting the transition time $t_{14}$, for multiple tracks of the same object type to a Weibull distribution.

3.6.2.5 The Inspection and Renewal Time

The Inspection interval in this study is an input parameter. $T_4$ is a deterministic transition in the model. The inspection time is varied in each simulation to observe the change in model outputs.

The renewal period ($T_{17}$) in this study is kept constant to 30 years. After every 30 years, all the tokens in the model are reset.

3.6.2.6 Maintenance Response Times

The Maintenance response times are constant in the model.

$T_9$ - The response time for the state needing maintenance – a normal distribution with a mean of 200 days
The response time for the state needing maintenance – a normal distribution with a mean of 30 days.

The response time for the state needing maintenance – a normal distribution with a mean of 7 days.

### 3.7 Simulation and Results

#### 3.7.1 The Input parameters

The threshold values for the states P1, P2, P3, and the Inspection Interval are varied, Table 5.

<table>
<thead>
<tr>
<th>Inspection Interval</th>
<th>Inspection Interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>30 days</td>
<td>60 days</td>
</tr>
<tr>
<td>90 days</td>
<td>120 days</td>
</tr>
</tbody>
</table>

**Table 5: Variation of the threshold values and inspection interval for model analysis**

<table>
<thead>
<tr>
<th>AL</th>
<th>IL</th>
<th>IAL</th>
<th>Inspection Interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.4</td>
<td>1.6</td>
<td>30 days</td>
</tr>
<tr>
<td>1.1</td>
<td>1.5</td>
<td>1.7</td>
<td>30 days</td>
</tr>
<tr>
<td>1.15</td>
<td>1.6</td>
<td>1.8</td>
<td>30 days</td>
</tr>
<tr>
<td>1.2</td>
<td>1.7</td>
<td>1.9</td>
<td>30 days</td>
</tr>
<tr>
<td>1.3</td>
<td>1.8</td>
<td>2</td>
<td>30 days</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Inspection Interval</th>
<th>Inspection Interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>60 days</td>
<td>120 days</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Inspection Interval</th>
<th>Inspection Interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>60 days</td>
<td>120 days</td>
</tr>
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<table>
<thead>
<tr>
<th>Inspection Interval</th>
<th>Inspection Interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>120 days</td>
<td>120 days</td>
</tr>
</tbody>
</table>

#### 3.7.2 The Model Outputs

The following outputs are obtained after the model simulation.

1) Number of Inspection- $N_{\text{insp}}$
2) Number of interventions- $N_i$
3) Number of Line closures - $L_c$
4) Number of speed Restrictions- $N_s$
5) Percentage of time in good state – P1
6) Percentage of time in state needing maintenance (including the known and unknown condition) - P2
7) Percentage of time in state needing speed restriction (including the known and unknown condition) - P3
8) Percentage of time in state needing line closure (including the known and unknown condition) - P4
Table 6: List of transitions in the track segment PN model

<table>
<thead>
<tr>
<th>Transition Number</th>
<th>Transition Type/distribution</th>
<th>Transition Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>t5</td>
<td>Immediate</td>
<td></td>
</tr>
<tr>
<td>t6</td>
<td>Constant Time</td>
<td>Input Variable- 30, 45, 60, 75</td>
</tr>
<tr>
<td>t7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>t8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>t15</td>
<td></td>
<td></td>
</tr>
<tr>
<td>t16</td>
<td></td>
<td></td>
</tr>
<tr>
<td>t4 (Inspection Interval)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>t17 (Renewal)</td>
<td></td>
<td>10,950</td>
</tr>
<tr>
<td>t9 (Maintenance Response Time for AL)</td>
<td>Normal</td>
<td>β=1 , η=300</td>
</tr>
<tr>
<td>t10 (Maintenance Response Time for IL)</td>
<td>Normal</td>
<td>β=1 , η=30</td>
</tr>
<tr>
<td>t11 (Maintenance Response Time for IAL)</td>
<td>Normal</td>
<td>β=1 , η=7</td>
</tr>
<tr>
<td>t1 (degradation time from good state)</td>
<td>Weibull</td>
<td>β1 , η1 (input variable)</td>
</tr>
<tr>
<td>t2 (degradation time from degraded state)</td>
<td>Weibull</td>
<td>β2 , η2 (input variable)</td>
</tr>
<tr>
<td>t3 (degradation time from degraded state)</td>
<td>Weibull</td>
<td>β3 , η3 (input variable)</td>
</tr>
<tr>
<td>t12 = t2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>t13 = t3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>t14 (degradation time after tamping)</td>
<td>Weibull</td>
<td>β4 , η4 (input variable)</td>
</tr>
</tbody>
</table>

