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Maintenance Modelling, Simulation and Performance Assessment for Railway Asset Management

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Maintenance modelling, simulation and performance assessment for railway asset management

Abstract:

The aim of this thesis research work is to propose maintenance models for railways infrastructures that can help to make better maintenance decisions in the more constrained environment that the railway industry has to face, e.g. increased traffic loads, faster deterioration, longer maintenance planning procedures, shorter maintenance times. The proposed maintenance models are built using Coloured Petri nets; they are animated through Monte Carlo simulations to estimate the performance of the considered maintenance policies in terms of cost and availability. The maintenance models are developed both at the component and network levels, and several different maintenance problems are considered. At the rail component level, maintenance policies with different level of monitoring information (level of gradual deterioration vs binary working state) are compared to show the benefits of gathering monitoring information on the deterioration level. The effect of preventive maintenance delays is also investigated for both condition-based inspection policies and periodic inspection policies on a gradually deteriorating component. At the line level, a maintenance policy based on a two-level inspection procedure is first investigated. Then, considering the case when the deterioration process depends on the operation modes (normal vs limited speed), a maintenance optimization problem is solved to determine an optimal tuning of the repair delay and speed restriction.

Keywords: Railroads–Track - Maintenance and repair, Railroads–Track - Deterioration, Condition-based maintenance, Petri nets, Reliability, Systems availability, System safety, Engineering inspection, Simulation methods

Modélisation, simulation et évaluation de performances de la maintenance des infrastructures ferroviaires

Résume: Les travaux présentés dans ce manuscrit visent à développer des modèles de coût/performances pour améliorer les décisions de maintenance sur les infrastructures ferroviaires exploitées dans un environnement de plus en plus contraint: trafic accru, détérioration accélérée, temps de maintenance réduits. Les modèles de maintenance proposés sont construits à base de réseaux de Petri colorés ; ils sont animés par simulation de Monte Carlo pour estimer les performances (en termes de coût et de disponibilité) des politiques de maintenance considérées. Ils sont développés aux niveaux "composant" et "réseau", et plusieurs problèmes de maintenance différents sont étudiés. Au niveau "composant" (rail), des politiques de maintenance mettant en jeu différents niveaux d'information de surveillance sont comparées pour montrer l'intérêt de surveiller la détérioration graduelle du composant. L'effet de l'existence d'un délai de maintenance est également étudié pour les politiques conditionnelle et périodique. Au niveau système (ligne), une maintenance mettant en jeu différents types d'inspections complémentaires (automatique ou visuelle) est d'abord étudiée. On s'intéresse ensuite au cas de figure où l'évolution de la détérioration dépend du mode d'utilisation et de la charge de la voie : le problème de maintenance étudié vise alors à définir un réglage optimal des paramètres d'exploitation de la voie (vitesse limite) et de maintenance (délai d'intervention).

Les mots clé: Voies ferrées-Entretien et réparations; Voies ferrées-Détérioration; Maintenance conditionnelle; Réseaux de Petri; Fiabilité; Disponibilité (systèmes); Contrôle technique; Méthodes de Simulation

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Part I

INTRODUCTION:

PROBLEM STATEMENT, OBJECTIVES AND MOTIVATION

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Introduction

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1.1 Importance and necessity of railway asset maintenance

SNCF (Société nationale des chemins de fer français) maintains and monitors around 30,000 km of track in France, and around 15,500 trains run on this huge network carrying 126.9 million passengers per year[50]. According to the statistics on the website of world bank, Network Rail controls more than 16,000 km length of track and carries 2.75 million passenger journeys per weekday [160]. In China, the railway network expands to reach 66,298 km and more than 12,000 km are the high speed passenger dedicated lines [131].

For these large scale transport system, safety and availability are the most basic and important requirements since the failures on the railway system may lead to traffic disorders, and even disasters.

1.1.1 Effects of failures on railway

Railway assets and infrastructures play an important role in railway safety and service. The failures of the railway assets may cause emergency maintenance, hence the traffic stops, and even lead to accidents.

The first unexpected event due to the railway asset failure is the traffic stop which leads to train delays and traffic disruption. For example, a rail breakage occurred in 2006, results in a track circuit failure and traffic stop for 6 hours at Urchfont and 10 hours at Kennington in UK [149]. According to the report of Office of Rail Regulation, around 16,000 infrastructure incidents arose and they were associated with 1.7 million minutes of train delays in 2013[129]. Open data on the website of SNCF indicates that there were around 37 safety incidents due to the track faults, such as the twist, broken rail and so on during 2013/2014. These incidents did not cause railway accidents but they resulted in heavy maintenance on the railway section [50].

Another consequence due to the failure is the accident which may damage the other infrastructures and ruin the environment. For example, the derailment of a freight train happens near Gloucester station in 2013 damaged the signal cables for 4 miles, as well as 4 level-crossing and 2 bridges [153]. A freight train derailed in North-west London in October 2013 due to a track twist fault; even though there is no injuries reported, the accident damaged the overhead line electrification, and the maintenance at the accident location forced the stop of the passenger and freight service for 6 days [152]. A serious accident may lead to injuries and fatalities that are the most unexpected disaster in the railway operation. Several passengers trains derailments in UK during 2000-2010 are reported by the Rail Accident investigation Branch, including a derailment in Grayrigg due to a fault of point machine leading to injuries in 2007 [150]; the derailment at Potters Bar leading to the consequence of fatalities [80, 158], the accident investigation reports for them mentioned that the inspection failed in identifying the defects. Let us mention as well a derailment reported due to the lack of maintenance at the right location: it happened in Leeds in 2000 which not only leaded to fatalities and injuries but also to the permanent speed restriction and replacement for more than 1 year [128]. In France, an accident due to the track fault happened in Bertigny/Orgy in July 2013, a train derailed and crashed to the station due to the loose of rail connection and resulted in 7 fatalities and nearly 200 injuries; in addition, investigation report pointed out that the regular inspections are carried out for the devices but it seemed the failure was not detected and maintained in time [26].

During 1991-2001, around 23.7% of derailments were caused by the track faults [143] and 10% of the derailments occurred due to both of the defective track and vehicle condition in UK [105].Therefore, it is important to carry out the inspection and maintenance to reduce the potential railway failures and enhance the safety and availability of the railway line.

1.1.2 Existing railway maintenance

Maintenance of railway asset contributes by a high proportion to the total railway expenditure. Netherlands railway company spent €250 million for 4,500km of track in 2006 [54]. In the financial Report of SNCF, €746 millions is spent for the upgrades to the stations and buildings including track renewal, replacement of the communication system and so on [175]. Network Rail has spent £391.8 million for track maintenance during 2013-2014[121].

Three types of maintenances are carried out for railway assets:

- preventive maintenance, which is planned to be carried out to prevent the failures, including time-based or condition-based strategies;
- corrective maintenance, which is performed after the failure is detected to recover the function of railway devices, sometimes which is unplanned;
- renewal/replacement, which replaces all the devices or components in the railway section.

Renewal costs the most of railway expenditure: cost of track renewal in Netherlands in 2006 represented more than 70% of the overall maintenance cost. In order to ensure the safety and at the same time perform an economic maintenance, maintenance strategies are studied to improve the maintenance decision and schedule a cost-effective maintenance strategy for railway system within the safety constraints. Railway infrastructure owners make efforts to optimise maintenance scheduling for a cost-effective maintenance strategies: The renewal strategies considers the type of rails [73] or the number of failures [8, 9]. Reliability-centred maintenance (RCM) is introduced to the safety critical infrastructure in 2000 [178] and some researches discuss the applications of RCM on the railway subsystems, such as point machines and signalling devices [31, 99, 106, 138]. Risk-based maintenance (RBM) is another maintenance strategy for the railway assets [144]. These two maintenance strategies have similar steps but they have differences:

- Different events are analysed: RCM considers the functions and functional failures; RBM considers the hazardous events (or functions) and their corresponding functions. Since RBM and RCM may concern about different events, the system can be divided into different subsystems.
- RBM needs to consider the integrated risk (Risk=FrequencyŒConsequence); RCM considers the probability of failures.
- RBM needs to firstly satisfy the acceptable risk level and then optimize maintenance cost and availability. RCM considers failures probability and try to make maintenance plans to minimize maintenance cost and maximize system availability.
- For safety-related or safety-critical system, RBM is needed; for the system which is not related to safety, we can just use RCM.

RCM needs to carry out HAZOP, FMECA (FMEA), and FTA, etc before making maintenance decision. Risk-based maintenance also needs to consider the failure modes and their effects so it also carries out the techniques such as FMEA, HAZOP and FTA. Before we set up RBM, we need to implement RCM in some extents.

Under these maintenance frameworks, preventive maintenance is scheduled to improve the system reliability and safety; it can be carried out depending on time or the detected states since the preventive maintenance on railway is not as expensive as the track renewal.

Some researches focus on improving the monitoring techniques (monitoring the voltages and pressure for Point machine or using ultrasonic inspection for rail cracks) to detect more hidden defects which is more cheaper than the preventive maintenance or renewal and helps to make decisions for preventive maintenance [133].

1.1.3 Challenges of railway assets maintenance

More and more people choose trains for long distance journeys. Network Rail's data shows that the growth of passenger journeys increase from 1 billion in 2002/2003 to 1.5 billion in 2012/2013. They believe that the rail capacity should have to increase 25% if 2% road traffic changes to rail [160]. The clients want to arrive to the destination as quickly as possible; in addition, they want to take the trains within a shorter waiting time.

Thus, effective maintenance scheduling and execution on railway need to consider the conflict between the maintenance actions and the operation requirements. In the future, this conflict will become more and more important since the railway system may be developed in order to facilitate faster trains, more trains per hours, longer operating time and higher punctuality.

1.1.3.1 Faster deteriorations

According to the route utilization strategy report of Network Rail, in the next 10 years, only in the east midland, the speed of most of the passenger trains will increase from 110 mph (177km/h) to 125 mph (200km/h). Network Rail sets the aims that for the long distance high speed train, in the next ten years, the journey time will reduce by 1%-6% [120]. TGV ran with the maximum speed of 500km/h for a test of the high speed rail in 2007 and it is possible to run the TGV trains at the average speed of 320-350km/h in the regular operation[176]. China built high speed railway in these years, the maximum speed on the high speed railway line can reach to 400 km/h for the testing commissions.

Some studies reveal that the track quality deterioration rate depends on the train speed, thus the higher speed in the high speed railway line may lead to a faster deterioration rate. In China, most of the trains running on the high speed line keep their maximum speed at 250km/h[131].

Not only the high speed but also the heavier loads on the lines may lead to faster track deterioration rate. In the report of Efficiency of Network Rail, the traffic statistics indicates that there are 10% more trains kilometers in the year 2014/5 than in the year 2004/5 [121]. China railways was running over 1,330 pairs of high-speed trains a day on both this dedicated network and on upgraded conventional lines in 2014 summer which is more than in the same period in 2013[131].

These higher speed and heavier loads may accelerate the deterioration of track according to the researches in [51, 96], and thus it may require to plan more maintenance or inspections on the running lines.

1.1.3.2 Longer planning procedure

Given the complex railway operation procedures, maintenance planning is a complex negotiation procedure. In some cases, a complete track renewal work may take 28 hours, and it takes the adjacent lines to be closed [119]. These railway line closures are always scheduled at night during the train traffic stops or during weekend when there are less passengers. However, rescheduling maintenance and planning emergency maintenance is difficult, it must be agreed with the railway companies and the clients several months ahead. In the

other hand, since the maintenance is a noisy task, sometimes it should be agreed with the residences being affected. In the future, more trains, companies, residences and passengers are involved into the network operations and hence the maintenance implementation need to coordinate the schedules and the negotiation process may lead to a longer repair delay time.

1.1.3.3 Shorter maintenance time

The third challenge for the railway asset maintenance is the shorter track possession time (which is the downtime for maintenance).

The increasing capability of the railway line requires more trains running on the lines. With the development of the ERTMS (The European Railway Trains Management System), the concept of moving block is introduced to the train control principle, which reduces the distance between two trains [49]. According to Hunyadi's report[83], the headway (the interval between two trains) is shorter thanks to the new signalling system for the high speed trains and they plan to have a peak capacity of 18 trains per hour and direction. However, increasing speed and shorter headway sometimes cannot satisfy the passengers travelling requirements, and hence a longer operation time is needed, for example, more trains runs during weekend or some long distance trains are scheduled to run at night. As a result, the operation period may pre-empt the regular scheduled maintenance period which used to be planned to occupy the track for the whole night or weekend.

1.1.4 Conclusion

Maintenance is important to prevent the railway accidents hence to make sure trains running safely and enhance the passengers and working crews' safety. Since the maintenance may disrupt the railway operation and cost a large amount of money, the infrastructure conductors or companies make effort on the cost-effective maintenance decision making to save money and improve the availability without affecting the safety.

1.2 Motivations and objectives

To answer the practical needs and solve some of the maintenance problems presented in the previous section, it is necessary to have at our disposal maintenance models allowing the evaluation and optimisation of the maintenance policies for an improved maintenance decision making. Since it is a complex task to consider the details of deterioration, inspection and maintenance together and the operation for a multi-component system, the analytical solution seems not a good idea for developing these maintenance models; it is important to develop structured models and solve the problems by simulations.

Most of the maintenance models in the literature depends on the Markov assumptions, but the limitation of the Markov assumptions cannot satisfy the maintenance modelling requirement in railway system, we are thus interested in having a tool to help maintenance decision making; with this tool, we should be able to take into account the deterioration, maintenance and operation for the complex system more easily.

The major objective of this thesis is to evaluate the maintenance strategies for the railway system and estimate the hazardous event probability for the maintenance optimization.

The thesis aims to study the following problems in railway maintenance:

1. maintenance and scheduling effects for different types of collected data;
2. effect of delayed repair, during the waiting time, the component is still working;
3. maintenance strategies and operation configuration when the operation affects the failure process.

1.2.1 Inspection capability

Different maintenance policies can be planned for the component depending on the inspection data. Sometimes the data just indicate the working or failed states; in some cases, the inspection has limitation for the defects identification, which also needs supplement inspections; some inspection techniques can show the health in details. With the detailed inspection data, condition-based preventive maintenance can be planned otherwise age-based preventive maintenance is performed.

If the inspection cannot identify all of the defective states, a supplement inspection need to be considered. Multi-inspection for multiple failure modes [198] and the inspection for two kinds of deterioration process [195] are discussed based on delay time concept; they focus on the maintenance cost optimization. In this thesis,we want to assess some multi-level inspection policies for multiple component system considering the operation and accident scenarios.

1.2.2 Delayed repairs

As mentioned in Section 1.1.3.2, it is a long waiting and negotiating procedure for the asset maintenance in railway system. In addition, due to the long distance travelling and the limited number of repair machines, we cannot implement maintenance once we detect the failures or the defects. In this work, we want to study the effect of the preventive maintenance delay on the condition-based maintenance for railway track component.

1.2.3 Maintenance and operation configurations

In some maintenance models for railway section, speed restriction is considered, however, they do not concern about the effect of the speed restriction on the deterioration [5, 144]. In [219], the effect of speed restriction on the deterioration is considered and a model is built to study the train delays on a railway section.

The operation configuration affects the loads on the tracks. If we implements speed restriction as a kind of degraded operation for a section, the lower speed and less train passages slow down the deterioration. On the other hand, the restriction may reduce the benefit,thus it is interesting to find a joint tuning of speed restriction and repair delays.

1.3 Structure of the thesis

After this introduction Part I, the thesis is organized as follows:

Part II consists in three small chapters to introduce the research background and the tools using in the thesis: Chapter 2 introduces a traditional railway region as an example; a ballasted track system and an example of point machines are described, and the failures and the corresponding maintenance methods are introduced. Chapter 3 reviews the literature on the failure models, existing inspection and maintenance modelling for single component system or multi-component system. Chapter 4 introduces some mathematics tools used in the thesis, especially, we introduce the concept, formal definitions and modelling rules of Colored Petri net and give an example of CPN to show the ability of Colored Petri Net.

Part III focus on the maintenance modelling for the single component system. Chapter 5 compares the maintenance strategies based on two kinds of stochastic failure descriptions, which describe the same physical failure process. Chapter 6 investigates the effects of repair delays on condition-based maintenance; the effect of the periodic inspection policies and condition-based inspection policies are compared.

Since the railway network is a multi-component system, it is not enough to consider the maintenance modelling for single component system. Therefore, Part IV describes the maintenance model for a series track section. Chapter 7 shows a maintenance model considering the limitation of maintenance machines in a railway network. Chapter 8 gives a multi-component maintenance for railway asset management and risk analysis considering the imperfect inspection scheduling. Chapter 9 models the railway network, the components in the network suffer to the gradual track deterioration depending on the speed and the number of trains, a cost function and an unavailability function are used to evaluate the performance of the section. Part V is a general conclusion for the thesis.

Part II

BACKGROUND:

RAILWAY SYSTEM AND MAINTENANCE, LITERATURE REVIEW

CHAPTER 2

Railway system description and asset maintenance introduction

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2.1 Introduction

Railway assets play an important role for the railway transportation. The condition of the assets contribute to the railway safety and maintenance. As mentioned in Chapter 1, railway companies spend thousands of money on the track maintenance to decrease the number of accidents every year. In order to plan the maintenance to satisfy the safety and economic requirement, maintenance modelling is important.

In this thesis, we want to study the effect of multiple inspection on railway section maintenance and the effect of delayed preventive maintenance on the railway section performance to help us to optimize the maintenance strategies and then to make decision. Therefore, not only the failure modes and corresponding maintenance for railway assets, but also the general operation for a railway section are needed to be considered for the railway section modelling. In this section, we introduce an example of a railway section in UK, to give a general idea about the train operation rules for a railway section. In order to

make a better decision for the railway assets, a ballasted track system is introduced in this chapter, to present the structure and function of the ballasted track, the failures which may lead to the accidents and the corresponding maintenance and inspection methods.

The chapter is organized as follows: Section 2.2 describes a railway section as an example which consists of plain line, switches and crossings (S& C), points machines and signalling devices. The general operation rule of the section and the functions of the assets are introduced.

Section 2.4 presents the representation of track quality, track geometry faults and rail faults. The corresponding maintenance methods and inspections for each failure mode are described in order to help us to specify the modelling problems mentioned in Chapter 1.

In Section 2.5, we outline the maintenance specifications according to our motivation and the system description for this thesis.

2.2 Example of a railway section

An example of a railway section is introduced in this section to give some general ideas about the general operation rules of railway system.

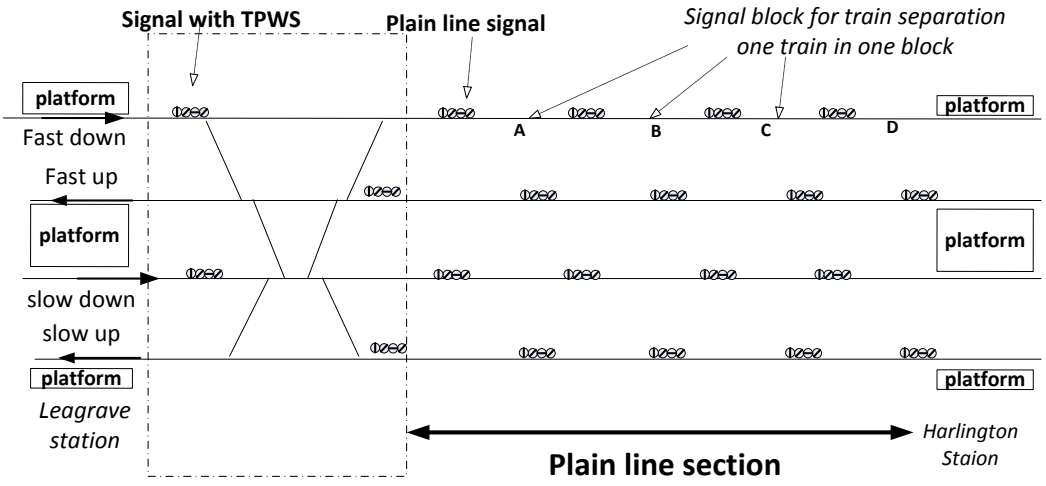


Figure 2.1: An example of a railway section

Figure 2.1 shows an example of a railway section which locates between station Leagrave and station Harlington in UK, it starts at the milestone 32.75 miles (52.7 km away from London) and ends at 37.25 miles (60 km away from London). There are 2 stations (the rectangles in Figure 2.1 represent the platforms in the stations), 1 Switches and Crossings (S&C) areas (the dash rectangle in Figure 2.1) is located near the station Leagrave , which is used to control the routes of trains arrival or departure; the length of the S&C is about 1 mile(1.6 km). Between the S&C area and station Harlington, there are the plain line segments, each of them are around 4 miles long (6.5 km).

On this example railway segment, there are 2 fast lines for up (to London) and down (from London) direction and the other two lines are slow lines. The speed of the fast lines

is from 90 mph (144.9 km/h) to 110mph (177.1km/h) ; the speed of the slow lines is from 70 (112.7 km/h) to 90 mph(144.9 km/h).

The speed at the S&C is limited from 15 mph to 50 mph (24.15-80.5 km/h) when a train needs to change the railway line. Figure 2.1 shows the signals lamps with Train Protection Warning System (TPWS), which are fitted at the entrance of each S&C area to prevent Signal Passed at Danger(SPAD). According to the structure of S&C in Figure 2.1, each train may pass different routes at S&C, which contains different number of point machines. Independent of the route assigned to the train, the train will pass TPWS at each S&C entrance. For this part of section, there are 12 pairs of point machines are installed in the S&C area.

In this study a train is assumed to travel in one direction, i.e. up or down, but it can change between fast lines and slow lines. Therefore S&C can be only used for trains to change lines in the same direction. Signals without TPWS are installed on the plain line to separate running trains to prevent the train collision accident, the section between two signals is called “a signal block". 4-aspects signals are adopted to control the traffic (red means “stop", green is ok, yellow means caution and double yellow is caution and trains should stop); permanent speed restriction(PSR), temporary speed restriction (TSR) and permissible maximum speed are indicated at the entry of each signal block.

In practice, the speeds in the adjacent blocks are not independent: for example, if the signal at the entry of block C (in Figure 2.1) is double yellow, and thus the signal for block B is yellow and for D is red. In order to simplify the operation of system, we assume that the speed of each train at different signal blocks are independent and it does not need to consider the existence of another train on the running line.

2.3 Railway assets

According to the railway section shown in Figure 2.1, the structure of the railway system can be seen in Figure 2.2, which shows some relationships of the railway devices involved. In this section, we introduce the functions and basic requirement of track and S&C.

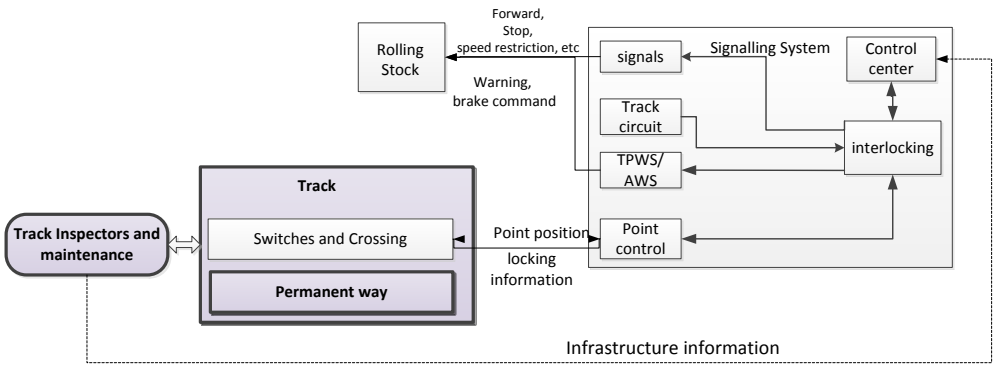


Figure 2.2: Railway System structure

Figure 2.2 shows the major devices of signalling system: control centre, interlocking system, signals, track circuit, point machines and the protection system which contains train protection warning system (TPWS) and automatic warning system (AWS). Track circuit is used to identify the railway block occupied by a train and it is also a means of broken rail detection. The signal devices (including the 4-aspect signal lamps, track circuit and point machines) are assumed to be controlled by the interlocking system. Considering the time tables and the occupation of the railway line, control centre arranges a route and the permissible speed (including permanent speed restriction (PSR), temporary speed restriction (TSR) and maximum speed) for the coming train and then the interlocking system sends the signal commands to signals, point movement commands to the point machines and the moving authorities to the protection system.

In the following sections, we present some details of track, S&C and point machines. Track is the railway asset which the trains travel on. S&C can be considered as a special type of track, which contains movable and fixed rail. The movable rails are controlled by the point machines and the point control commands come from the signalling system. The point machine has to move the switch rail to the right position and maintain the correct track gauge in order to make sure a train can pass through safely.

2.3.1 Track

Track is one of the railway assets which support trains, it should maintain its gauge, cant, cross level and alignment of rails within the limits to make sure train can go through safely, these are the critical geometry parameters of track.

Track is known as the permanent way on a railway line an it can be classified into three types: ballasted track, slabbed track and embedded track [45]. The track system discussed in this thesis is positioned on ballast. It consists of rail, rail joints, fastening systems, sleepers and ballast, as shown in Figure 2.3.

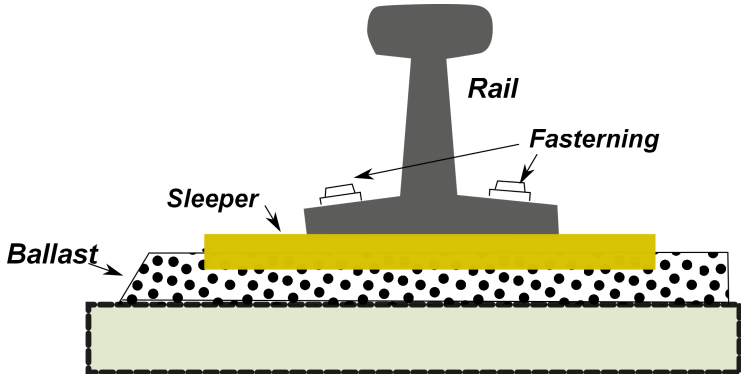


Figure 2.3: Track structure

Ballast is a "single sized granular material of specified properties, placed on the blanket, subgrade or structure to provide vertical and lateral support to the sleepers or bearers" [64, 156]. The ballast bed consists of a layer of loose coarse grained material[120]. It is used to resist forces applied to sleepers to maintain track position; it suffers from stress

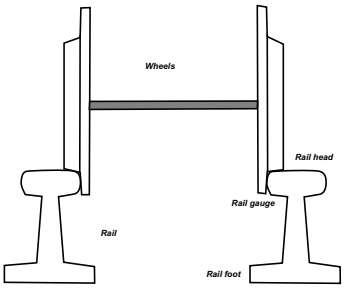


Figure 2.4: Rail



Figure 2.5: Rail Joints and the fastening on sleepers [169]

caused by moving train, this vertical force will cause the ballast crushing and abrasion. Therefore, the track on the defective ballast will subside which may lead to a track vertical fault and then cause a derailment; in addition the defective ballast can result in track losing the lateral stability, which may increase the risk of track buckle [103].

A sleeper is a transverse beam that provides vertical and lateral support to running rail and rail fastening [64]. It can be made of wood (timber), concrete or steel. In this thesis, the sleepers are assumed to be wooden sleepers. The life cycle of wooden sleepers is around 25 years [69, 12]. The distance between two sleepers is usually 60cm. The rail is fixed on the sleepers by fastenings, which are used to prevent the rotation and movement of the rail. The condition of sleepers and fastenings have impact on the track gauge, which is 1435mm [120]. The sleepers may be bent due to the traffic load, improper installation and so on, which will result in a wider track gauge. Furthermore, the rotten or fractured sleepers may also lead to a defective track gauge. Poor fastening such as the chair shuffle, baseplate, screw shank polishing or loose screw may also widen the track gauge[151].

The rails support and guide the trains, which are installed on the sleepers. They contact to the wheels directly, the shape of rail head and the surface of the rail determine the wheel-rail contacting angles. According to the Nadal's derailment formula, the angles determine the derailment condition as shown in Figure 2.4 . The rails either are welded together or are assembled by rail joints as shown in Figure 2.5. Rail joints (normally known as fishplates) should make sure the rails are insulated for the track circuits.

2.3.2 Switches & Crossing

S&Cs also contain rail, rail joints, fastenings, bearers and ballast so the defective S&Cs have the same failure modes as the straight lines do: track geometry faults and the rail faults. However some additional failure modes need to be considered. S&C area is a special track system which has a structure different of the plain line track system. Figure 2.6 illustrates a simple example of S&C, which contains two parts: switch part and crossing part. The switch part consists of stock rails, switch blades, switch points; crossing part consists of through Rails, wing rail, crossing, check rails [54].

The stock rail is a fixed rail; the switch rail is a movable rail. The switch blades can be closed to stock rail. The end of the switch blade is called switch toe, there should be a gap between the switch toe and the stock rail to permit the wheels passing. A minimum

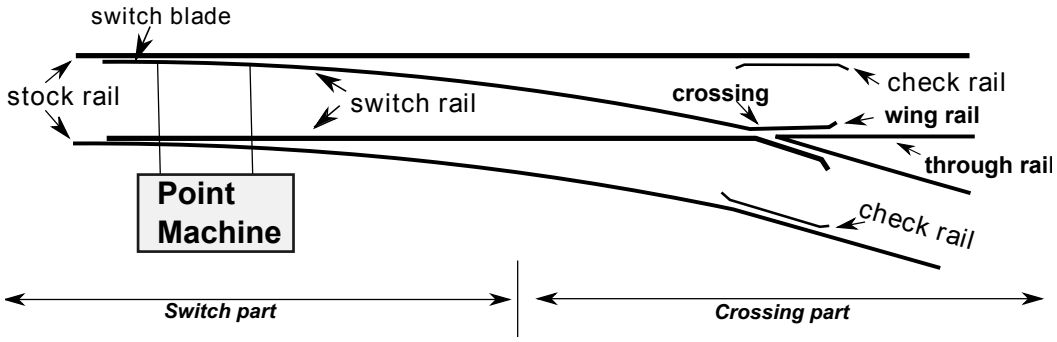


Figure 2.6: S&C structure

flange-gap of 100mm should be maintained at the switch toes. The closure rail guides the train to the other track and the check rail and wing rail are used to guide the wheel to go straight and maintain flange-gap for wheels. The triangle between the wing rails is called crossing nose, it is the end of through rail. Figure 2.6 shows the normal position of the switch; trains go straight from left to right at this S&C, if the gap between the up stock rail and the up switch rail achieves the flange-gap requirement. If the gap is too small, the wheels will climb up the rail and train derails. There are two stretcher bars connecting with the pair of the switch rails, one at the switch toe and the other at the switch heel (the red points in Figure 2.6); the stretchers are used to ensure the flange-gap is achieved on the open side (right hand side) and the switch blade on the left hand side is closed to the stock rail at the same time. The switch rails are moved by a point machine.

2.3.3 Point machine

Point machine is used to move switch rails to the required position according to the interlocking commands and then it should make sure that the switch rail will not move before the interlocking send another command.

There are many different kinds of point machines used in railway: electro-mechanical points, electro-pneumatic points and electro-hydraulic points [179]. The electro-mechanical points are assumed to be used on the example railway line. Points are installed at the wayside, they drive the switch rails in order to close switch blades to the stock rails on the closed side and keep a flange-gap on the open side when they receive the command from the interlocking system. It needs to be able to lock the switch rails at the required position and make sure that they will not move when the train passes[138].

Figure 2.7 shows the structure of a eletronic-mechanical point machine.A motor is used to move the drive bars; the drive bars are connected to the stretchers, which move the switch rails and stretchers together. The detector bars connect corresponding switch rails to the point detection device. The lock bar is used to connect the stretcher and the point machine to prevent the switch rail moving when a train is passing. The circuit controller processes the commands from the interlocking system and then control the behaviour of the motor, the locking devices and the detection devices.

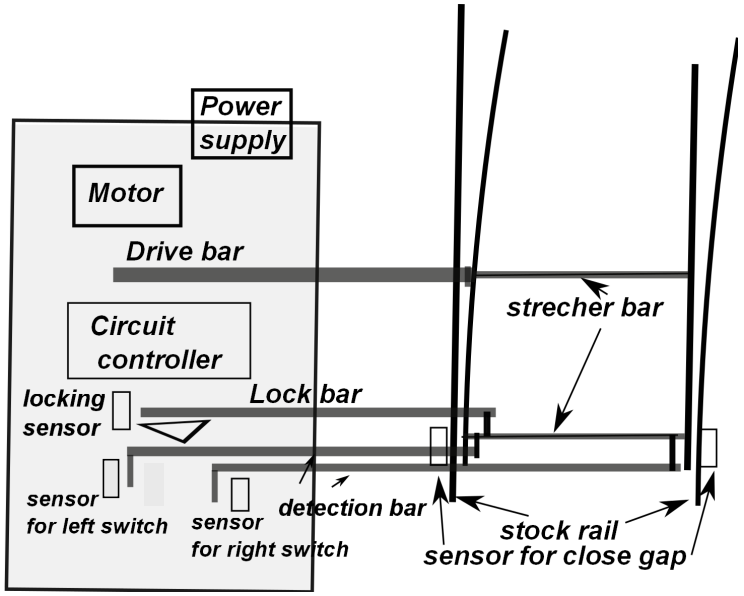


Figure 2.7: Point machine structure

2.4 Railway assets failures and maintenance

According to the track introduction, degradation of three main devices (the sleepers, the ballast and the rails) may cause the track system failures. Since they have different degradation mechanism and patterns, a presentation of their failures and corresponding maintenances is given in this section.

Track dangerous failures include track geometry faults and rail faults, which may cause the derailments. The corresponding maintenance methods and their effects should be considered when the maintenance decisions are made. Considering some existing derailment investigations, the dangerous faults of point machines are also introduced briefly in this section.

2.4.1 Track geometry faults and maintenance

Since the geometry condition of track has impact on passenger safety, life cycle cost and train punctuality, it is important to learn about the failure modes and their corresponding maintenances. Above all, we need to find the representation for the track condition (quality). There are several approaches to indicate track quality in different countries [168].

2.4.1.1 Track geometry quality measurements

Some countries prefer to analyse the track geometry parameters (gauge, cant, level and alignment) separately using standard deviation(SD) of short wave (3-25 meters) or long wave (35m). Standard deviation(SD) is a universally used technical measure of the variation of a random process. Track profiles have been found to have sufficiently similar

statistical properties to random processes to enable a measure of the magnitude of track irregularities to be obtained from the standard deviation of the vertical and horizontal profile data. This form of analysis provides track quality indices [64]:

$$\sigma = \sqrt{\frac{1}{m}\Sigma(a_1 - a)^2} \tag{2.1}$$

σ is the standard deviation; a_1 is the actual measures; a represents the average of the measures; m is the number of measurements.

Some countries describe track quality with a synthesis indicator which includes all of the track geometry parameters (gauge, cant, level and twist). Track Quality Index(TQI) is used to indicate the track quality in China, Zimbabwe and so on. The general TQI is defined in Equation 2.2:

$$TQI = \sum_{i=1}^{n} a_i \delta_i \tag{2.2}$$

δ_i is the track geometry parameters, such as the gauge, cants, level and alignment. a_i is the coefficient parameters. In China, Equation 2.2 is specified to be Equation 2.3, there are 7 parameters (not only including the gauge, level, alignment and twist, but also SDs of each rail surface for both left rail and right rail) in the equation, and δ_i denotes the standard deviation of the geometry parameters [191].

$$TQI_{china} = \sum_{i=1}^{7} \delta_i \tag{2.3}$$

In Sweden, TQI is changed to be Equation 2.4 [56]:

$$TQI_{sweden} = 150 - 100(\frac{\delta_{LL}}{\delta_{TH_LL}} - 2\frac{\delta_{AC}}{\delta_{TH_AC}})/3 \tag{2.4}$$

δ_{LL} is the the average of the standard deviations of left and right profile;δ_{AC} is standard deviations of the combined alignment and cross level. δ_{TH_LL} and δ_{TH_AC} represent the comfort threshold of the parameters.

The above track quality representation focus on the track geometry and profile, but sometimes, track maintenance needs to consider the condition of the devices and hence Sadeghi et al describe track quality considering both the geometry condition and the devices condition with Track Geometry Indicator (TGI) and Track Structure Indicator (TSI): [166].

$$TGI = \frac{2UI + TI + 6AI + GI}{10} \tag{2.5}$$

$$TSI = (BCI, SCI, RCI) = 0.5CI(low) + 0.35CI(mid) + 0.15CI(high) \tag{2.6}$$

Track Geometry Index (TGI) is similar to TQI, taking into account twist (TI), alignment (AI), gauge (GI) and unevenness (UI); these four parameters are calculated by the standard deviation of the measured result.

TSI is used to indicate the average condition of the track structure. BCI, SCI and RCI are ballast, sleeper and rail condition indices and $CI(low)$, $CI(mid)$ and $CI(high)$ are the

lowest, medium and highest amounts for the condition indices of ballast, sleeper and rail respectively.

Furthermore, J synthetic coefficient is used in Polish railway which also considers the gauge, vertical, horizontal and twist parameters together [17]. Key Performance Indicator (KPI) is another track quality indicator which combines the plain line, switch and crossing, maintenances together [203].

According to the best practical experience, CEN standards adopt standard deviations to indicate the track quality. In order to guarantee the safety, EN standard EN 13848-5 requires three maintenance levels for the track geometry faults in order to guarantee the railway safety [55]:

- Immediate Action Limit (IAL): if the standard deviation exceeds this value, it requires taking measures to reduce the risk of derailment to an acceptable level. This can be done either by closing the line, reducing speed or by correction of track geometry.
- Intervention Limit (IL): the value, which, if exceeded, requires corrective maintenance in order that the immediate action limit shall not be reached before the next inspection.
- Alert Limit (AL): the value requires that the track geometry condition is analysed and considered in the planned maintenance operations.

Even though EN13848-5 recommends three maintenance levels for track geometry faults, there is not the mandated values for these geometry parameters; thus infrastructures conductors have their own optimized maintenance thresholds considering the cost, the availability, the human sources and usages of maintenance machines.

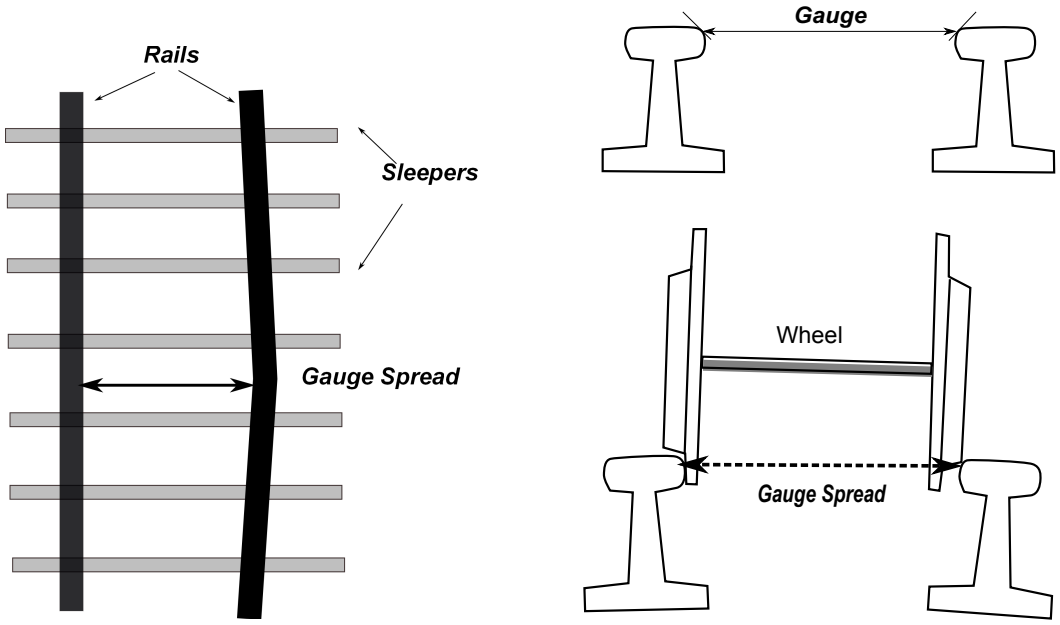
In the following sections, the major geometry track faults, rail faults and their corresponding maintenance are presented.