3.7.3 The Cost Calculations

The Life Cycle Cost of the Railway Track Asset Management can be calculated in three steps:

1) Determine the cost of inspection, tamping and the penalty cost for the speed restriction and line closure states.
2) From the model, extract the values for number of interventions and number of speed restrictions and line closures.
3) The total life cycle cost can be calculated using the formula

Equation 3: The total Life cycle cost

\[ C_{\text{total}} = N_{\text{insp}} \cdot C_{\text{insp}} + N_{\text{i}} \cdot C_{\text{i}} + N_{\text{s}} \cdot C_{\text{s}} + L_{\text{c}} \cdot C_{\text{lc}} \]

1) \( N_{\text{insp}} = \) Number of Inspections
2) \( C_{\text{insp}} = \) Inspection Cost
3) \( N_{\text{i}} = \) Number of Preventive Tamping
4) \( C_{\text{i}} = \) The cost of preventive Tamping
5) \( N_{\text{s}} = \) Number of Speed Restriction
6) \( C_{\text{s}} = \) The Penalty Cost for Speed Restrictions
7) $L_c$ = Number of Line Closures
8) $C_{lc}$ = The Penalty Cost for Line Closure

The figures, regarding the number of inspections, number of interventions and the number of line closures and speed restrictions can be obtained from the model after the simulation for a specific time. The cost figures estimated by experts from Traffikverket are listed in Table 7. The cost for penalty and interventions in switches is different than others track types in Table 3.

Table 7: The Intervention and Penalty Costs from Traffikverket for the line 414

<table>
<thead>
<tr>
<th>Cost in SEK</th>
<th>Others</th>
<th>Switches</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_{insp}$</td>
<td>300</td>
<td>$C_{insp}$</td>
</tr>
<tr>
<td>$C_i$</td>
<td>4200</td>
<td>$C_i$</td>
</tr>
<tr>
<td>$C_s$</td>
<td>10000</td>
<td>$C_s$</td>
</tr>
<tr>
<td>$C_{lc}$</td>
<td>40000</td>
<td>$C_{lc}$</td>
</tr>
</tbody>
</table>

3.7.4 Results and Discussions

The Simulation was run for a period of 20 years

The Object Types selected were

1) Plain Track – ‘0’
2) Circular Track – ‘3’
3) Switches – ‘5’

The transition times between states P1, P2 P3 and P4 for 5 different combinations of threshold values of SDL level, for different object types are listed in Table 8, Table 9 and Table 10 for a Plain track, Circular Track and Switches.

Table 8: The Weibull parameters for transition times for a Plain track

<table>
<thead>
<tr>
<th>Object Type - Plain Track '0'</th>
<th>AL</th>
<th>IL</th>
<th>IAL</th>
<th>$b_1$</th>
<th>$\eta_1$</th>
<th>$b_2$</th>
<th>$\eta_2$</th>
<th>$b_3$</th>
<th>$\eta_3$</th>
<th>$b_4$</th>
<th>$\eta_4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.4</td>
<td>1.6</td>
<td>0.90076</td>
<td>2687.91</td>
<td>0.94262</td>
<td>2215.72</td>
<td>0.94262</td>
<td>1107.86</td>
<td>0.96785</td>
<td>2420.13</td>
<td></td>
</tr>
<tr>
<td>1.1</td>
<td>1.5</td>
<td>1.7</td>
<td>0.90076</td>
<td>3135.89</td>
<td>0.94262</td>
<td>2215.72</td>
<td>0.94262</td>
<td>1107.86</td>
<td>0.96785</td>
<td>3025.17</td>
<td></td>
</tr>
<tr>
<td>1.15</td>
<td>1.6</td>
<td>1.8</td>
<td>0.90076</td>
<td>3359.89</td>
<td>0.94262</td>
<td>2492.68</td>
<td>0.94262</td>
<td>1107.86</td>
<td>0.96785</td>
<td>3327.68</td>
<td></td>
</tr>
<tr>
<td>1.2</td>
<td>1.7</td>
<td>1.9</td>
<td>0.90076</td>
<td>3583.88</td>
<td>0.94262</td>
<td>2769.65</td>
<td>0.94262</td>
<td>1107.86</td>
<td>0.96785</td>
<td>3630.2</td>
<td></td>
</tr>
<tr>
<td>1.3</td>
<td>1.8</td>
<td>2</td>
<td>0.90076</td>
<td>4031.86</td>
<td>0.94262</td>
<td>2769.65</td>
<td>0.94262</td>
<td>1107.86</td>
<td>0.96785</td>
<td>4235.23</td>
<td></td>
</tr>
</tbody>
</table>