2.4.1.2 Track gauge spread

Track gauge is defined as: the smallest distance between to running rail surfaces. Two kinds of track gauges are defined according to the load of the track. Measured gauge with the load is defined to be the dynamic track gauge, while the measured gauge without the load is static track gauge. [64, 157].

Gauge spread is the tendency of the gauge of inadequately maintained track to become greater as shown in Figure 2.8a. According to the definition of track gauge, gauge spread is classified to be static gauge spread and dynamic gauge spread respectively. As shown in Figure 2.8, the top one shows the static gauge and the bottom one shows that the gauge widens when a train passing.

According to Ellis' British Railway Engineering Encyclopaedia, gauge spread can be caused by a defective fastening system, such as the chair shuffle, loose screw and so on. Also a defective baseplate and rotten sleepers can lead to gauge spread [53]. If the poor fastening is detected and fixed, gauge spread may not happen; otherwise, different track maintenance actions need to be carried out according to the level of gauge spread. In



(a) Overhead view of track gauge spread

(b) Static track gauge and dynamic gauge spread

Figure 2.8: Track gauge spread

practice, we can carry out the following maintenance to control gauge spread:

Tie bar:	a rod used to maintain the track gauge temporarily; in some cases, the mean time of tie-bar failure is around 60 days .
Spot-resleepering:	replacement of the sleepers at the defective location.
Track renewal:	a term of maintenance work for a track segment consisting of the rail replacement, sleepers replacement, ballast replacement and so on.

According to the requires in EN13848-5, gauge spread can be divided into 3 levels. For example, in UK, the standard static track gauge is 1435 mm and the tolerant dynamic track gauge is 1465 mm. Therefore, level 1 of gauge spread defines to be at the range of 1435-1465 mm; for this low gauge spread, the defect can be controlled by speed restriction or restrain controls including tie-bar and spot re-sleepering. If the dynamic gauge exceeds 1465mm (medium gauge spread), speed restriction and restrain controls should be carried out to control the defects. If the gauge spread is high (the loaded gauge is over 1480mm), the line should be closed and the track should be renewed.

2.4.1.3 Track top and twist

Track twist and top faults are the problems of the track cant which are caused by ballast problems. Track vertical profile (top) fault is one of track vertical geometry problems, as shown in Figure 2.10, which means there is a hole of the track. The definition of twist fault is given as: A difference in cross-levels over a short distance (3 metres) that is greater

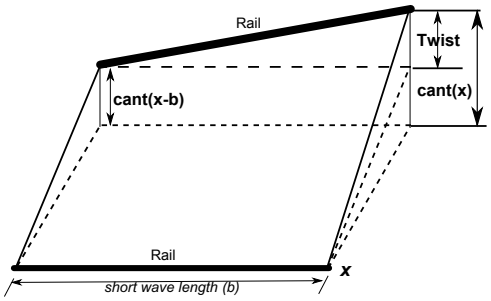


Figure 2.9: Track twist

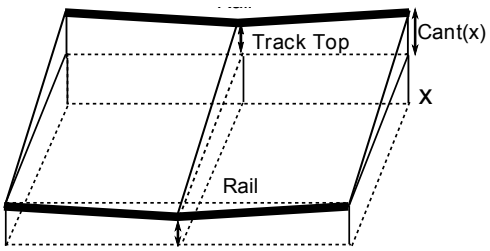


Figure 2.10: Track top fault

than a predetermined amount . As shown in Figure 2.9, the bold black lines represent the tracks, and the twist can be calculated as cant(x)-cant(x-b)[54], where cant is the difference in level between the rail head centres.

Twist can be caused by the uncontrolled poor ballast condition. There are 3 levels of twists. A tamping can be carried out to control twist and top. For example, if the twist is between 1 in 126 and 1 in 199, the maintenance should be carried out in 10 days, and between 1 in 91 and 1 in 125, the track should be maintain in 36 hours. For worse situations, immediate line closure is needed.

Maintenance methods for vertical problems: The alignment problem and the vertical profile problem can be fixed by several maintenance methods, such as tamping, stoneblowering and renewal.

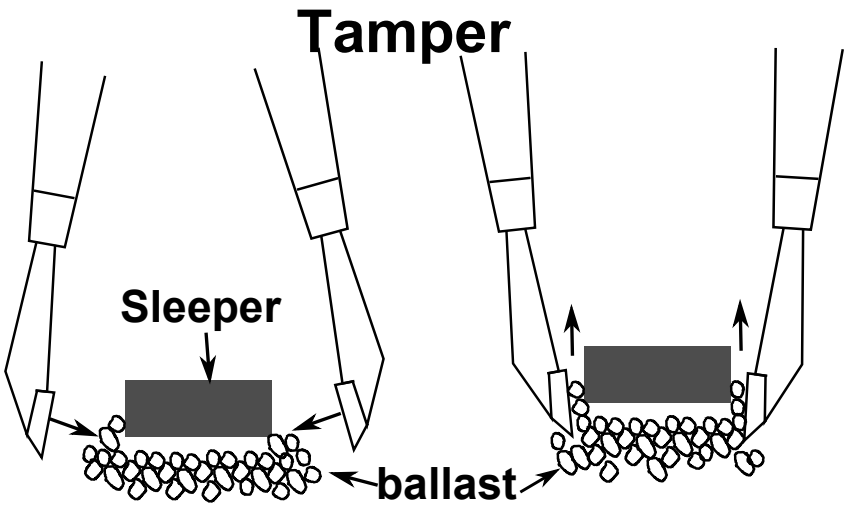


Figure 2.11: Track tamping mechanism

Tamping is a common ballast maintenance method, the machine firstly lifts the track to the determined level, then it squeeze the ballast under the sleeper, tamping can level and line the track to the determined position by the measured machine. The mechanism is shown in Figure 2.11.

Stone blowing is another ballast maintenance method, the stone blowing process firstly

lifts the sleeper to create a void, then the stone blower tube fits the grades into the void, when the sleeper is lowered onto the added stones, the process is completed as shown in Figure 2.12.

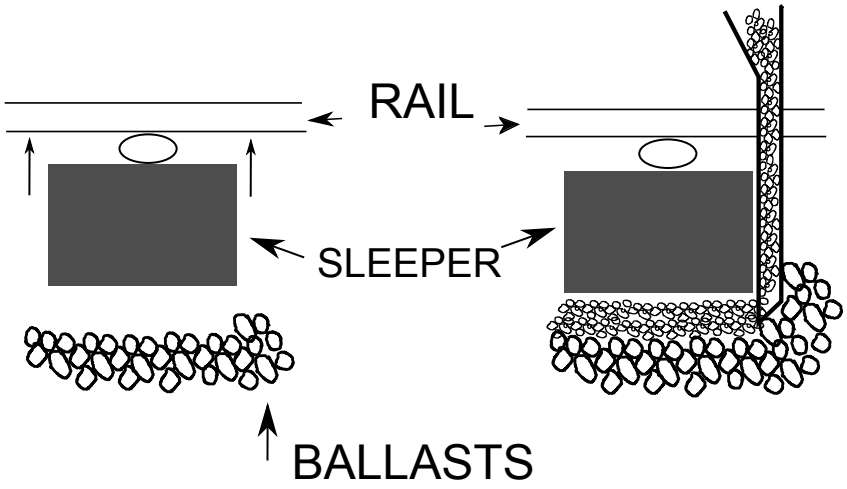


Figure 2.12: Stone-blowing mechanism

Since the mechanical of tamping tool may damage the ballast, tamping makes new contact point of the grades which may break down after the traffic loads. Compared to the tamping, the ballast damage with the stoneblower is insignificant. Thus, the need for cleaning and replacing ballast is postponed. This effect is amplified by the fact that tamping is required more often than stoneblowing. Since stone blowing uses a consistent material for geometry adjustment, the geometry correction lasts longer with stoneblowing than with tamping. However, stoneblower cannot lift the wooden sleeper adequately and it cannot be used for S&C [44].

2.4.1.4 Track buckle

Buckle is a large scale lateral movement of the track, which can be caused by high rail temperature, leading to the compressive longitudinal thermal force on the rails [96, 205]. As shown in Figure 2.13, the red lines show the normal geometry of the track, and the blue lines show the buckled track.

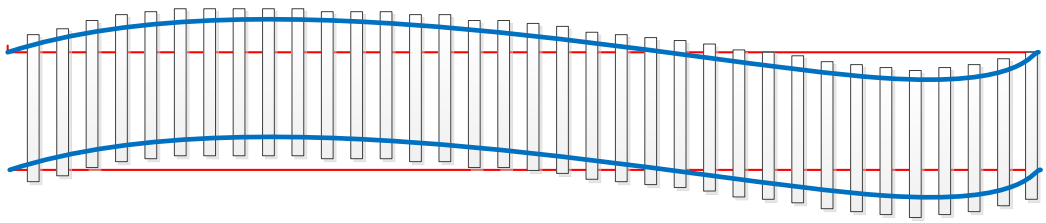


Figure 2.13: Track buckle

Buckle can be fixed by slewing the track when the buckle is slight. In the case of significant buckle, the traffic should be stopped and the renewal should be carried out as soon as possible.

2.4.2 Rail faults and maintenance

According to the rail fault location on the track, Rail fault can be classified into two types [155]:

- Broken rail joint: if the breakage exists at the fish-plated joint or at the welded joint, it is defined as broken rail joint,
- Broken rail: if the breakage occurs more than 1.8m away from joint, it is broken rail.

Broken rail and rail joint can be caused by rolling contact fatigue and different kinds of rail cracks inside the rail.

Rolling contact fatigue is the surface fatigue damage of rail[29]. Contact stress between the wheels and the rail can lead to the damage of the rail materials and then cause the rolling contact fatigue. It can be divided into three major types: rail head checks, gauge corner checks and squats; Head checks are fine surface cracks resulting from cold working of the metal under contact stress. This is typically a very fine array of small, closely spaced, nearly parallel cracks as shown in Figure 2.14. If these cracks occur at the gauge corner, they can be called gauge corner checks as shown in Figure 2.15. Squat is a micro cracks below the surface of the track as shown in Figure 2.16. Squats are very rare when the continuous cast steel is used. Therefore the causes of rolling contact fatigue breakages are considered to be the head checks and the gauge corner checks [107, 192].

Besides the surface rail faults, the contact stress may cause the rail crack inside. Rail crack can be classified into several types depending on their position and shape, such as: transverse rail crack, star crack and so on [54].

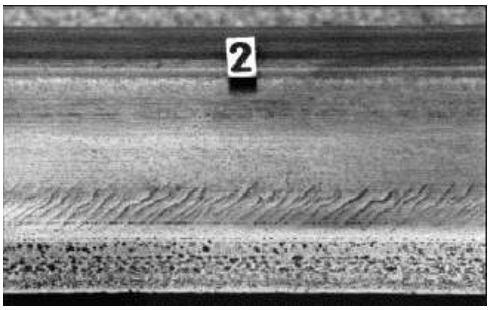


Figure 2.14: Rail head checking [98]



Figure 2.15: Gauge corner cracking [112]

Maintenance methods for Rail faults: If there is rolling contact fatigue, grinding can be carried out [113]. Grinding is implemented by rail grinder, the grinding wheels of the grinder are set at controlled angles to restore the rail to the correct profile. Clamping and bridging can be carried out as a temporary control method for the small cracks which are less than 5mm on the rail. When there is a rail breakage due to crack and a broke rail joint,



Figure 2.16: Rail squat [139]

train speed restriction will be required [154, 159]. The rail will be replaced if the rail fault is serious, the condition of the replacement is specified in the railway standards [72, 159].

2.4.3 Inspections for track

There are a few types of inspections for the track: visual inspection is carried out to locate track geometry and obvious rail defects; train recording car is an automatic inspection method which can detect track geometry parametres (gauge, cant, twist and so on) and rail faults at the same time; ulstrasonic inspection is used to identify the small cracks of rails. A minimum inspection frequency is required in the track requirement in UK track standard[64].

The inspection of track geometry is classified into loaded track inspection and non-loaded track inspection. Track recording cars are used to measure the loaded track geometry parameter and the visual inspection trolleys are adopted when we need the non-loaded track geometry measurements [124].

For the rail faults, track record cars can also detect track geometry and rail breakages, but it is difficult to detect the small rail cracks, ultrasonic inspection can be used to detect the rail tiny cracks [144].

In railway standard, the inspection intervals are given in order to maintain the safety as shown in Table B.1 and B.2. The rail on plain line without fishplate will be tested by ultrasonic inspection at the basic intervals; while the plain line with fishplate should be tested at the enhanced interval. In addition, the rail in tunnel and the rail at S&C should be inspected at a shorter interval.

2.4.4 Point machine failures

Dangerous faults of point machines can be divided into two kinds: point at a wrong position but not detected; point moving under train[86].

According to the existing derailment investigations, if a point moves under the train, the derailment also occurs. It can be caused if the point is not locked before a train arrives so

the switch rail can be moved easily by wheel-rail contact force, when the train passes. This situation appears if the locking devices fail and the detection devices fail to identify the unlock status, for example the lock stretchers are broken, or the locking gear cannot hold the lock blade. According to Potters Bar derailment accident, the defective connection devices, i.e. stretcher bar and its fastening will lead to point movement under train.

The dangerous faults of point machine mentioned above can be a single point fault of the point machine or a combination of several faults. Some researches have been conducted on the faults of point machine depending on the experiment current, voltage or stress data; some important faults have been listed as follows [63, 111, 133]:

- Tight lock on reverse side which prevents the point from moving out of position because of vibration;
- An obstruction at toe on normal side;
- Back drive slackened off at toe end on left (right) hand side, the stretcher bar holds the mobile rails a fixed distance apart;
- Back drive tightened at heel end on left (right) hand side, the stretcher bar holds the mobile rails a fixed distance apart;
- Drive rod stretcher bar loose, connecting bar between the switch rails is loose.

2.5 Conclusion for the maintenance modelling of railway infrastructure

An example of a railway line is described in this chapter to present some general operation rules and show the system construction. It consists of plain line, S&C and stations. The signal devices are used to separate the trains and manage the traffic; following the signals, trains can pass a railway section under the permissible speed. And then we present a ballasted track system and introduce track faults and rail faults in details since they are the most dangerous events leading to railway accidents.

According to the system description in this section, some interesting problems are outlined as follows:

- There are several types of methods can describe railway asset failures: we can consider the time to failure of the components and its deterioration or we can describe the condition by monitoring standard deviations of measurements.
- Speed is one of the deterioration factors for track twist and top faults; we can take into account the speed for the track deterioration modelling.
- Some defective condition of track cannot be detected by only one inspection methods, for example, static gauge spread and dynamic gauge spread depends on different inspection condition with or without loads; tiny rail cracks need ultrasonic inspections. Thus, it is interesting to make maintenance decision based on these multi-level inspection situations for a plain line section with several track components.

- Preventive maintenance for railway asset cannot maintain the component as good as new; the effects after maintenance may depend on the number of implemented repair actions or the maintenance methods, or on the asset materials.
- According to some railway standards, delayed preventive maintenance is allowed in railway maintenance, for example, the maintenance of track twist can be schedules in one month.
- The example in Section 2.2 describes a railway section and some operation rules in it. The maintenance rules of track faults also require operation co-ordination, such as line closure, speed restrictions. To ensure the safety, the traffic needs to slow down in the defective section or to stop beyond the section.

In order to solve these problems, some existing models for the deteriorations, inspections and maintenance policies are introduced in Chapter 3 to learn from some related existing researches on railway maintenance in the literature.

CHAPTER 3

Deterioration/failure and maintenance models for railway application: state of the art

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3.1 Introduction

In this thesis, we want to work on the maintenance modelling for railway assets. Regarding to the system description in Chapter 2, we can describe the health of track by standard deviation of the short wave measurements; infrastructure conductors have their freedom to set the preventive maintenance threshold but they should follow the mandated corrective maintenance threshold in the standards. In addition, inspections for the track condition are carried out depending on different track types, materials and operation modes.

The existing models for deteriorations, inspection and maintenance are presented in this section, especially the models for railway applications.

There are several kinds of description for failure processes which have different characteristic in the modelling. Some maintenance strategies are not suitable for some special

failure processes. We review the existing researches in the literature which work on the deteriorations, maintenance modelling and optimization, especially the researches on the railway industry.

In section 3.2, we summarize the existing failure models in order to help us to learn about the properties of the deteriorations and their application. Section 3.3 summarizes some inspection policies in the literature. Section 3.4 reviews the maintenance policies for the single component and for the multiple component. In section 3.5, Applications of Fault tree and Petri Net in risk analysis are reviewed.

3.2 Failure modelling

Railway systems consist of several kinds of devices, they suffer of several kinds of failures, such as the aging behaviours, the wearing on the rail surface, the shocks which may cause rail breakages and so on. In this section, we want to investigate some existing failure models; depending on the different failure models, different maintenance policies can be adopted on the system, and then these policies have different effects on the system performances, such as maintenance cost, system risks and system availability.

3.2.1 Deterministic deterioration model

Some researchers have been concerned in the relationship between the factors (such as loads, speed, materials, temperature and so on) and the deterioration. The deterministic deterioration models describe the average deterioration according to the environment, materiel and operation in railway asset failure researches.

Kish et al. describe track buckle using a linear equation, which reveals that the track buckle index depends on Young's Module, rail temperature and train speed [96]. Similarly, another linear equation is proposed to predict the rolling contact fatigue index of the rails according to the stress and the radius of the rail[51].

In order to model the significant deterioration evolutions of track deterioration, a general form of a power function is used to describe the deterioration condition of track. Traffic load and train speed are considered to be the main factors of these deteriorations. A track deterioration index can be calculated by a power function of the tonnage of the line, the axle load and the train speed of the line [220]. Another deterioration model of switches and crossing is an extension of the power function for a plain line, it also depends on the tonnage, the speed, the switch angle and the solid quality [221].

Sadeghi et al. suppose a track deterioration model considering the environment factors of the track, Track Quality Indices (TQI) are used in [166, 167], which is an integer representation of track quality. However, the index cannot show the relationship between the deterioration and maintenances. Westgeest et al. propose a regression model containing KPIs to describe degradation of track geometry depending on the local circumstances and the Key Performance Indication(KPI) maintenance models, where KPI is used to describe the track quality with a certain length [203]. The linear regression model which is obtained by regression analysis according to the observation data was used to relate the deterioration to the tonnage, tamping, subsoil and switches.[4]

These deterministic models describe the relationship between the factors (environment, physical characters and structure) and deterioration. Even though the evolution against time can be described in these models, they lack of ability to model the variations of the evolution since the deterioration increments are determined and cannot model the varied deteriorations behaviours probability.

3.2.2 Stochastic deterioration modelling

Stochastic deterioration models are adopted to describe the uncertain behaviours and states based on time. In contrast, the deterministic model, the state or condition at time t is not known and we can only predict the probability of the occurrence of the states.

3.2.2.1 Component lifetime models

Lifetime distributions offer a first solution to model the probabilistic failure behaviour of an item. They only consider the binary states of the system and describe the probability of the failure occurrences at time t, to this extent they cannot be considered strictly as deterioration models, but some of them can nevertheless captures ageing properties through an increasing failure rate of the item resulting from its deterioration.

The most simple lifetime model is the exponential distribution because the failure rate at any time is the same and it is memoryless. But it cannot model a distribution with an increased or decreased failure rate. Weibull distribution (as shown in Equation 3.1) is used widely to describe the deterioration of the ballast [5, 7, 146, 28] , the aging behaviour of signalling devices[9], the residual life function of rail defect [113] and the occurrence of the rail defect at time t [137], because Weibull distribution can represent many kinds of shapes by choosing different parameters, and hence many different ageing behaviours.

$$F(t) = 1 - exp(-(\frac{t}{\eta})^{\beta}) \tag{3.1}$$

There are two parameters in Weibull distribution. β is the shape parameter and η is the scale parameter. When $\beta = 1$, Weibull distribution turns to be exponential distribution. According to the paper [11], using a Weibull distribution with two parametres is a better way to model the failure process of track with tampering in the railway.

As already outlined, with the lifetime distribution models, we can predict the failure probability at time t, however, we cannot get more detailed information from them for maintenance decision making.

3.2.2.2 P-F interval and delay time concept

We can only consider two states in the lifetime model: failed or worked; in some cases, before the devices fail, the devices have abnormal states between good and failure, which can be detected by inspections. These defective states help to schedule the inspection and preventive maintenance and thus we can take these states into account for the maintenance.

To describe the defective states and the corresponding maintenance, two similar failure process models are introduced in the literature:

- Potential-Failure (P-F) interval;
- Delayed time concept.

P-F interval divides the failure process into two stages as shown in Figure 3.1, which is defined in [117]. The initial state of devices after installation is good, inspection can detect the defect after point “P" appears. The period between point “P" and “F" is defined as “P-F interval". According to the definition of point “P", preventive maintenance can be planned.

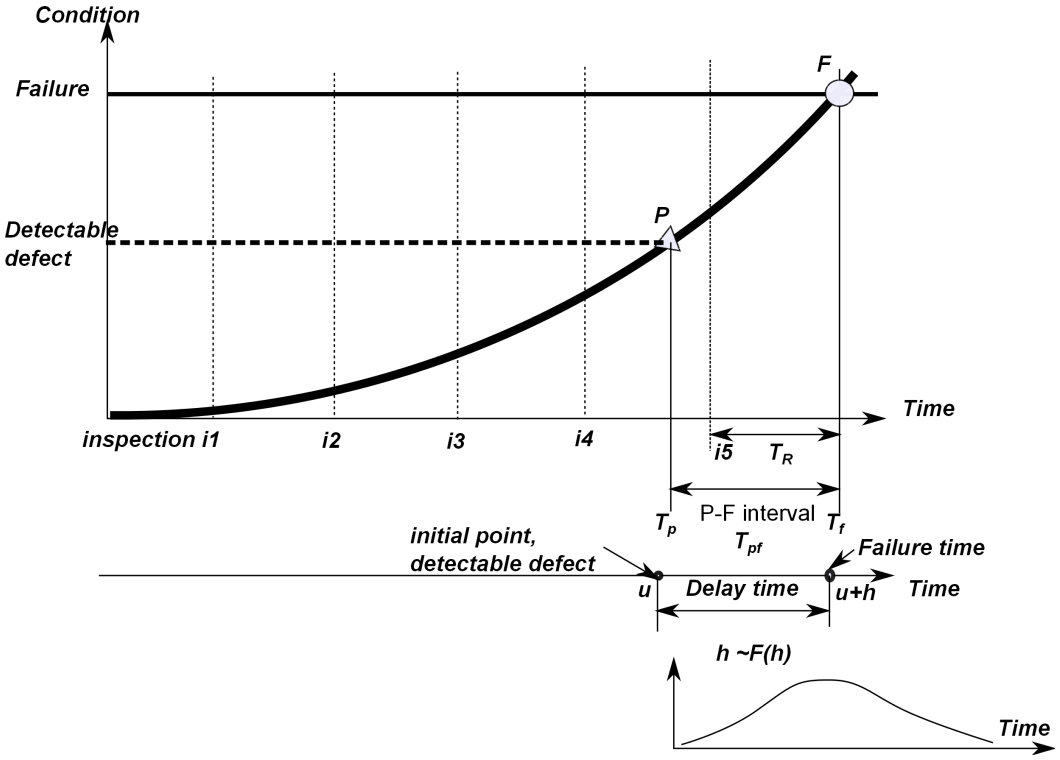


Figure 3.1: P-F interval model and Delay time model

In the P-F interval model, the probability of “P" (in Figure 3.1 between $I4$ and $I5$) between the ith inspection and $(i+1)$th inspection (i.e. $Pr(t_i < t_p < t_{i+1})$) is used to indicate whether defect “P" arises between two inspection actions. Time to repair T_R and the P-F interval T_{pf} are known in the model. There are several applications of P-F interval for the inspection interval optimization. In [144, 137, 135, 136], the evolution from crack to rail breakage is described as a multi-stage failure based on Potential-to-functional Failure interval (P-F interval), the point “P" is related to the condition which can be detect by both visual inspection and ultrasonic inspection. In [35], P-F interval is introduced to model the periodic inspection model with replacement for the pipelines to optimize the inspection interval.

Christer introduces delay time model for unrevealed failures [41, 43]. The delay time model also divides the failure into two stages: the first stage is the normal working stage; and the second is the failure delay time stage.

In Figure 3.1 the label u means the initial point of the defects and h means the delay time to failure and follows a distribution $F(h)$. If there are inspections during$[u, u + h]$, the defect can be observed and the maintenance activities can be carried out to prevent the failures. If the defective point u arrives with a rate λ, the expected number of failures can be calculated as: $E(N_f(t)) = \int_0^t \lambda F(h)dh$

Christer et al. demonstrate that if the initial state arrival has the Markov property, delay time concept and semi-Markov model has the same results, while if the arrival is not Markovian, the semi-Markov model may lead to the wrong estimation of the maintenance cost, but delay time concept can be used in this situation regardless of the Markov property [42]. The differences between P-F interval and delay time concept are discussed in [197, 194].

The delay time model is useful for optimising inspection planning according to the initial point arrival time; furthermore, some extensions such as three-stages delay time models, nested-inspection policies are introduced to fit the practical situations[13, 104, 195, 201, 210, 58, 130].

3.2.2.3 Models for deterioration

With the development of inspection technology, more data are available than before. These collected data cannot only indicate the binary state or the three stages process but also reveal the exact condition of the monitored system. To describe the evolution indicated by the monitoring and to use them in maintenance decision making purpose, models for the deterioration process are needed.

Some damages are due to discrete events such as shocks: if the damage size is constant, Poisson process can be used to model the deterioration process, Shafiee et al. consider the track deterioration depending on the usages which follows a non-homogeneous Poisson Process [171]; if the damage size is random, Compound Poisson Process can be used [14, 90, 62, 78, 180].

If we consider the aging process, wearing process and other continuous process between two maintenances, we need to describe the gradual deterioration. Quiroga et al proposed a stochastic model for track geometry deterioration. The deterioration process assumes that the evolution between two tamping is exponentially distributed $(Ae^{(b_n(t-t_n))}$,where b_n follows a normal distribution $b_n \sim LN(\mu_b(n), \sigma_b^2(n)))$, $t_n$is the time of the last tamping and the measurement noise is $\varepsilon_n(t) \sim N(0, \sigma_\varepsilon^2)$, A is denoted the state after tamping [148, 147]. Meier et al propose a Gamma process to describe the track geometry deterioration[114]. VanNoortwijk summarize the application and maintenance models based on Gamma process [182]. In [183, 184], the gradual deterioration based on a Gamma process is compared to the corresponding lifetime model. Vale et al. propose track deterioration model based on Dagum probabilistic distribution for condition-based maintenance [181].

If two failure modes, both of which follows a Gamma process, are considered for the maintenance, a bivariate Gamma process is proposed[115]. If the environments factors are taken into account for the deterioration, the parameters of Gamma process (such as the shape parameter α) needs to change and represent the impact of the factors on the

deterioration process [48, 47, 84].

3.3 Inspection policy

Inspections are used to identify the component or system condition/state. In practice, several kinds of inspections are possible, depending on the monitoring time, the inspection can be classified to be the continuous monitoring and the discrete inspection; depending on the capability, inspections are classified to be perfect and imperfect (full inspection or partial inspection).

Based on the deterioration process, a perfect inspection can be also described as a stochastic process. In some cases, the imperfect inspection is modelled by introducing a combination of real measured condition and a noise, for example, another process combined by the original deterioration process with a normally distributed measurement errors [91].

Some researches introduce the detection probability p to indicate the inspection capability[210, 211]. In [20], Berrade et al assume the inspection is imperfect: a probability of positive responses for failure and a probability of the false alarms are introduced to model the inspection results.

With the P-F interval and the delay time model , defective states are introduced to divide the failure process to be detectable and undetectable. They can model the non-Markovian assumptions for the defect arrivals. The inspection may incorrectly identify the errors or they may ignore the errors, these two situations are represented by a probability p and q before and after the initial point arrives in delay time model [59].

The safety critical equipments consists of several parts, partial inspections for some parts and the full inspection is scheduled for the whole equipments; in addition, the dependent failures are also considered in the model. Pascual et al. propose a $\rho\beta$ diagnose coverage model for the complex safety system, ρ indicates the defect detected probability by partial inspection and β is used to represent the dependent failure [134].

If there is the continuous monitoring, the component state can be modelled as a revealed failure[18, 37].

Inspection performance interval for discrete inspection is another issue in the modelling since the different inspection schemes lead to different maintenance strategies and results different effects of maintenances. Regularly, we plan the periodic inspection to monitor component states, and the inspection intervals are the maintenance decision variables [177].

Age-based or time dependent inspection policies are discussed in the literature [33]. According to the collective data, inspection can be planned according to the previous state or the time: Golmakani et al. apply an age based inspection policy for the condition based maintenance [67, 68].

Once the devices suffer to different failure modes which can be detected by different inspection methods, multi-level inspections are scheduled for the devices, the optimization for the nest inspection planning are discussed based on delay time concept [193, 195, 196, 199]. Ferreira et al propose a decision model to optimize the periodic inspection interval based on delay time concept for multiple evaluation indices[58].

An inspection scheme depending on the cumulative distribution of Q value of track geometry quality is proposed, taking into account the inspection interval and the tamping horizon after inspections to find an optimized inspection interval and frequency [10].

If the observed track quality data can indicate the component state, periodic or non-periodic inspections can be scheduled. The observed states by periodic inspection can be modeled as a semi-regenerative process [114]. Based on the precise inspection data, inspection interval can be scheduled as non-periodic according to the observed states [32, 71, 16, 212, 215, 97].

3.4 Maintenance policy

With inspection for unrevealed failures, renewal or corrective maintenance are carried out to prevent the component failures and to maintain the system in an acceptable operating condition. In the railway system, we need to make decision for maintenance, in [74], a decision making process is proposed. There are thousands of maintenance policies, some of them are suitable for general applications, while some of them are proposed for the special system. Wang summarizes the major maintenance policies and gives their advantages and disadvantages [188].

3.4.1 Maintenance effects

Similar to inspection models, maintenance actions can be classified into three types according to their effects: perfect maintenance, imperfect maintenance and minimal maintenance [163]. After a perfect maintenance (replacement or renewal), the component is fixed to the original new state. An imperfect maintenance cannot repair the component to be "as good as new" but better than the minimal repair. A minimal repair is a kind of repair which fixes component to a state as bad as old, under which it can continue work but it is not good enough for a long time.

The maintenance effects are the key issue in maintenance modelling because they may introduce different deterioration models, they can lead to the limited opportunity of maintenances. In order to describe the maintenance effects, several methods are considered.Pham et al. introduce the imperfect maintenance models between 1985 to 1996 [142].

If the failure models focus on the lifetime, virtual age is a method to describe the imperfect maintenance [52]. Virtual age model is suitable for the components which suffer from an aging process, it assumes that the maintenance can either reduce the virtual ages as a proportional to the value before maintenance or reduce the increment of the virtual age [94, 141]. The rail grinding effect is described by a reduced amount of virtual age model [113].

Some imperfect maintenance actions may change the failure rate after the maintenance [38, 81]. Both repairable and unrepairable failure modes are considered in [206], they assumed that the hazard rate of the maintainable mode increases as a consequence of the deterioration of the unrepairable failure mode. Wang et al consider the imperfect maintenance represented by decreased functional time and increased the maintenance time [189].

3.4.2 Maintenance policies for single component

Several kinds of maintenance policies are discussed in the literature, such as reliability-centred maintenance [138], risk-based maintenance[100, 82], time-based maintenance, age-based maintenance and condition-based maintenance. The probability to implement either one of these strategy depends on the level of information available on the system. [3]. The choice of a maintenance strategy is also a strategy for a company.

If the monitoring data can just indicate the working state (OK or failed), time-based or age-based maintenance can be scheduled based on the failure time analysis [3, 126]. The problem of time-based or age-based maintenance (ABM) is to find out a optimized maintenance interval T_M to get a minimal maintenance cost. For the replacement strategies in railway maintenance, Antoni et al compare age-based replacement to a replacement strategy based on the number of failures for the signalling devices, which follows a Weibull lifetime distribution, one of the replacement is age-based, another one is carried out depending on the number of defects [8]. Shafiee et al propose a maintenance policy considering the usage and they compare the age-usage policy to the age-based policy, and the numerical results show that the combination policy (i.e.age-usage maintenance policy) can reduce the service cost [171]. A Proportional hazard model is used to describe the aging process with increasing rate of single component[110]. Age-based maintenance is extended to discuss the minimal repair for a system which has two types of failures [89]; Huynh et al. also consider age-based minimal repair for the competing failure modes [85].

Condition-based maintenance (CBM) can be performed if the inspection can collect the deterioration state of the component [71, 70, 200]. The preventive maintenance threshold can be one of the maintenance decision variables, which can implicitly predict the lifetime of the equipments. In 1995, Fararooy propose a condition-base maintenance for the "train stop" devices next to the signal lamps by monitoring the air pressure[57]. Condition-based maintenance strategies are also adopted to consider the maintenance for the combined failure process [27, 36, 216] and the failure process exposed to a dynamic environments[209].

3.4.3 Maintenance modelling for multi-component

All of the issues mention in the previous sections such as the deterioration model, the inspection and maintenance model can be applied to a multi-component system. In order to model a multi-component system, we need to consider the system structure, the interaction between the components, the common effects of environments on the components and so on; all of these issues are summarized as the structural dependence, economic dependence and stochastic dependence [46, 123].

In the literature, some researches consider the dependence between components. The most basic stochastic dependence in the multi-component modelling is the common cause failures (CCF), a basic model divides the component with common failure to be two part, one is part represents the independent failure and another one is the dependent failure, then the system is re-constructed according to the settings [6, 163]. α factor and β factor models are two important extensions for the common cause failures. In the recent years, lèvy copulas is used to describe the stochastic dependence for the deterioration models [92,

102]. Some researches considers the components in the system are structural dependencies, for instance, effect of maintenance for a series system with correlated failure [190] and a redundancy for a series-parallel system [127].

Grouped maintenance takes advantage of economic dependence for multi-component system. Block replacement is one of the grouping policy which implements a preventive maintenance for all the component in a block group. Since the time tracking for the component is complicated and difficult, Li et al introduce a modified age-based replacement [101]; with the bivariate stochastic process, a condition-based block replacement is proposed for the dependent failures without knowing the correlation. Castanier et al. discuss the condition-based maintenance grouping for a series system and they show that a new threshold for the system can reduce the long-term maintenance cost [34]. An age-based grouping for multi-series system is proposed to optimize the group preventive interval [170]. In [2], they summarize some existing researches about the opportunistic maintenance in order to save system downtime and maintenance cost. A condition-based grouping for opportunistic maintenance is discussed in [208]. In some cases, the planned fixed grouping needs to be adjusted according to the environments or operation context, Bouvard et al. propose a dynamic maintenance grouping decision model for the vehicles based on the monitoring information[23].

There are two kinds of opportunistic maintenance considered for railway asset maintenance: one is the combination of components in the same railway track segment; the other one is the combination of component renewal in adjacent track section. Luis et al. [28] concludes the opportunistic maintenance model to combine the component renewal in adjacent track section.

The maintenance modelling for multi-component mentioned above considers structural dependence, economic dependence and stochastic dependence; however these are not enough for the railway network maintenance strategies, the allocation of the maintenance activities and the arrangement of crews should be taken into account, as well as the operation of the trains. Therefore, it is interesting to find an optimal maintenance strategy for a global railway network, concerning system functions, failures, railway operations and maintenance configurations. Some global maintenance schedules are proposed for the railway network in [125, 132, 116]. There is a preventive railway scheduling for a routine maintenance work and the major preventive maintenance activities, in order to save the cost of the preventive maintenance [140, 164] and the whole system downtime [77], the maintenance activities are wished to be carried out as much close as possible[25], but in this research it is the scheduling for one segment jobs. And then there is an optimal scheduling of a railway region taking the residual life of the devices and the travelling time of the teams into account[207]; and two scenarios of the segments of the track are considered to improve the maintenance models[145].

Since we need to consider the functions, failures and maintenance configurations for the railway maintenance modelling, it is important to pay attention to the model the failures which may lead to the accident, and hence the railway network maintenance model may need to describe the possible risks.

3.5 Railway risk modelling

Safety is important for railway system, in order to guarantee the risk of the system at an acceptable level, risk modelling is required to evaluate the accident frequency and consequences. In railway industry, Safety Risk Model (SRM) is used to estimate system risk, SRM consists of Fault Tree Analysis (FTA) and Event Tree Analysis (ETA). Fault tree estimates accident frequency considering system failure logic [118]. It calculates top event frequency or probability using minimal cut sets. Basic events in fault tree describe the component failures; they can model revealed repairable failure, revealed un-repairable failure and unrevealed repairable failure with periodic inspection [6]. The above failure models for basic event are not enough to consider the effects of maintenances on risk as these models cannot describe multi-level repairs or inspections in details.

Petri nets are used in the railway risk model due to their capability to describe concurrent events in accident scenarios [214]. Petri nets estimate accident frequency or probability by thousands of Monte Carlo simulations. Colored Petri nets(CPN) are a kind of high level Petri nets. They introduce colored set into the Petri nets, so it is possible to build an object-oriented Petri net model for complex systems.

Malhotra et al introduced an automatic way to convert fault trees to Petri nets [108]. Vernez et al gave an overview of accident modelling using Petri nets; they introduced the conversion process of safety concepts to Petri net structures[185]. Nivolianitou proposed to build a scenario-based Petri Net model with Unified Modelling Language(UML) [19]. The Petri net model converted from a fault tree can show direct causes of an accident, it is a good way to obtain all possible accident contributions in the model. However it does not describe the failure process of a system or interactions between components.

Several studies include modelling railway accidents, with a focus on the collision on the railway line, and only adopting simple repair activities in the models. Ghazel used stochastic Petri net for the level crossing collision risk assessment [65]. Wei et al proposed the Petri net models for the collision at a station and at a level crossing[213, 214]. The failure model does not considers the details of component degradation and the preventive maintenance strategies. Petri net model for maintenance modelling needs to be considered in this study to describe several levels of failures and kinds of inspection and repairs in the model.

3.6 Conclusion for the existing failures and maintenance models for railway assets management

In this chapter, some existing failure models, inspection models, maintenance models and risk modelling in the literature are reviewed.

Chapter 2 presents some interesting problems of railway maintenance. In this chapter, we learn some existing works related to the problems identified in Section 2.5:

- lifetime distribution can be used to model the data only indicates the time to failure; stochastic process is a way to model the component deterioration;

- The deterministic models are used to model the deterioration based on different environment factors, physical factors and system structure;
- Inspection capacity can be modelled by several methods: they assume that different condition stages to model the inspection capacity.
- Condition-based maintenance can be performed for the component or system according to the observed health condition; in addition, condition-based inspection can be applied to the system.

However, the solutions of the existing models need to be extended to model the following details for the problems in this thesis:

- The condition-based maintenance models existing do not consider the preventive repair delays: during this delay time, component is still working and the deterioration continuous which may lead to the accident.
- Multi-level inspection models based on the delay time concept are introduced for a multi-component system to optimize the inspection intervals. However, the multi-level inspection models for railway assets need to consider the system structure and the accident scenarios.
- A gradual deterioration model is needed, which depends on some environment and operation factors, such as the speed, the loads and so on. Thus, the deterioration model links the system operation and maintenance.

Thus, we work on the maintenance modelling for railway assets which considers the track health deterioration based on the operation factors; the multi-level inspection and maintenance models including accident scenarios; and a delayed preventive maintenance model for the track component.

Before we present our maintenance models developed in this thesis, some important mathematical modelling tools and Coloured Petri Nets are presented in Chapter 4, which are useful for the modelling framework considered in this thesis.

CHAPTER 4

Modelling tools

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4.1 Introduction

To evaluate the maintenance strategies performance and operation risk for the railway systems, it is necessary to have at one's disposal models for the deterioration/failure of the railway infrastructure and its components, for the inspection/ maintenance policies and for the system operation. In this chapter, the concepts and properties of some probabilistic mathematics models for the failure process are introduced, including both of the probability distributions and the stochastic processes.