The sample input parameters and the output from the Petri Net model are demonstrated in Table 11. The major part of the maintenance cost comes from inspections. Hence, the overall cost, as shown in, is reduced as the number of inspections over the period of 20 years is halved. When the inspection interval changes from 60 to 120 days, there is a steep decrease in cost, because the cost of inspection has reduced while penalty cost of corrective maintenance has not increased. When the inspection interval is increased further, there is still a decrease in cost, but not as steep. The reason behind this is that though the inspection cost is decreased, the cost for
corrective maintenance, i.e. speed restrictions and line closures has increased to some extent, balancing out the difference. It is to be noted that, the cost of renewal is not included in this model as, for this study, the renewal time is fixed at a period of 30 years after the simulation. In this case, the model is simulated for a period of 20 years. So, renewal condition is not reached in the simulation time.

Table 9: The Weibull parameters for transition times for a circular track

<table>
<thead>
<tr>
<th>Object Type - Circular Track '3'</th>
<th>AL</th>
<th>IL</th>
<th>IAL</th>
<th>( \beta_1 )</th>
<th>( \eta_1 )</th>
<th>( \beta_2 )</th>
<th>( \eta_2 )</th>
<th>( \beta_3 )</th>
<th>( \eta_3 )</th>
<th>( \beta_4 )</th>
<th>( \eta_4 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.4</td>
<td>1.6</td>
<td>0.62646</td>
<td>3378.93</td>
<td>0.75091</td>
<td>2480.08</td>
<td>0.75091</td>
<td>1240.04</td>
<td>0.85441</td>
<td>2553.04</td>
<td></td>
</tr>
<tr>
<td>1.1</td>
<td>1.5</td>
<td>1.7</td>
<td>0.62646</td>
<td>3942.08</td>
<td>0.75091</td>
<td>2480.08</td>
<td>0.75091</td>
<td>1240.04</td>
<td>0.85441</td>
<td>3191.3</td>
<td></td>
</tr>
<tr>
<td>1.15</td>
<td>1.6</td>
<td>1.8</td>
<td>0.62646</td>
<td>4223.66</td>
<td>0.75091</td>
<td>2790.09</td>
<td>0.75091</td>
<td>1240.04</td>
<td>0.85441</td>
<td>3510.42</td>
<td></td>
</tr>
<tr>
<td>1.2</td>
<td>1.7</td>
<td>1.9</td>
<td>0.62646</td>
<td>4505.24</td>
<td>0.75091</td>
<td>3100.1</td>
<td>0.75091</td>
<td>1240.04</td>
<td>0.85441</td>
<td>3829.55</td>
<td></td>
</tr>
<tr>
<td>1.3</td>
<td>1.8</td>
<td>2</td>
<td>0.62646</td>
<td>5068.39</td>
<td>0.75091</td>
<td>3100.1</td>
<td>0.75091</td>
<td>1240.04</td>
<td>0.85441</td>
<td>4467.81</td>
<td></td>
</tr>
</tbody>
</table>

Table 10: The Weibull Parameters for transition times for Switches

<table>
<thead>
<tr>
<th>Object Type - Circular Switches '0'</th>
<th>AL</th>
<th>IL</th>
<th>IAL</th>
<th>( \beta_1 )</th>
<th>( \eta_1 )</th>
<th>( \beta_2 )</th>
<th>( \eta_2 )</th>
<th>( \beta_3 )</th>
<th>( \eta_3 )</th>
<th>( \beta_4 )</th>
<th>( \eta_4 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.4</td>
<td>1.6</td>
<td>0.98551</td>
<td>3332.48</td>
<td>1.31857</td>
<td>2258.55</td>
<td>1.31857</td>
<td>1129.27</td>
<td>1.54746</td>
<td>2240.17</td>
<td></td>
</tr>
<tr>
<td>1.1</td>
<td>1.5</td>
<td>1.7</td>
<td>0.98551</td>
<td>3887.9</td>
<td>1.31857</td>
<td>2258.55</td>
<td>1.31857</td>
<td>1129.27</td>
<td>1.54746</td>
<td>2800.22</td>
<td></td>
</tr>
<tr>
<td>1.15</td>
<td>1.6</td>
<td>1.8</td>
<td>0.98551</td>
<td>4165.61</td>
<td>1.31857</td>
<td>2540.87</td>
<td>1.31857</td>
<td>1129.27</td>
<td>1.54746</td>
<td>3080.24</td>
<td></td>
</tr>
<tr>
<td>1.2</td>
<td>1.7</td>
<td>1.9</td>
<td>0.98551</td>
<td>4443.31</td>
<td>1.31857</td>
<td>2823.19</td>
<td>1.31857</td>
<td>1129.27</td>
<td>1.54746</td>
<td>3360.26</td>
<td></td>
</tr>
<tr>
<td>1.3</td>
<td>1.8</td>
<td>2</td>
<td>0.98551</td>
<td>4998.73</td>
<td>1.31857</td>
<td>2823.19</td>
<td>1.31857</td>
<td>1129.27</td>
<td>1.54746</td>
<td>3920.31</td>
<td></td>
</tr>
</tbody>
</table>