In addition, since we want to model the maintenance process using Petri Net, the formal definitions and properties of Colored Petri Net and the interface of CPN Tool are presented. A CPN model for a component maintenance is described as an example to show the capacity of CPN tool.

4.2 Probabilistic models for deterioration/ failure modelling

4.2.1 Lifetime distribution

A lifetime distribution is denoted as $F(t)$, it only considers that the system state is binary: worked or failed. It calculates the probability that the failure occurs before time t. Let T

indicates the failure time, then we have:

$$F(t) = Pr(T \leq t) \tag{4.1}$$

And, the failure rate , the probability that the component fails after it works during (0,t]. It is a conditional probability:

$$\lambda(t) = \frac{Pr(t \leq T \leq t + \Delta t | T \geq t)}{Pr(T \geq t)} \tag{4.2}$$

Unavailability is the probability that the component will not work at time t, which is denoted as $Q(t)$, the opposite of unavailability is availability $A(t)$.

4.2.1.1 Exponential distribution

Exponential distribution is the most common life time distribution. The probability function is written as:

$$F(t) = 1 - e^{-\lambda t} \tag{4.3}$$

The failure rate in exponential lifetime distribution is a constant λ.

In the classic reliability theory, exponential distribution is discussed in details to calculate the unavailability, failure frequency of the components, for example, in Fault tree. In reliability and risk assessment [6, 163], the formulas are given to calculate the unavailability of the revealed failures and unrevealed failures. If the time to repair also follows a exponential distribution with parameter τ, the stationary unavailability of the revealed failure is given as Equation 4.4:

$$Q = \frac{\lambda}{\lambda + \tau} \tag{4.4}$$

If the failure is unrevealed and the inspection is carried out with the period θ to identify the failures, the average unavailability is calculated as Equation 4.5:

$$Q_{avg} \approx \lambda(\frac{\theta}{2} + \tau) \tag{4.5}$$

Since exponential distribution is memoryless with a constant failure rate λ, it cannot model the fatigue, wear and aging of the component, exponential distribution has limitation to be used in mechanical degradation. Although exponential distribution cannot be used to describe the deterioration states of the mechanical components, it can be used as an approximate failure distribution model for components to estimate the failure probability.

4.2.1.2 Weibull distribution

Weibull Distribution is widely used to model the mechanical failure and so on because it is capability to model different kinds of failure time distribution.

The probability density function is:

$$f(t, \eta, \beta) = \begin{cases} \frac{\beta}{\eta}(\frac{t}{\eta})^{\beta-1} e^{-(\frac{t}{\eta})^{\beta}} & t \geq 0 \\ 0 & t < 0 \end{cases} \tag{4.6}$$

The cumulative function is:

$$F(t) = \begin{cases} 1 - e^{-(\frac{t}{\eta})^{\beta}} & t \geq 0 \\ 0 & t < 0 \end{cases} \tag{4.7}$$

The failure rate function for the Weibull distribution is written as

$$\lambda(t) = \frac{\beta}{\eta}(\frac{t}{\eta})^{\beta-1} \tag{4.8}$$

β is the shape parameter, which has effect on the Weibull failure rate function; η is the scale parameter and it has effect of the stretching out of probability function density.

Regarding to Equation 4.8, if $\beta = 1$, it is an exponential distribution with the failure rate $\frac{1}{\eta}$; if $\beta \geq 1$, the degradation accelerates depending on time; if $\beta \leq 1$, the failure rate function decreases by time.

4.2.2 Stochastic processes

A stochastic process is a collection of the random variables, in this thesis, the random variables are the states of system which are denoted as $X(t), t \in T$, where T is time index set [163].

4.2.2.1 Counting process

A counting process is a special stochastic process, the variable is $N(t)$ which is defined as the number of failures during $(0, t]$.

A counting process has independent and stationary increments. Poisson process and the extended Poisson process are well known counting processes considered in maintenance modelling.

4.2.2.1.1 Poisson process Poisson process is one of the most useful jump process for maintenance engineering which has the same jump size but has random interarrival time between two jumps.

Homogeneous Poisson Process (HPP) is a counting process in which the interarrival time between the events are exponential distributed with a constant arrival rate λ [165]:

$$Pr(N(t+s) - N(s) = n) = \frac{(\lambda t)^n}{n!} e^{-\lambda t} \tag{4.9}$$

The mean number of failures during $(t, t+\tau]$ is : $E(N(t)) = \lambda\tau$, and $var(N(t)) = \lambda\tau$. Homogeneous Poisson Process is one of the models for perfect maintenance .

If the arrival rate is not a constant but a time dependent function, Non-Homogeneous Poisson Process is used to describe the process [163]:

$$Pr(N(t+h) - P(N(t) = 1) = \lambda(t)h + o(h) \tag{4.10}$$

NHPP is used to describe the minimal repair in the literature since the interarrival time between two events are shorter and shorter depending on time.

4.2.2.1.2 Compound Poisson Process Poisson process is usually used to model the shocks or the deterioration with the same increments size. It is interesting in considering the deterioration process which has random increment size, thus Compound Poisson process is introduced in this situation.

The Compound Poisson Process is defined in Equation 4.11.

$$X_t = \sum_{k=1}^{N_t} Y_k, t \in R \tag{4.11}$$

N_t is a Poisson Process, $(Y_k)_{k\geq 1}$ denote a random variable with probability distribution $y(dx)$, independent to the Poisson process $(N_t)_{t\in R_+}$.

The Compound Poisson Process has the expectation $E(X_t) = \lambda t E(Y_1)$. The characteristic function of the increment $X_T - X_t$ has the property as Equation 4.12:

$$E[\exp(i\alpha(X_T - X_t))] = \exp(\lambda(T-t)\int_{-\infty}^{\infty}(e^{ix\alpha} - 1)y(dx)) \tag{4.12}$$

for all $0 \leq t_0 \leq t_1 ... \leq t_n$, we have

$$E[\prod_{k=1}^{n}(e^{i\alpha_k(X_{t_k} - X_{t_k-1})})] = \prod_{k=1}^{n} E[e^{i\alpha(X_{t_k} - X_{t_k-1})}] \tag{4.13}$$

It shows that the Compound Poisson Process Xt has the independent increments as the standard Poisson process [93].

According to the definition of Compound Poisson Process, they only have a finite number of jumps on any interval. However, Compound Poisson Process can just model the deterioration process with a finite number of jumps; if we want to model a deterioration process with infinite jumps, we need to adopt other lèvy processes which have infinite jumps, such as Gamma process.

4.2.2.2 Gamma process

Gamma Process is one of the lèvy process. In the review of J.M.van Noortwijk [182], he mentions that Gamma process has the following properties:

- $X(0) = 0$ with probability 1;
- $X(t)$ has independent increments. $X(t+\Delta t) - X(t) \sim \Gamma(\alpha(t+\Delta t) - \alpha(t), \beta)$ for all $\Delta t > 0$, where X has a Gamma distribution with shape parameter α and scale parameter β:

$$f_{\alpha(\Delta t),\beta}(x) = \frac{1}{\Gamma(\alpha(\Delta t))}\beta^{\alpha(\Delta t)}x^{\alpha(\Delta t)-1}e^{-\beta x} \tag{4.14}$$

α is the shape parameter and β is the scale parameter. If the shape function $\alpha(\Delta t)$ is defined to be a linear function, for instance, $\alpha(\Delta t) = \alpha\Delta t$, the Gamma process is a stationary process, which means the increment of the process for any time period has the same distribution.

T_δ is used to indicate the time when the state exceeds the threshold δ, The distribution of T_δ that the process reaches the predetermined state δ is written as:

$$F_{T_\delta}(t) = Pr(T_\delta \leq t) = Pr(X(t) \geq \delta) = \frac{\Gamma(\alpha t, \delta\beta)}{\Gamma(\alpha t)} \tag{4.15}$$

The mean value of the deterioration for time t equals $E(X) = \frac{\alpha t}{\beta}$. The variance is $VAR = \frac{\alpha t}{\beta^2}$.

For Gamma process, $X(T_\delta) \neq \delta$. If δ_1 and δ_2 denote two condition levels, and we know $\delta_1 - \delta_2 \neq X_{T_{\delta_1} - T_{\delta_2}}$. The survival function for $(T_{\delta_1} - T_{\delta_2})$ is given in [18]. An approximation is proposed as Equation 4.16 [85].

$$F_{T_{\delta_1} - T_{\delta_2}}(t) \simeq F_{T_{\delta_1 - \delta_2 - \frac{1}{2\beta}}}(t) \tag{4.16}$$

Although Gamma process can be approximately modelled by Compound Poisson process, but it is not an efficient way. In the simulation, we sample Gamma increments for time period Δt using its independent increment property: $\Gamma(\alpha(t + \Delta t) - \alpha(t), \beta)$.

4.3 Petri Nets

In this thesis we work on the maintenance modelling for railway assets. According to the existing researches, Markov process is one of the methods considering states for the modelling. However, the problem we want to study may not be appropriate to use Markov chains or semi-Markov process to solve: one of the problems that we want to study is the effect of delayed preventive maintenance, which is not a Markovian process. Furthermore, in the railway system modelling, accident scenarios or system operation needs to be considered.

As mentioned in Section 3.5, Petri nets are a powerful tool of risk modelling. Some papers show that Petri Net is able to model the degradation processes in a comprehensive way and their repairs, including logistics aspect. Fouathia et al used Petri nets to model on-demand and spurious failures in the power supply substation system, considering periodic inspections[61, 60]. Chang et al used Generalized Stochastic Petri Net (GSPN) for a serial-parallel automatic manufacturing system, considering scheduled preventive maintenance for different levels of failures[39, 40]. One of the limitations of them is that they adopted exponential distribution to describe the degradation of component. Hosseini et al [79, 78] used Stochastic Petri Net (SPN) model to model a system with aging failures and Poisson failures, they also studied optimal detection time and maintenance mode for condition-based maintenance. Volovoi [186, 187] introduced aging token to model the degradation of repairable complex system, that is particularly suited for system reliability modelling with non-exponentially distributed firing time. Rana et al [162] converted the non-exponential process with mixed Erlang process or hyper geometric process to several exponential distribution, this mapping process does not need to introduce the aging tokens in the model. Zille et al propose PN models to describe the multi-component maintenance process for multiple failure modes[217, 218]. Therefore, Petri net is proved to be a relevant tool to model the failure process of component with different maintenance strategies.

We choose Coloured Petri Nets, in one hand, they can model behaviours which are not Markovian; in the other hand, the coloured set and the time representation make CPN to be more flexible than SPN or GSPN.

4.3.1 Basic Petri Nets

Petri net is known as a Place-Transition Net, or P/T Net or P/T system, it is introduced by C.A.Petri in 1962 in his PhD Thesis. Petri Net is a graphical method, it contains 3 basic elements originally: P-element is represented by circles; T-element is represented by rectangles and arcs connect the P-elements and T-element.

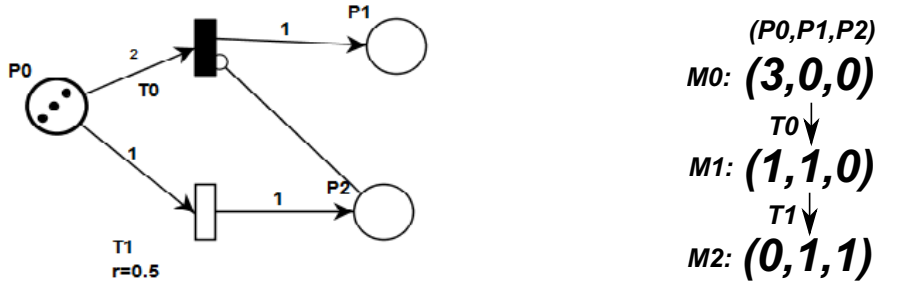
Definition:A place/transition net (P/T net) is defined by a tuple $PN =< P, T, F, W >$, where $< P, T, F >$ is a net with finite sets P and T, and $< W : F >$ is a function (weight function) [66].

The standard Petri Net has weighted functions and markings; tokens can be put in the places to indicate the state, the whole Petri Net state is called Marking, and it is a vector contains the number of token at each place. Initial marking should be defined to specify the initial state of Petri Net. If a transition is fired, the marking will change; after a sequence firing, a set of markings can be obtains which is called a Reachability Graph (RG). Reachability Graph can show all the system states.

The standard Petri Net has the limitation in system modelling, therefore some high level Petri Nets are introduced, such as Stochastic Petri Net and Coloured Petri Net. The principles of the Stochastic Petri nets can be read in Haas [75] and Coloured Petri net can be found in Jensen [88].

4.3.2 Stochastic Petri Nets

Stochastic Petri Net allows timed transitions which are associated to exponentially distributed firing delays. The Stochastic Petri Nets are defined as $PN = (P, T, I, O, W, M_0)$ where $P = (p_1, p_2, ..., p_p)$ is the set of places. $T = (t_1, t_2, ..., t_T)$ is the set of transitions. $I \subset (P \times T)$ is the set of input of arcs, $O \subset (T \times P)$ is the set of output arcs. $W : T \to \mathbb{R}$ is the rate to each transition. $M_0 = (m_{01}, m_{02}, ..., m_{0p})$ is the initial marking [15].



(a) Generalized Stochastic Petri Net concept

(b) Reachability graph

Figure 4.1: An example of GSPN and its reachability graph

If there are times transitions and immediate transitions (with and without priority) in a Petri Net which means there are immediate transition and inhibitor arcs, it is a Generalized Stochastic Petri Net (GSPN) [109].

Figure 4.1 shows an example of Generalized Stochastic Petri Net and its reachability graph is shown in Figure 4.1b. Transition $T0$ is a immediate transition and transition $T1$ is an exponentially distributed transition with a rate $r = 0.5$ as shown in Figure 4.1a. At the beginning, tokens are in place $P0$ and thus the initial marking is $M_0 = (3, 0, 0)$. Transition $T0$ consumes 2 tokens and sends 1 token in place $P1$ and it can not fires if there is a token in place $P2$. After the firing of transition $T1$, the marking of this example is $M2 = (0, 1, 1)$.

4.3.2.1 Time in SPN

There are three basic ways of representing time in Petri Nets:firing duration, holding duration and enabling duration.

For the firing duration, the transition will remove tokens in the input place as soon as it is enabled, and after the duration, it will put the tokens to the output places. The holding duration means that the transition will move tokens from input places to output places as soon as it is enabled, but the tokens in output places are not enabled until the duration is over. In the enabling duration case, the transition will fire at the end of duration, and the tokens will stay at the input places until transition fires.

The enabling duration is easy to model the interruption. The interruption can be seen as Figure 4.2

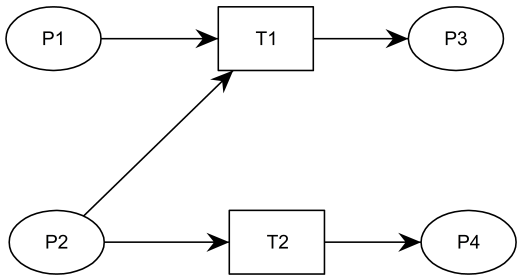


Figure 4.2: An example of interruption in SPN

State P2 is enabled at time 0, it will turn to be P4 through the transition T2 after time t2. If P1 arrives during [0,t2), transition T1 may fire and state P2 changes to be P3 instead of P4.

4.3.3 Colored Petri Nets

A Coloured Petri Net is a high level stochastic Petri Net with coloured sets and the extended functions, which has more flexibility for the modelling. Buchheit et al propose a methodology to generate a model automatically with CPN to assess the dependability for railway system [24].

4.3.3.1 Concepts of CPN

A Coloured Petri Net (CPN) is defined as shown in Equation 4.17 [87].

$$CPN_t = (P, T, A, \Sigma, V, C, G, E, I) \tag{4.17}$$

CPN_t is a timed CPN, P is the set of places, T is the set of transitions, A is the set of arcs, Σ is the set of coloured set, V represents the set of variables. G is the set of guard functions, I is the initial marking of the net, C is the set of coloured set functions and E is the set of the arc expression functions, $E(p,t)$ represents the arc from a place to a transition and $E(t,p)$ represents the arc from a transition to a place.

4.3.3.2 Marking process in CPN

The marking is defined as shown in Equation 4.18.

$$M(p) \in C(p)_{\mathrm{TMS}}, p \in P \tag{4.18}$$

The timed marking of place p at time t^* is defined to be a pair $(M(p), t^*)$, where $C(p)_{\mathrm{TMS}}$ in equation 4.18 is timed coloured set with timestamps, and t^* is the value of global clock. The following condition should be satisfied to enable and fire a transition at time t' in marking $(M(p), t^*)$:

1. $\forall(t,b) \in Y : G(t)\langle b\rangle$. (t,b) is the binding element for the transition t. b is a function mapping each variable of transition t into a value $b(v)$. Y is a firing step. To enable the transition, firstly all (t,b) in step Y is required to satisfy the guard function: $G(t)\langle b\rangle$.

2. $\sum_{(t,b)\in Y} E(p,t)\langle b\rangle_{+t'+t''}$ <<<= $M(p)$ for all places $p \in P$, that is the tokens in $M(p)$ need to be larger than the token needed to enable transition t at step Y at time t'. Then the transition adds current time t' and delay time t'' assigned by transition t to timestamps. The symbol "<<<=" is introduced specially for the comparison in timed Coloured Petri Net, t' is the smallest value of global clock and $t^* \leq t'$.

3. The new marking of the place p after step Y is defined as:

$$\begin{aligned} M'(p) = \quad & (M(p) - - - \textstyle\sum_{(t,b)\in Y} E(p,t)\langle b\rangle_{+t'+t''}) \\ & + + + \textstyle\sum_{(t,b)\in Y} E(t,p)\langle b\rangle_{+t'+t''} \end{aligned}$$

   The symbols "− − −" and "+ + +" are used for addition and subtraction in timed Coloured Petri Net.

Figure 4.3 shows a simple timed CPN. “D” is a timed coloured set. The sets of places and transitions are $P = \{A, C\}, T = \{B\}$ and $M(P) \in D$.

At time $t' = 0$, the markings are $(M_0(A), 0) = (1\text{‘}0.0@0, 0)$, $(M_0(C)@0, 0) = (\Phi_{MS}, 0)$ where global time $t^* = 0$ and timestamp ’@0’ means the token is available at time ‘0’. when B fires, function Exponential(0.02) is carried out and generates a random number following exponential distribution, and time delay t'' of transition B assigned by ’@ + 1’ is added to the timestamp of output place. Transition B changes the markings:

$$(M_0(A), 0) \xrightarrow{B} (M_1(A), 0), (M_0(C), 0) \xrightarrow{B} (M_1(C), 0)$$

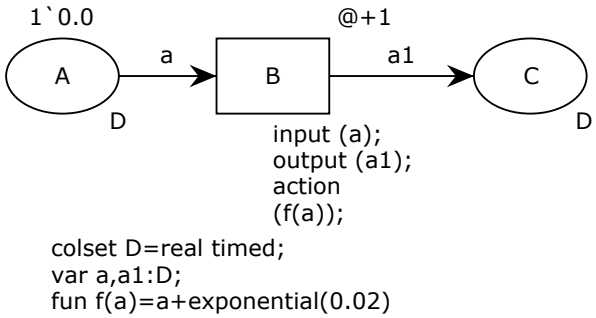


Figure 4.3: Coloured Petri Net concept

where

$$
\begin{aligned}
& \text{if} \quad G(a \neq 2) = true, \\
M_1(A) = \; & M_0(A) - - - E(A,B)\langle b(a,a1)\rangle \\
& + + + E(B,A)\langle b(a,a1)\rangle \\
= \; & (1`0.0@0) - - - (1`0.0)_{+0+1} + + + \Phi_{MS} \\
= \; & \Phi_{MS} \\
M_1(C) = \; & M_0(C) + + + E(C,B)\langle b(a,a1)\rangle \\
& - - - E(B,C)\langle b(a,a1)\rangle \\
= \; & \Phi_{MS} - - - \Phi_{MS} + + + (1`a1@0)_{+0+1}) \\
= \; & (1`a1@1)
\end{aligned}
$$

After transition B firing, the global time is still $t^* = 0$ and the timed markings are $(M_1(A), 0) = (\Phi_{MS}, 0)$ and $(M_1(C), 0) = (1`a1@1, 0)$, this is a marking process in Coloured Petri Net and is used to model the track deterioration.

In CPN tool, the model as shown in Figure 4.2 cannot carry out the interruption because transition T2 will fire at time 0, transition T1 will not fire in this case. The model can be modified as Figure 4.4.

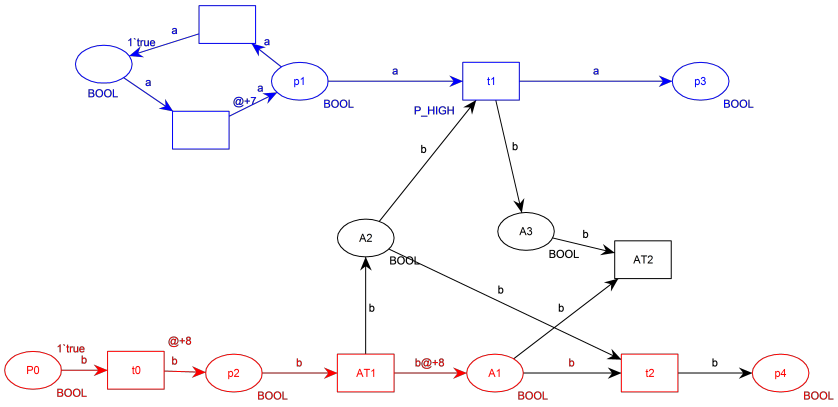


Figure 4.4: An example of interruption modelling in Coloured Petri Net

The state will develop from p2 to p4: p2 arrives at time 8 and it will take 8 units time from p2 to p4, which means that p4 will arrive at time 16; but if p1 arrives during time 8 to

16, the process will be interrupted and t1 will occur and p3 will arrive. And the timestamp of p3 should be the same as the timestamp of p1. In this case the t1 is set as a high level priority transition and the interval between p2 to p4 is put on the arc inscription from AT1 to A1. The process can be interrupted to the p3 once the p1 occurs.

4.3.3.3 Hierarchical modelling in CPN

Substitution transition represents the sub-module of CPN, it cannot be enable, cannot be fired. Each module can be seen as a small CPN. The modules can exchange tokens via port places. Port places are the input and output places of substitution transitions (CPN module). They have different tags "input or output or input and output" to distinguish the relationship of port places and modules.

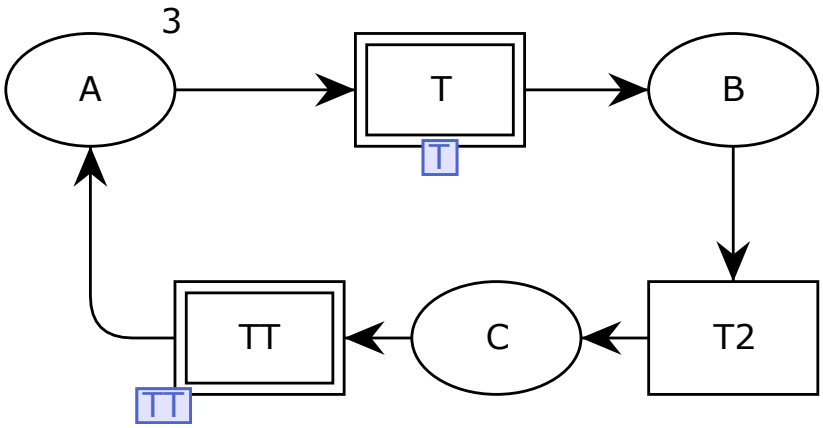


Figure 4.5: Modular of CPN example

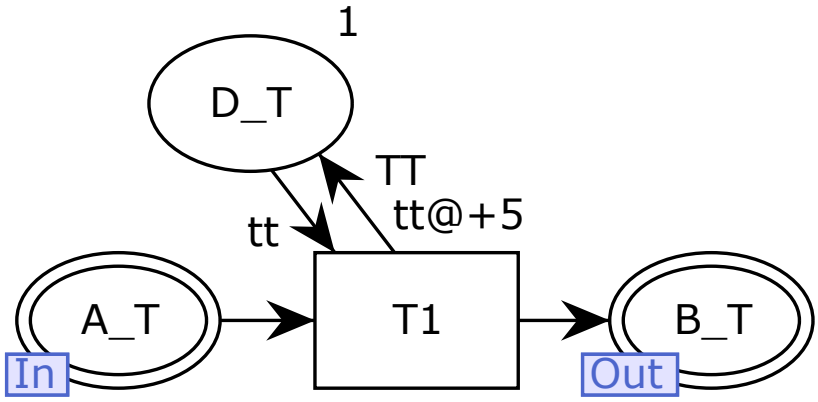


Figure 4.6: CPN for substitution transition T

As shown in Figure 4.6 to 4.8, place A in Figure 4.5 has 3 port places: place A_T in substitution transition T, place A_TT in substitution transition TT and place A_TTT in

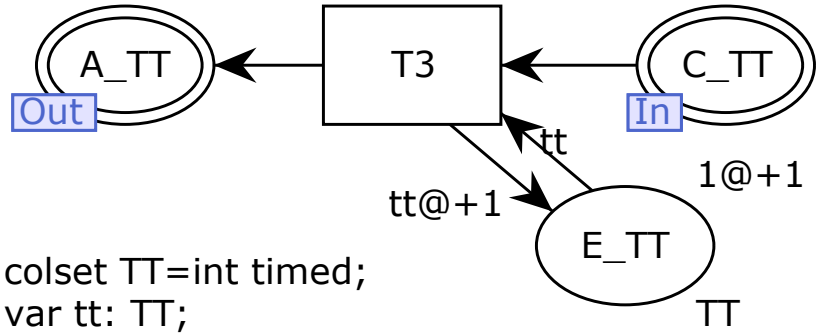


Figure 4.7: CPN for substitution transition TT

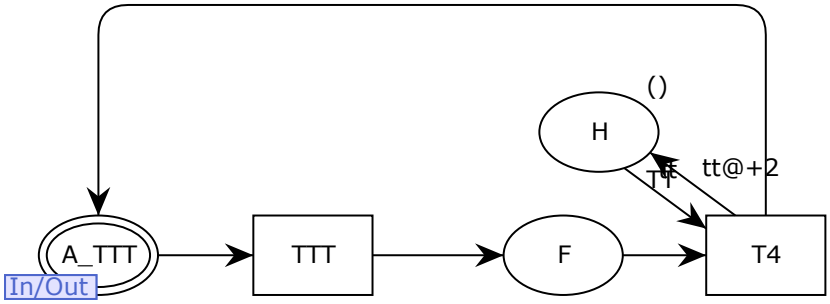


Figure 4.8: CPN for substitution transition TTT

substitution TTT. In substitution transition T, A is input place so place A_T is tagged as "In" and the arc between place A and substitution transition T is from A to T. In Figure 4.8, since place A_TTT sends tokens to transition TTT and receive tokens from transition T4, it is the input and output place for substitution transition TTT, so it is tagged as "In/out" and the arc between A and TTT in Figure 4.6 is bi-direction arc.

Marking in place A is the marking in place A_T, A_TT and A_TTT. In another word, places A_T and A_TT are folded into a single place A. Place B_T is folded into place B and place C_TT is a port place of C in substitution transition TT. $M(A) = M(A_T T) = M(A_T) = M(A_T TT)$. When A_T enables transition T1 in Figure 4.6 and sends 1 tokens in place B_T, place A, T_TT,A_TTT lose 1 token at the same time. If transition T3 fires in Figure 4.8, A_TT get 1 token and then place A, A_T and A_TTT get 1 token.

The model shown in Figure 4.5 to 4.8 can be illustrated as Figure 4.9 if there is no port place and substitution transition.

4.3.4 CPN tool

CPN tool is a free graphic modelling and analyzing tool developed by CPN Group at Aarhus University from 2000 to 2010. From the autumn of 2010, CPN Tools is transferred to the AIS group, Eindhoven University of Technology in Netherlands.

This tool has a graphic interface which is developed in Java, the modelling language is Standard ML programming language(SML). It allows users to define different modelling

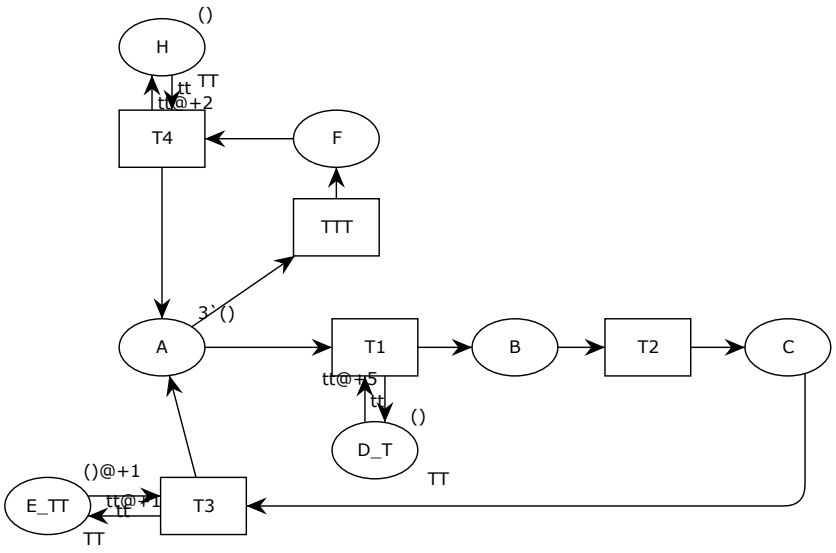


Figure 4.9: Extended CPN for the modular

functions for transitions and monitors regarding to the modelling requirements.

CPN tool has the timed coloured set, arc inscription, inhibit arc and initial arc. Furthermore, it can build hierarchical models with the port places and the substitution transitions as mentioned in Section 4.3.3.3.

4.3.5 Component maintenance model using CPN tool

To illustrate the modelling capability and expressivity of CPN tool, let us consider the example of a single track component which is one eighth mile long. The tampering and replacement can control the track quality. The assumptions of the track deterioration and maintenance are described in Section 4.3.5.1. This is a redo maintenance model using CPN tool, the original maintenance model is built by Stochastic Petri Net in paper [5].

4.3.5.1 Assumptions of the model

The same assumptions as in [5] are used here,expect than in paper [5] the degradation is continuous but in this model the degradation is modeled as a multi-stages process. The maintenance assumptions are illustrated in Figure 4.10:

1. Track failure and deterioration.

    - The model focus on track twist. Standard Deviation (SD) of the track cant measurement is used to describe track deterioration.
    - Three thresholds (δ_{Tresh}, δ_{speed} and δ_{close}) divides track deterioration process into 4 levels. The original track states is good; if the SD exceeds δ_{Tresh}, the track needs maintenance; if SD exceeds δ_{speed}, temporary speed restriction (TSR) is carried out and the fourth stage needing line closure when SD exceeds δ_{close}.

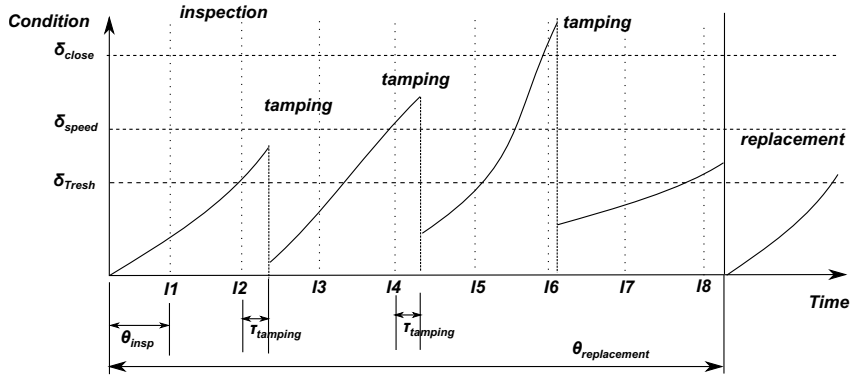


Figure 4.10: Track degradation and maintenance process in the assumptions

- The lifetime distribution of track is assumed to be a Weibull distribution. The lifetime of each level is assumed to be a Weibull distribution, i.e. $T_{\delta_i} \sim Weibull(\alpha_i, \beta_i)$.
- The lifetime distribution from good to state δ_{Tresh} after a tamping depends on the number of tamping implemented since last replacement.

2. Track inspection policy:

   - Track component is inspected monthly, the inspection interval is θ_{insp}
   - Track deterioration continues even though the defect is identified.

3. There are two kinds of maintenance in this model- tamping and replacement:

   - Track maintenance arrives within a delay time $\tau_{tamping}$, which is assumed to follow the Normal distribution $\tau_{tamping} \sim N(\alpha, \beta)$.
   - Track maintenance is imperfect, the effect of the maintenance depends on the number of previous tamping $N_{tamping}$.
   - Track component is replaced periodically, the replacement period is $\theta_{replacement}$.
   - Replacement is perfect which can fix the component to be as good as new.

Based on the above assumption, a CPN model is built to estimate the number of tamping and the total days of defective states of component.

4.3.5.2 CPN model description

Figure 4.11 describes the track deterioration process. Colored set $Track$ represents track states number. Colored set T represents the time. Colored set $TrackT$ is the product of $Track$ and T, since $TrackT$ is a timed colored set, the time stamp records the time when the token is valid. $TrackP$ is an untimed colored set, which has the same meaning as $TrackT$ without time stamp.

Place $P1$ represents the original track state, the initial marking of $P1$ is $(1, 0.0)$, which means the first state at time 0.0. When the token in $PP1$ is valid, the good state is over.

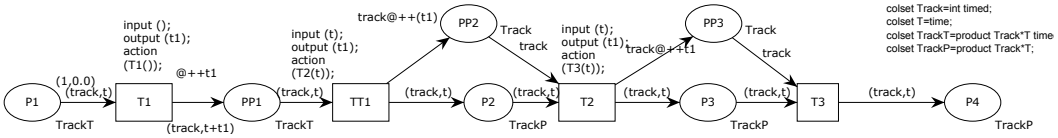


Figure 4.11: Failure process CPN model

A token in $P2$ means that the track state exceeds threshold δ_{Thresh}. Place $PP2$ with time stamp $t1$ controls the time to fire transition T2, which means track states exceeds threshold δ_{speed} in $t1$. $t1$ of place PP2 is the output of function $T2(t)$, transition $TT1$ implements the function. Similarly, place P3 and P4 represent the track level which needs speed restriction and line closure respectively.

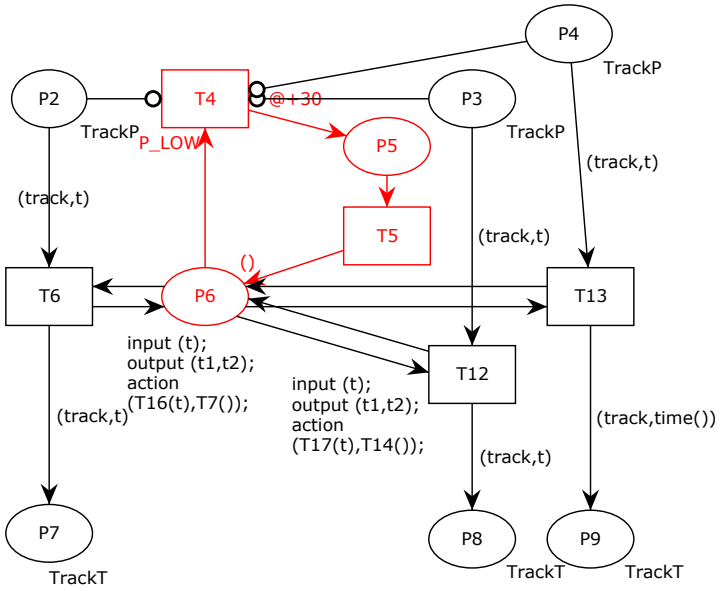


Figure 4.12: Defects detection CPN model

The periodic inspection process is modeled in red in Figure 4.12. $P6$ represents there is an inspection; $P5$ represents there is no inspection; transition $T4$ controls the next inspection time with time delay @ + 30, it is low priority, so $T4$ is the last transition firing in the same time slice to ensure the inspection can definitely detect the corresponding track states. This CPN circle in red represents the inspection arrives periodically. Track states can be identified by inspections. $T6$ fires when inspection arrives and track is at state 2 ($P2$). Place $P7$ represents that track state $P2$ is detected, similar to place $P8$,$P9$.

Function $T16(t)$ (or $T17(t)$) calculates the time $t1$ in which the detected state $P7(P8)$ changes to be $P8(P9)$. Function $T7()(T14())$ calculates the maintenance arriving time $t2$. The maintenance for place $P7$ is illustrated in Figure 4.13. Place $PP7$ with time stamp $t1$ means that after time $t1$, track stage 2 will degrade to be detected stage 3 (Place $P8$).In the

other hand, after $t2$, the stage 2 defect will be fixed to be acceptable state (place $P10$). $t1$ and $t2$ decide which transitions will fire (transition $T7$ and $T16$). If $t2$ is smaller than $t1$, transition $T7$ fires and the track state change to $P10$. Place $P10$ represents the track state is not as good as new but it is better than $P2$. Place $P11$ records the number of previous tamping in this track section. The time stamp of $PP10$ means the ending time of this state. The ending time is sampled by function $T8(n)$, n is the number of tamping. If the token in Place $PP10$ is valid, track state deteriorates to be P2.

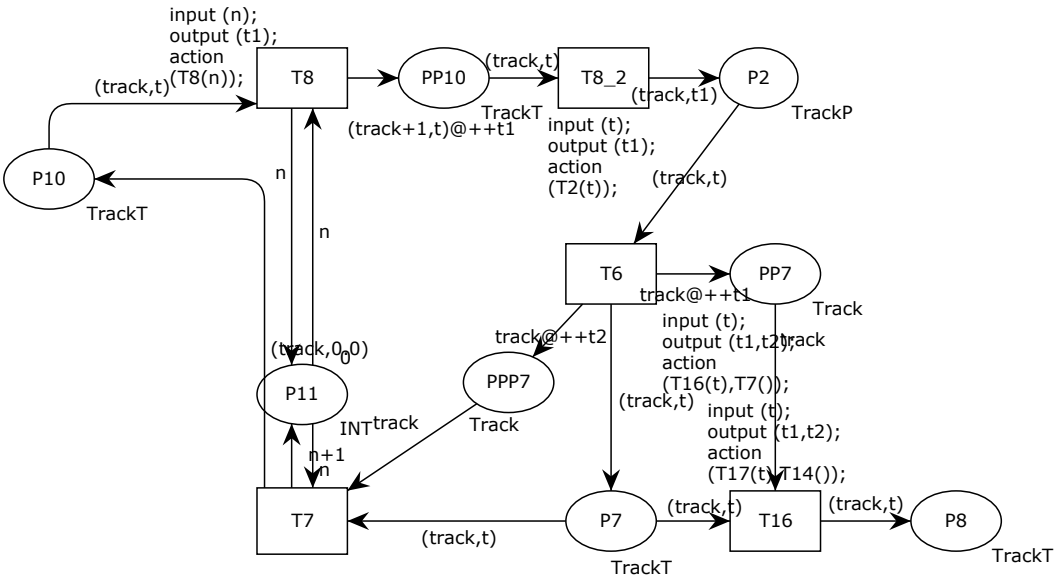


Figure 4.13: Defects repair CPN model

The track component is assumed to be replaced periodically. Figure 4.14 shows the periodic replacement. Transition $T11$ is high priority so it will fire before other transitions associated to place $P1$, then it puts token to place $PP0$ and set the replacement time to be 36500; Place $P12$ are used to control transition $T11$ not to fire for a second time before replacement.

Transition $T9$ means that the replacement is carried out, then replacement restores track to be new (place P1) and resets the number of tamping to be 0 (the value of token in place P11). All the arcs from place $P2$,$P3$,$P4$,$PP1$,$P10$ and $PP10$ are reset arcs, these arcs can reset all these places to be empty, and the enable bind element of $T10$ is: $P13$ and $P11$ are not empty no matter there is a token in $P2$,$P3$,$P4$,$PP1$,$P10$ and $PP10$.