The major part of the maintenance cost comes from inspections. Hence, the overall cost, as shown in Table 7, is reduced as the number of inspections over the period of 20 years is halved. When the inspection interval changes from 60 to 120 days, there is a steep decrease in cost, because the cost of inspection has reduced while penalty cost of corrective maintenance has not increased. When the inspection interval is increased further, there is still a decrease in cost, but not as steep. The reason behind this is that though the inspection cost is decreased, the cost for corrective maintenance, i.e. speed restrictions and line closures has increased to some extent, balancing out the difference. It is to be noted that, the cost of renewal is not included in this model as, for this study, the renewal time is fixed at a period of 30 years after the simulation. In this case, the model is simulated for a period of 20 years. So, renewal condition is not reached in the simulation time.

As observed in Table 11, the scale parameter is in the range of 2500 to 3000. This indicates that the track condition is in a good state. It takes around 10 years to degrade from an SDL level of 0.4 to an SDL level of 1.15. The major cost of maintenance comes from Inspections which are happening every 60 days. Also, the stages of speed restriction and line closure were not reached in the period of 20 years.

In Table 12, the Inspection interval was changed to 120 days. The total life cycle cost was reduced to almost half with no increase in the number of speed restrictions and line closures. This is again because of the good condition of track. Even if the track is inspected every 120
days, it does not degrade to speed restriction and line closure levels. In a track condition which had a higher degradation, increasing the inspection interval would typically lead to a greater number of speed restrictions and line closures. However, for this data there is no remarkable increase in the speed restrictions and line closures.

*Table 11: The model results and cost calculation for a Plain Track for an Inspection interval of 60 days*

<table>
<thead>
<tr>
<th>Case 1</th>
<th>Object Type - 0 - Plain Track</th>
<th>Input</th>
<th>Output</th>
<th>Cost in SEK</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>AL=1.15</td>
<td>Ninsp</td>
<td>Cinsp</td>
</tr>
<tr>
<td></td>
<td></td>
<td>IL=1.6</td>
<td>Ni</td>
<td>C1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>IAL=1.8</td>
<td>Ns</td>
<td>C2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>I=60 days</td>
<td>Lc</td>
<td>C3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>β1=0.90</td>
<td>P1</td>
<td>C4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>β2=0.94</td>
<td>P2</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>β3=0.94</td>
<td>P3</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>β4=0.96</td>
<td>P4</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>η1=2016</td>
<td>η1=2016</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>η2=2492</td>
<td>η2=2492</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>η3=1107</td>
<td>η3=1107</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>η4=2117</td>
<td>η4=2117</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Case 1</th>
<th>Object Type - 0 - Plain Track</th>
<th>Input</th>
<th>Output</th>
<th>Cost in SEK</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>AL=1.15</td>
<td>Ninsp</td>
<td>Cinsp</td>
</tr>
<tr>
<td></td>
<td></td>
<td>IL=1.6</td>
<td>Ni</td>
<td>C1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>IAL=1.8</td>
<td>Ns</td>
<td>C2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>I=120 days</td>
<td>Lc</td>
<td>C3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>β1=0.90</td>
<td>P1</td>
<td>C4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>β2=0.94</td>
<td>P2</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>β3=0.94</td>
<td>P3</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>β4=0.96</td>
<td>P4</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>η1=2016</td>
<td>η1=2016</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>η2=2492</td>
<td>η2=2492</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>η3=1107</td>
<td>η3=1107</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>η4=2117</td>
<td>η4=2117</td>
<td></td>
</tr>
</tbody>
</table>
In Figure 23, the increase or decrease in the number of tamping, number of line closures and number of speed restrictions is shown. When the Inspection interval is increased, the number of preventive tamping action decreases, as in this model, the tamping is done based on a degraded condition identified after inspection. In case of less inspections, degraded condition is identified less frequently and hence, fewer tamps. The number of speed restrictions and line closure is seen to increase, which is the typical and expected behavior. When there are fewer inspections, the track is left to degrade in an unidentified state of maintenance. This leads to a greater number of degradations to the state P3 and P4. However, as discussed above, though increasing, the change in the number of speed restrictions and line closures are not remarkable enough to affect the cost contribution. The model outputs could have been better realized with a more sensitive track condition over time. The two variable inputs in this model are, inspection interval and threshold levels. In Table 13, the threshold levels are varied, and number of interventions decrease. However, this analysis might not be a reliable method of assigning threshold levels. Here, the decreasing number of interventions can completely be attributed to the fact, that the threshold for tamping, speed restriction and line closure is raised, hence those conditions are raised after still further degradation. This analysis is incomplete without considering the risk factor of increasing the threshold values. The threshold is generally preset by the organization but can be varied and optimized within a specified range. Another suggested approach to address the threshold level is to keep the IL and IAL constant as these conditions are related to safety risk and vary the AL to observe the change in model values.
3.7.5 Consideration of Risk