4.3.5.3 Simulation results

Figure 4.15 shows the intervention convergence depends on the number of simulations over a simulation horizon of 180 years. The number of intervention converges if the number of simulation is larger than 20000, we run 25000 simulations to get the maintenance results.

There are some differences between this CPN model and the SPN model in [5]: In Andrews's paper, $T2$ (the time from state δ_{Tresh} to state δ_{speed}), $T3$ (the time from state

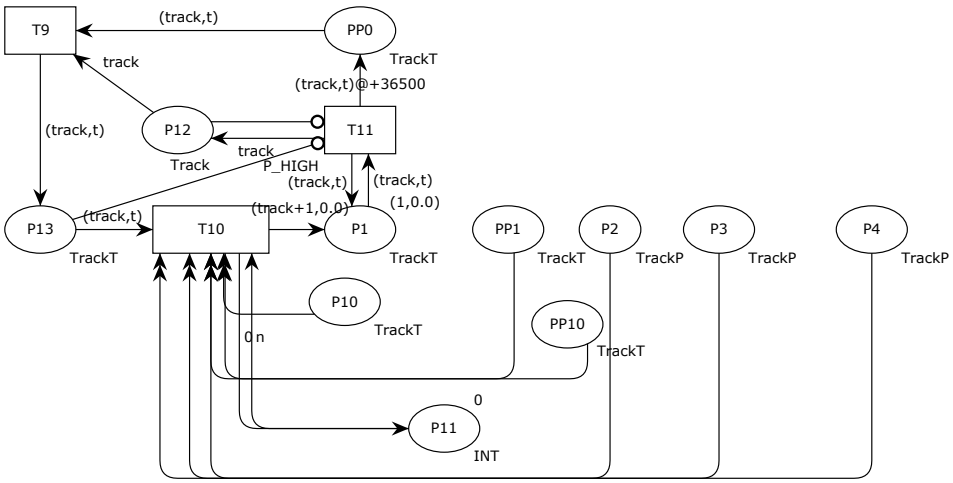


Figure 4.14: Periodic replacement

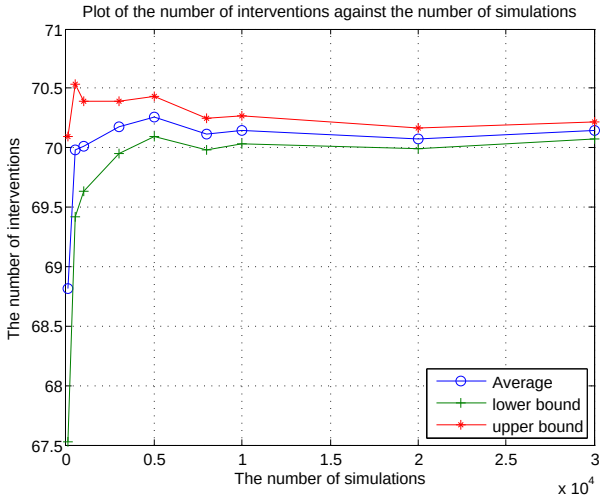


Figure 4.15: Number of simulations and intervention convergence; simulation horizon: 180 years

δ_{speed} to state δ_{close}), $T16$ (the time from observed state δ_{Tresh} to state δ_{speed}) and $T17$ (the time from observed state δ_{speed} to state δ_{close}) are convolution transitions; however, in this model we assume that the degradation process is a multi-stage process, and the functions for transition $T2$,$T3$,$T16$ and $T17$ are assumed to follows Weibull distributions. We run 25000 simulations over a simulation horizon of 180 years for two degradation configurations as shown in Table 4.1. The simulation results are shown in Table 4.3.

As the lifetime distribution from place $P2$ to $P3$ is defined to be a Weibull distribution, the duration of state 2 and state 3 is not the same as the ones defined in [5]. Table 4.2 shows the mean time to each defective state for both of the degradation configurations.

Table 4.1: Functions of transition in CPN model for two configurations

		Configure 1		Configure 2		
	Function	α	β	α	β	type
Degradation	T1	1.3	1200	1.3	1200	Weibull
	T2	1.4	1500	1.4	300	Weibull
	T3	1.6	1800	1.6	300	Weibull
	T16	1.4	1500	1.4	300	Weibull
	T17	1.6	1800	1.6	300	Weibull
Inspection	T5	30				Fixed
	T9	36500				Fixed
		α		β		
Maintenance delays	T7	1		350		Normal
	T14	1		48		Normal
	T15	1		48		Normal
		α		β		Weibull
Maintenance effect	T8	1.4		1000		$n \in [0, 3]$
		1.9		900		$n \in [4, 6]$
		2.4		800		$n \in [7, 9]$
		2.9		700		$n \in [10, 12]$
		3.4		600		$n \in [13, 15]$
		3.9		500		$n \in [16, 18]$
		4.4		400		$n \in [19, \infty)$

Configuration 1 has a longer time to state δ_{speed} and to state $\delta_{closure}$ than configuration 2.

Table 4.2: Mean time to defective states, unit:days

	Configuration 1	Configuration 2
Mean time to State 2 (δ_{Tresh})	1125.09	1115.93
Mean time to State 3(δ_{Speed})	2512.93	1393.82
Mean time to State 4 ($\delta_{Closure}$)	4142.54	1666.99

Table 4.3: Simulation results for 180 years

Event	Configuration 1	Configuration 2
Average number of closure	0.000012	0.000936
Average number of temporary speed restriction (TSR)	0.18308	2.03
Total (average) days with TSR	13.23684	84.53
Total (average) days needed maintenance	31127.33	26646.81

Since configuration 1 has longer time to defective states, it has less number of closure and speed restriction than configuration 2, as well as the total days with speed restric-

tion.Total days need maintenance is around 85 years for configuration 1 which means that around 47% time of the track are used with a defective state and 73 years for configuration 2 which is around 40% time in 180 years. However, the configurations are based on some assumptions which might not be the actual data, and hence the period,during which component needs maintenance, is not an actual case in practice.

The simulation results for both configurations show that CPN tools can model the multi-stages failure and with different degradation configuration, we can have the different estimations for performance evaluation.

4.4 Conclusion for the modelling tool

In this chapter, we introduce some useful mathematics models, which are adopted in the maintenance models in the following chapters.

The concepts of Petri Nets are introduced for the basic knowledge of the modelling. We review several timed marking mechanisms and find out the equivalent models for different time duration mechanism.

The formal definition and marking process of Coloured Petri Net are reviewed since in this chapter we adopt CPN tools to model the maintenance process in railway system.

In addition, we work on a published example, which worked out using SPN, to show how CPN modelling and simulations can be implemented to analyse the performance of the maintenance policy on single track component. The number of maintenance actions and the duration between two component states are collected by the simulations, which can be used to estimated system performance evaluation indices, such as maintenance cost and system unavailability.

Part III

COMPONENT MAINTENANCE MODELLING

CHAPTER 5

Comparison of failure models for maintenance optimization

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5.1 Introduction

Railway track maintenance decisions are made based on the track condition. Since track faults are non self-announcing, inspections are carried out regularly to collect the track condition measures in order to supervise the track quality. Regarding to the inspection techniques, we sometimes have different types of condition data. The first type of data just indicates the binary health states of the track - worked or failed. With the development of inspection devices, we can collect more precise condition data to show more details of the track quality; for example, we can use the standard deviation for a certain number of track condition data to indicates the health of the track for a certain length. Based on these two kinds of inspection data, two failure models are adopted to describe the track deterioration

evolution and then different maintenance policies are scheduled to maintain the track quality. In this chapter, we want to assess the impacts on the maintenance performance of two level of monitoring information, and of the two corresponding failure models. One of the interest of this study can be to evaluate the benefit of monitoring the track deterioration, instead of only considering a lifetime model.

We adopt two failure models to represent the same physical failure process: one models the physical process as a gradual deterioration process and the other one uses the failure probability at time t to model the failure arrival. The relationship between the models are shown in Figure 5.1.

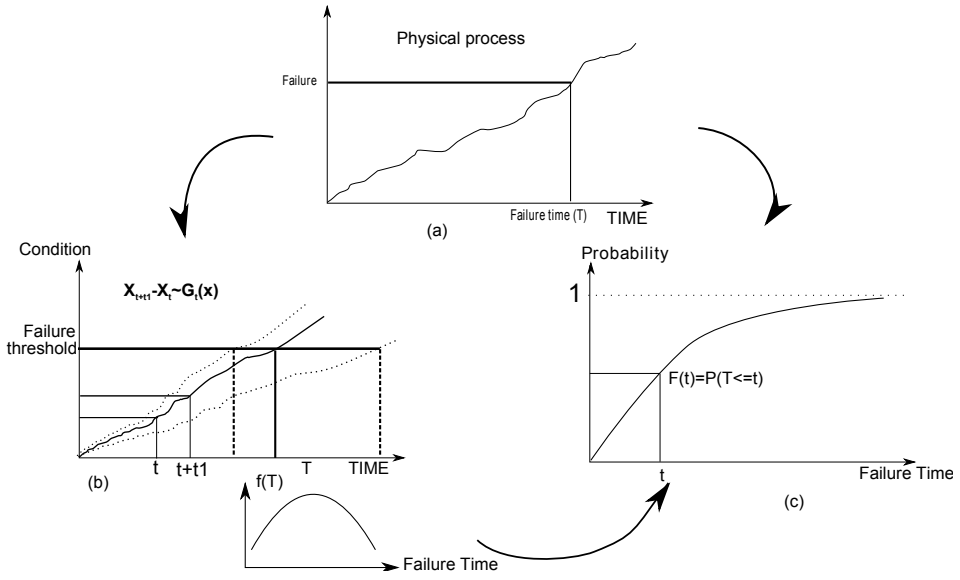


Figure 5.1: Two ways to model the physic failure process at two different levels of information

We assume that the track has an actual physical failure process as shown in Figure 5.1-(a), if there is no intervention, the track health keeps deteriorating and reaches the failure condition at time T. This process is described by two methods, as shown in Figure 5.1-(b) and (c) separately.

Figure 5.1-(b) assumes the physical deterioration is a gradual and continuous deterioration process. The deterioration has independent increments, which follow a certain distribution (eg.$F(T)$). The failure time T when the component state exceeds the failure threshold has a density distribution $f(T)$. In Figure 5.1-(c) $F(T) = P(T \leq t)$ (the failure probability at time t) is used to describe whether the component is failed or not at time t. The failure time distribution $f(T)$ is the linkage between the two models as shown in Figure 5.1-(b) and Figure 5.1-(c).

In this chapter, deterioration process in Figure 5.1-(b) is modeled by a Gamma process whereas the failure in Figure 5.1-(c) focus on the failure probability is represented by a lifetime distribution inferred from this deterioration process.

For the different failure models, we assign different maintenance policies to maintain

track quality: periodic inspection policies and condition-based maintenance. Periodic preventive maintenance is planned to maintain the track condition for the lifetime model. The average maintenance cost for a long time, the unavailability and the failure frequency per unit time are used to evaluate the performance. Monte carlo simulations are carried out to obtain the numerical solutions.

The structure of this chapter is organized as follows: Section 5.2 introduces the two degradation models and the corresponding maintenance policies assumptions. Section 5.3 describes the Colored Petri Net models for the two models and the maintenance policies. Section 5.4 shows the simulation results for the two models with different maintenance policies and tries to compare the two models regarding to the numerical experiment results. Section 5.5 gives a brief conclusion for this chapter.

5.2 Assumptions for deterioration model and lifetime model

J.M.van Noortwijk et al. [183] discuss the two probability models for the deterioration process, they considered the periodic preventive maintenance for them and show the simulation results. Henry et al [76] propose a age based model which is equivalent to the condition based maintenance. H.Pham et al [142] summarize the existing imperfect maintenance policies from 1985 to 1996, in which they introduce the age based maintenance and the periodic maintenance with the minimal repair.

In this chapter, the component is considered to be a track of 1 kilometer long, and the track fault is the track top [1]. Tamping is used as the preventive maintenance method and the renewal is considered to be the corrective maintenance.

5.2.1 Gradual deterioration model

The deterioration of track is assumed to be gradual and continuous process with positive independent increments. X_t is denoted as the condition at time t. J.M.van Noortwijk [182] mentions that Gamma process has the following properties, which can be used to model the track deterioration:

- $X(0) = 0$ with probability one;
- $X(t)$ has independent increments.$X(t+\Delta t)-X(t) \sim Ga(\alpha(t+\Delta t)-\alpha(t),\beta)$ for all $\Delta t > 0$, where X has a Gamma distribution with shape parameter α and scale parameter β:

$$f_{\alpha\Delta t,\beta}(x) = \frac{1}{\Gamma(\alpha\Delta t)}\beta^{\alpha\Delta t}x^{\alpha\Delta t-1}e^{-\beta x} \tag{5.1}$$

A failure occurs if $X_t \geq \delta_{DL}$, then a corrective maintenance is implemented. In order to reduce the failures, periodic inspections are carried out for the preventive maintenance. We assume two maintenance policies for this deterioration model: condition-based maintenance policy with periodic inspection and periodic preventive maintenance policy.

[1] As described in Chapter 2, track top is a kind of track vertical geometry fault

5.2.1.1 Condition-based maintenance policy

The scenarios of the periodic inspection policies are illustrated in Figure 5.2 and the details of the assumptions are listed as follows:

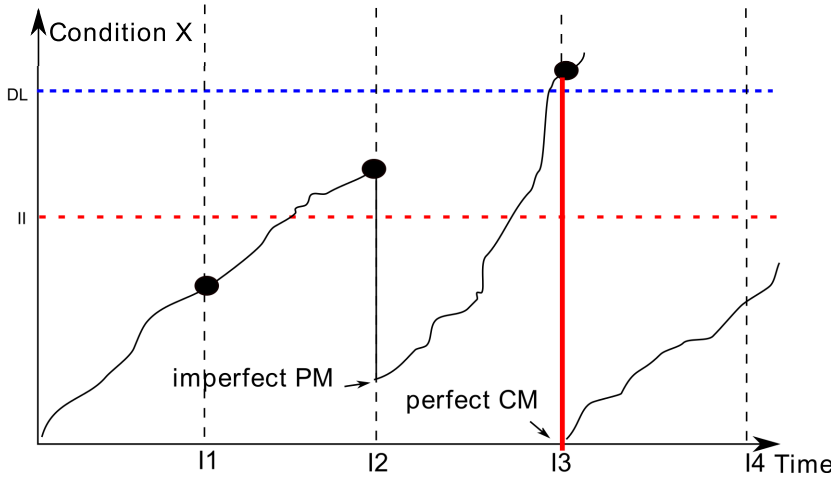


Figure 5.2: Scenarios of periodic inspection policy

1. The inspections are carried out periodically with an interval θ_{insp}. i is the index of the inspection; I_i means the ith inspection, and X_i represents the observed states by the ith inspection.
2. There are two thresholds for the maintenance:
   - If $X_i \geq \delta_{DL}$, a corrective maintenance is carried out immediately, eg. I_3 in Figure 5.2. It can restore the track to be a condition X_{cm} which means the state after the corrective maintenance is as good as new.
   - If $X_i \geq \delta_{II}$, a preventive maintenance is implemented, eg, I_2 in figure 5.2.
   - The preventive maintenance is imperfect. The preventive maintenance can fix the component to the state $X_{pm} > 0.0$ which means the state after the preventive maintenance is not as good as new .
3. There is no delays for the two levels of maintenances. It takes D_{cm} for one corrective maintenance action and D_{pm} for one preventive maintenance action as the downtime.

The preventive maintenance threshold δ_{II} and the Inspection interval θ_{insp} are the maintenance decision variables to optimize the maintenance configuration.

5.2.1.2 Periodic preventive maintenance policy

A periodic preventive maintenance is scheduled for the deterioration process, the inspection of which cannot identify the condition details and only detected the failure states.

The maintenance scenarios can be seen in Figure 5.3.

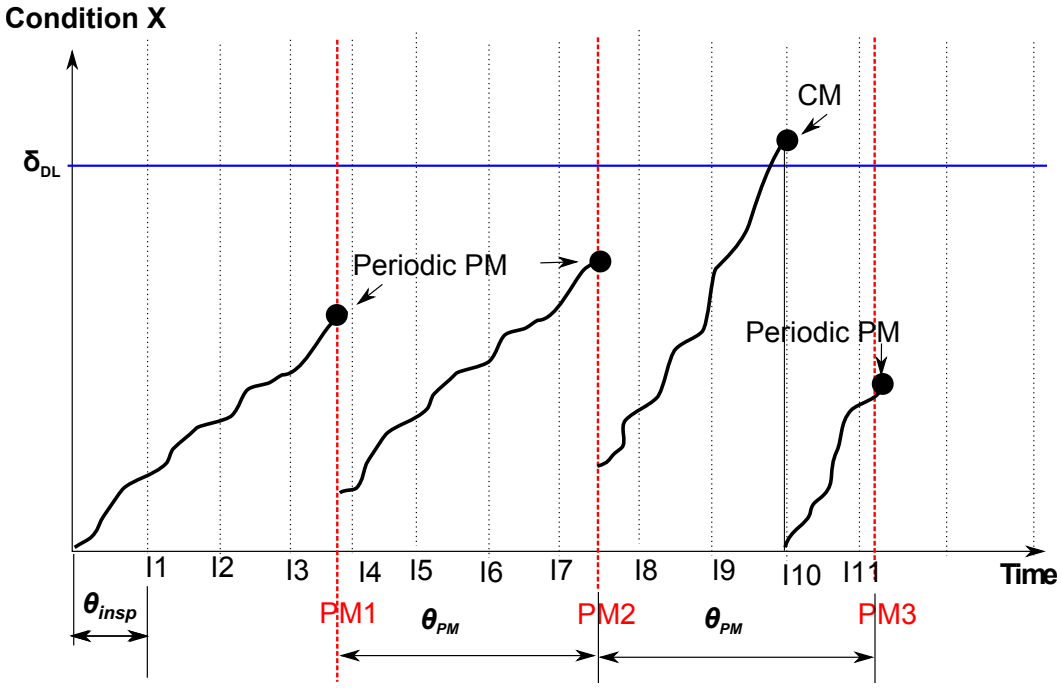


Figure 5.3: Scenarios of periodic preventive maintenance policy

1. Inspections are carried out periodically with the interval denoted as θ_{insp}, i.e. I_1 to $I14$ in Figure 5.3.
   - If $X_t < \delta_{DL}$, inspection cannot collect the exact condition.
   - Inspection can just identify the state which exceeds corrective maintenance threshold $X_t \geq \delta_{DL}$.
2. Two kinds of maintenance are carried out for the component:
   - If inspection identifies $X_t \geq \delta_{DL}$, a renewal is carried out to fix the component to be as good as new (i.e. $I10$ in Figure 5.3)
   - Preventive maintenance is planned to be implemented periodically with the interval θ_{PM}, for example, PM_1 to PM_4 in Figure 5.3.
   - Preventive maintenance can fix the component to a state $X_{pm} > 0.0$ which is not as good as new.

Inspection interval θ_{insp} and preventive maintenance interval θ_{PM} are the maintenance decision variables for this maintenance strategy.

5.2.2 Lifetime distribution model

If we only consider the binary states of the component-worked or failed, lifetime distribution model is used to model the component state. The lifetime of the component is

denoted as $T_{\delta_{DL}}$, which means the time when the component condition exceeds the failure threshold δ_{DL}. The probability of the component which fails during $(0, t]$ is defined as $F_{T_{\delta_{DL}}}(t) = Pr(t \geq T_{\delta_{DL}})$.

Since the failure model and the deterioration model are used to represent the same physical deterioration process, for the same failure condition δ_{DL}, the lifetime distribution is calculated as Equation 5.2, to be consistent with the deterioration process [182]:

$$F_{T_{\delta_{DL}}}(t) = Pr(t \geq T_{\delta_{DL}}) = \frac{\Upsilon(\alpha t, \beta\delta_{DL})}{\Gamma(\alpha t)} \tag{5.2}$$

For the lifetime distribution model, the inspections are only able to identify two states of the components: working or failed. Since the lifetime model cannot give the component condition to the decision maker, the maintenance can only be scheduled according to the usage time or component age.

5.2.2.1 Periodic preventive maintenance policy

Periodic maintenance policy for the lifetime model proposes a two level maintenance policy for the track component, as shown in Figure 5.3.