The decision making for a widely used infrastructure such as railways, is not complete without the consideration of the safety risk. The above model outputs in terms of cost are not enough to formulate a maintenance plan, without optimizing with risk constraints. The total risk needs to be calculated for each decision, and the availability of maintenance vehicles, the cost, the output of the petri net model and the total risk are to be optimized using the objective function.

### Table 13: Change in threshold levels

<table>
<thead>
<tr>
<th>Threshold Levels</th>
<th>Tamping</th>
<th>Speed Restrictions</th>
<th>Line Closures</th>
</tr>
</thead>
<tbody>
<tr>
<td>AL=1, IL=1.4, IAL=1.6</td>
<td>3.7</td>
<td>1.3</td>
<td>0.2</td>
</tr>
<tr>
<td>AL=1.1, IL=1.5, IAL=1.7</td>
<td>2.5</td>
<td>0.8</td>
<td>0</td>
</tr>
<tr>
<td>AL=1.15, IL=1.6, IAL=1.8</td>
<td>1.7</td>
<td>0.5</td>
<td>0.1</td>
</tr>
</tbody>
</table>

Figure 23: The trend in number of Tampings, Number of speed restrictions and number of line closures, with change in inspection interval
4 Future Work

The work done in thesis can be expanded and improvised in the following specific areas:

1) The output of the maintenance model depends on the accuracy of the degradation model. A degradation model that is closer to the real track behavior will give more accurate estimations of track degradation times.

2) Tamping Effectiveness has been considered in this research, in the process of calculation of transition times. However, it can be directly implemented in the petri net model by considering conditional transition (Andrews, 2013), where the improved condition of the track is dependent upon the number of tamping actions done.

3) The line model has been implemented in this thesis by considering consecutive track sections as one. Another approach for Opportunistic Maintenance is suggested in Andrews et al (Andrews, 2013), i.e. developing a separate model for each track segment and connecting the models at the inspection transitions.

4) The renewal process in this thesis, is assumed to be time dependent. The model can be developed to consider the possibility of renewal after a specific number of tampings have occurred.

5) The next step to developing the maintenance model based on cost, is to optimize it with risk constraints and vehicle availability.

6) The petri-net model developed in this work, only considers the SDL as the parameter for monitoring track degradation. The same model can be used for other track geometry degradation parameters.
5 Conclusion and Contributions

Petri Net modelling technique has been used to assess a maintenance strategy for a track segment to maintain the value of the SDL within specified thresholds. The model considers the degradation of the track, the maintenance actions performed, inspections and renewal on the track. The input parameters used to study the resulting track performance were, threshold levels specified for the SDL, Inspection intervals, renewal interval and maintenance response times. The life cycle cost for each set of inputs was calculated by assigning costs to the inspections, the tamping actions and penalty costs for speed restrictions and line closures. However, the best management strategy cannot be selected based on cost alone. The risk implications and other factors that affect the selection of threshold levels of SDL and Inspection intervals need to be considered. The model can be used for maintenance planning using other parameters for track geometry. It can be made efficient by improvising on the degradation modelling, consideration of the tamping effectiveness and renewal strategy.
References