Since the failure is unrevealed, inspection is needed to detect the component failure. The details of the periodic maintenance policy for the lifetime model are assumed as follows:

1. Inspection is carried out periodically with the interval θ_{insp} regardless of the corrective maintenance.

2. Two levels of maintenances are scheduled for the component

   - Preventive maintenance are planned for the component; it is implemented periodically, with the interval denoted as θ_T. The interval θ_T is a constant independent to the component failure history.
   - Preventive maintenance is imperfect, after the nth preventive maintenance the component is fixed to the virtual age V_n. We assume that the virtual age is equal to a constant value, $V_n = y, n = 1, 2, \ldots$.
   - The lifetime distribution after the nth preventive maintenance is obtained according to the actual age X_n [95]:

$$F_n(t) = F_2(t) = Pr(X_n \leq x | V_{n-1} = y) = \frac{F(t + y) - F(y)}{1 - F(y)} \tag{5.3}$$

   - If the ith inspection identifies the component failure, a corrective maintenance is carried out.
   - Corrective maintenance is perfect. After the corrective maintenance, the virtual age of the component is $V_m = 0$. m is the index of corrective maintenance.

For this maintenance policy, the decision variables are the preventive maintenance interval θ_{PM} and the inspection interval θ_{insp}.

5.2.3 Performance evaluations

Long-term maintenance cost $\mathbb{E}C_\infty$ and system availability Q are used to evaluate the different maintenance policies for lifetime model and stochastic model. They can be estimated by Equation 5.4 and 5.5 based on the number of inspection, corrective maintenance and preventive maintenance. For the long-term maintenance cost $\mathbb{E}C_\infty$, we consider than it depends on the inspection and maintenance performance, we don't consider the cost of unavailability in Equation 5.4 but this equation can be extended for the cost of unavailability in the future.

- **Maintenance cost**

$$\mathbb{E}C_\infty = \lim_{t\to\infty} \frac{C(t)}{t} = \lim_{t\to\infty} \frac{N_{insp}(t)C_{insp} + N_{pm}(t)C_{pm} + N_{cm}(t)C_{cm} + N_f(t)C_f}{t} \tag{5.4}$$

  C_{insp} is the cost of the inspection; C_{pm} is the cost of preventive maintenance, C_{cm} is the cost of corrective maintenance and C_f is the cost of failures.

- **Unavailability**

$$Q = \lim_{t\to\infty} \frac{N_{pm}(t)D_{pm} + (N_{cm}(t) + N_f(t))D_{cm}}{t + N_{pm}(t)D_{pm} + (N_{cm}(t) + N_f(t))D_{cm}} \tag{5.5}$$

  D_{pm} is the downtime for preventive maintenance, we assume that the downtime for failure and corrective maintenance are the same, so D_{cm} represents the downtime for corrective maintenance or failures in Equation 5.5.

In this chapter, a comparison of the models is carried out by simulations, hence we need to establish CPN models for the simulations and collect the simulation results to get the evaluation result from Equation 5.4 and 5.5.

5.3 CPN models

In this section, CPN models are proposed for the different failure processes and their associated maintenance procedures, Section 5.3.1 introduces the CPN model for the gradual deterioration process and Section 5.3.2 introduces the CPN model for the lifetime model and its maintenance policies.

The CPN model consists three parts: deterioration, inspection and maintenance. The framework of the models are shown in Figure 5.4.

5.3.1 CPN model for deterioration model

In this section, the CPN models for the stochastic deterioration process and both of the maintenance policies are introduced.

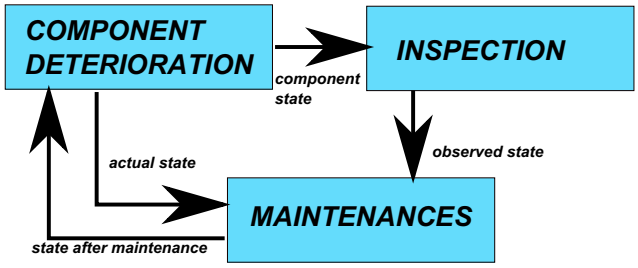


Figure 5.4: Modeling framework

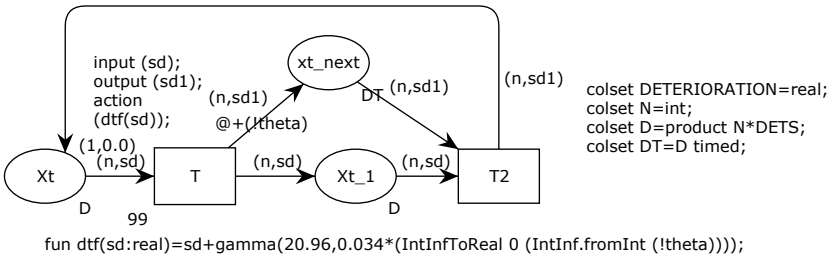


Figure 5.5: Deterioration process

5.3.1.1 Deterioration CPN model

The deterioration process is chosen as a Gamma process $\Gamma(\alpha,\beta)$, the CPN model shown in Figure 5.5 describes the track deterioration process: Color set DETERIORATION is defined to represent the deterioration whereas color set DETS has the same meaning as DETERIORATION with time stamps. Colour set D and DT are a product with the index of life (variable n) and the state of the component (sd or $sd1$), D is untimed colored set and DT is timed colored set. Variables sd and $sd1$ belong to these color sets and indicate the state of the component. The place Xt represents the current deterioration value, the initial marking of Xt is 0.0, transition T1 carries out function $dtf(sd)$. The deterioration increment time is defined to be 1.

Function $dtf(sd)$ generates the random deterioration increment during time ($!theta$) following a Gamma distribution with the parameters α (which is 0.034 in Figure 5.5) and β (which is 20.96 in Figure 5.5).

Place xt_1 represents the current component state, the token in this place without timestamps and it is connected with other transitions such as transition STD_R (preventive maintenance) in Figure 5.6; place xt_next represents the component state at next time, the token in this place is valid according to the time-stamp.

5.3.1.2 Condition-based mainteannce CPN model

Figure 5.6 illustrates the maintenance of the two thresholds. Transition STD_R and transition MAJ_R fires according to the observed track states. If the observed state exceeds δ_{II},

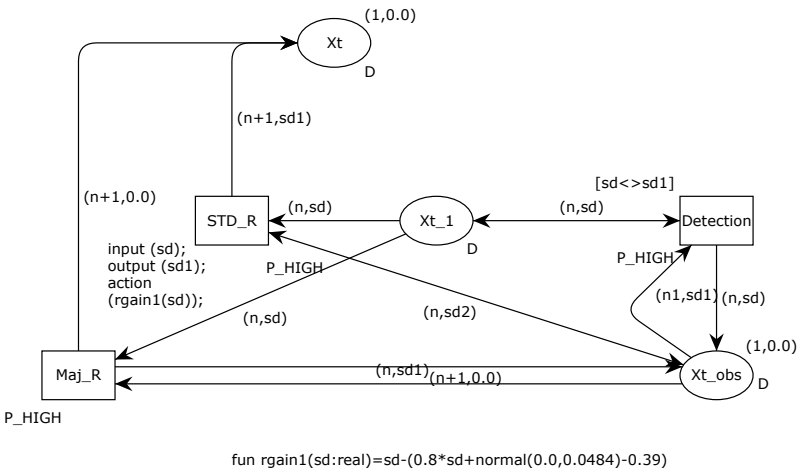


Figure 5.6: Maintenance activities

transition STD_R fires, whereas $X_t \geq \delta_{DL}$ transition MAJ_R fires.

If transition $STDR$ fires, function $rgain1(sd)$ is carried out to obtain the repair gains and then the state after PM (variable $sd1$) is calculated and sent to place Xt. Since the corrective maintenance is perfect, the state in place Xt after CM is set to be 0.0. The maintenance gain is distributed according to the parameters in Table 5.2.

5.3.1.3 Periodic preventive maintenance CPN model for deterioration process

For the Gamma process, we assume another maintenance policy with the inspection which cannot collect the precise component condition data. Periodic preventive maintenance is carried out for the component. The maintenance CPN model is shown in Figure 5.7.

Transition “Planning" set the time of preventive maintenance at place “pm". Once the token in place “pm" is enabled, transition “STDR" fires and set component state to place “Xt". If inspection identifies that component state exceeds corrective threshold, that is token in place “Xt_obs" exceeds global reference $!DL$, then transition “Maj_R" fires (corrective maintenance is carried out) and sends the token with $(n+1, 0.0)$ to place Xt, where 0.0 represents that the component is good again.

5.3.2 CPN model for lifetime model

The framework of the CPN for the lifetime model is the same as shown in Figure 5.4. The deterioration CPN for lifetime model focuses on the failure time, and the preventive maintenance is scheduled based on the time.

5.3.2.1 CPN model describing failure time

The lifetime CPN model is built as shown in Figure 5.8. There are two component states: good(place X_good) and failed(place X_Fail). Places X_Fail0 and X_good1 are used to

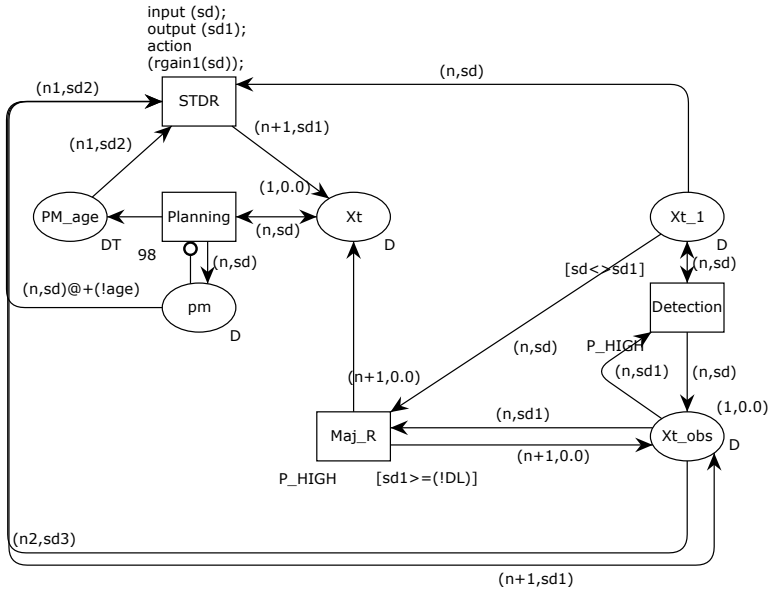


Figure 5.7: Periodic preventive maintenance CPN model

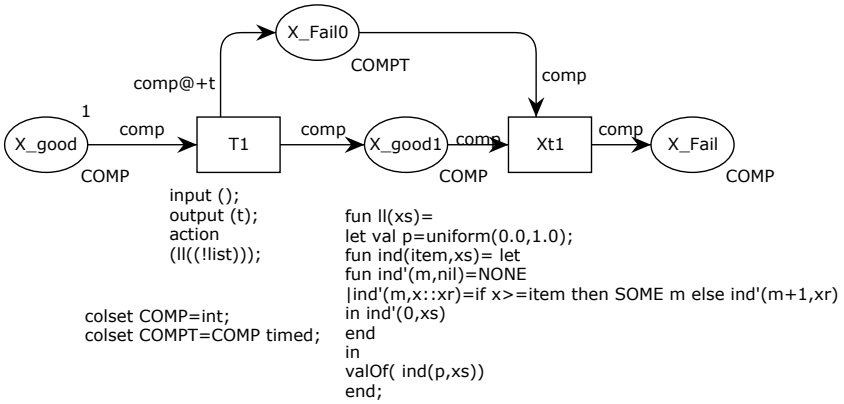


Figure 5.8: Lifetime CPN model

control the time to failure. Color set $COMP$ indicates the n-th failure of the component. COMPT is the timed color set which indicates the failure time of the component. This CPN lifetime model needs to generate the failure time according to the stochastic process model. Since there is no function in CPN Tool can be used directly, the random failure time is generated as follows:

Firstly, a global list "!list" is generated according to Equation 5.6. The elements in the list representing the probability and the element index represents the corresponding time for the probability.

$$F_T(t) = Pr(t \geq T_{DL}) = Pr(X_t \geq \delta_{DL}) = 1 - Pr(X_t \leq \delta_{DL}) = 1 - Gamma(\delta_{DL}|\alpha t, \beta) \quad (5.6)$$

Then, function II(xs) generates a random probability. inside function II(xs), function ind(item xs) finds out the corresponding failure time in the list xs and return the index of the item, which is the random failure time we need.

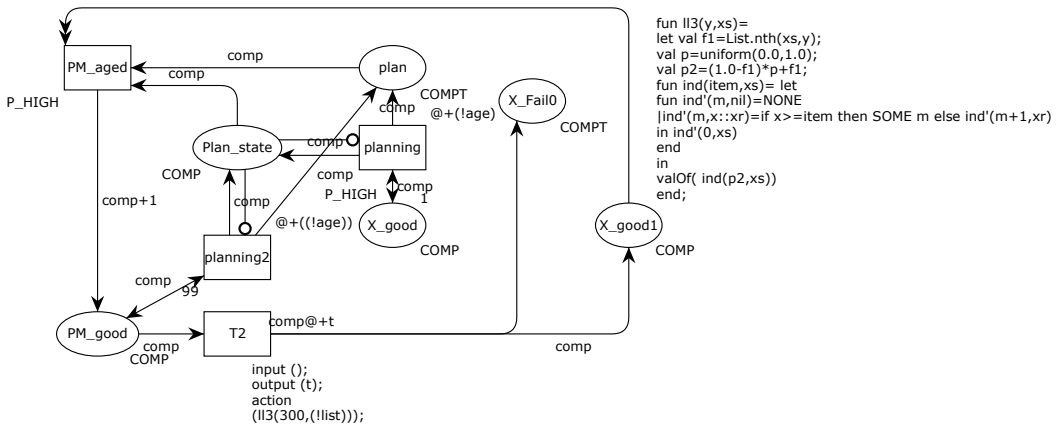


Figure 5.9: Periodic preventive maintenance

5.3.2.2 CPN model for periodic preventive maintenance

According to the modelling assumption, a periodic preventive maintenance is planned for the component to control the degradation based on the time.

Transition *planning* makes a periodic maintenance plan, *age* is a global reference variables, which can be optimised according to the maintenance cost. Transition PM_{aged} is fired when the planning time is over, and the component is fixed to be in place PM_{good}, which is not as good as new. The preventive maintenance is assumed to be imperfect, the time from PM_{good} to failure is shorter than for a new component. In this model, we assume that the lifetime distribution after the preventive maintenance is different from the one of new component. We need to generate the failure time after PM according to the equation 5.3 with a constant virtual age. Function II3(y,xs) returns a random failure time according to the virtual age and the lifetime distribution for the good condition. "y" is the virtual age before and xs is the list of original lifetime distribution probability.

Furthermore, the component is inspected periodically, and the inspection can identify the component failure and then a corrective maintenance is carried out immediately. The corrective maintenance is perfect, so the maintenance can fix the failure to be as good as new again (to place *X_good*). Meanwhile, the planned PM maintenance are re-scheduled, thus the token in place *Plan_state* is consumed by transition *REPAIR*.

Figure 5.10 shows the CPN model of the corrective maintenance.

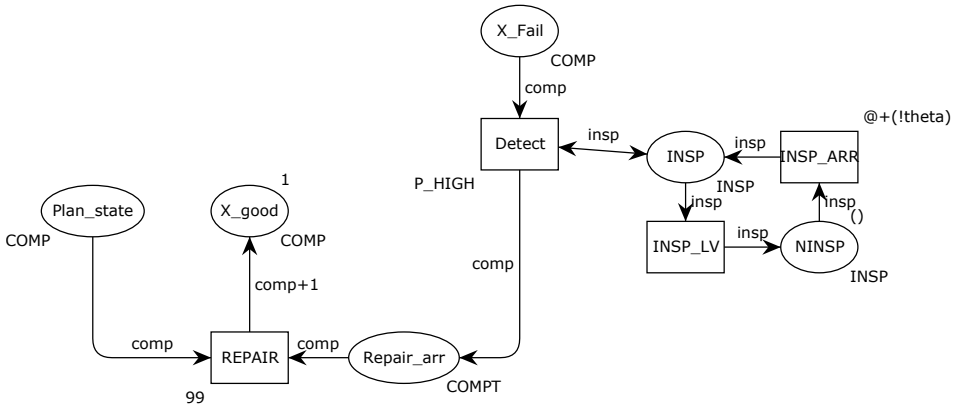


Figure 5.10: Periodic Inspection to check the failure

5.4 Monte Carlo simulations

In order to compare the two models, simulations are carried out to estimate the performance evaluation for the different failure model and maintenance policies. From the simulations, we can collect the number of the preventive maintenance, corrective maintenance and the inspections.

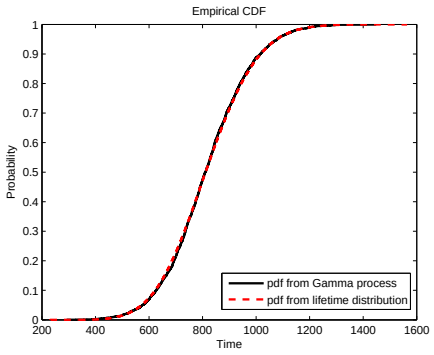
5.4.1 Parameters used in simulations

Let us to explain the simulation parameters in this model, such as time distribution to failure for lifetime model, the effect of preventive maintenance for both models. Firstly, we assume the parameters of deterioration model as shown in Table 5.1:

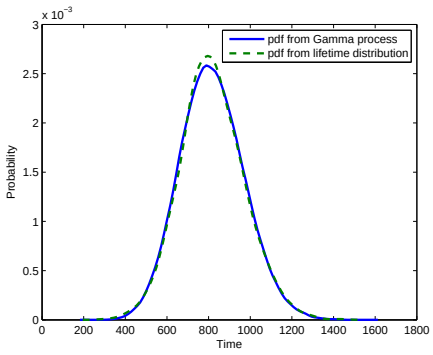
Table 5.1: Parameters of the model

Function	Parameters	
$Gamma(\alpha,\beta)$	α	β
	0.034	20.96
State after PM(X_{pm})	$0.2X_i + 0.39 + N(0.0, 0.0484)$	

For the lifetime model, we need to sample the time to failure ($x \geq \delta_{DL}$): one of the method is to generate random time according to Equation 5.2; another method generates the random time from Gamma process. We collect the time to failure t_F (from 0 to deterioration threshold $\delta_{DL} = 1.3$ in the Gamma process model), which is performed by a monitor of transition $T1$ (in Figure 5.8) to collect the value of variable t. The cumulative function is shown in Figure 5.11a. The plots of density functions are shown in figure 5.11b. In Figure 5.11 we show the probability density distribution and cumulative distribution for the time to failure from Gamma process and its lifetime function. The dash lines represent the distribution of lifetime collected according to Equation 5.2 and they are the same as the distribution sampled from Gamma process (the solid line in the figures).

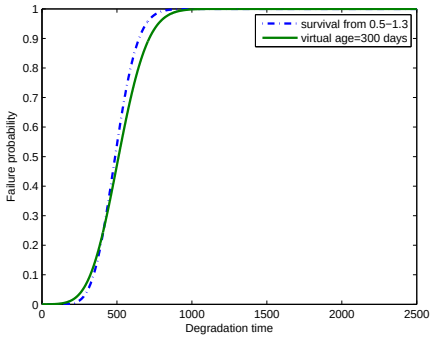


(a) Lifetime distribution from good condition to δ_{DL}

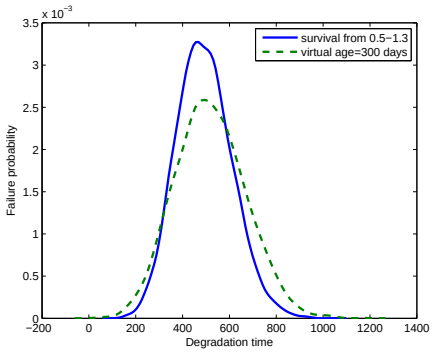


(b) Probability density of failure time form good condition

Figure 5.11: Plot of the distribution when the component is good



(a) Failure cumulative probability as a function of degradation time after PM



(b) Failure probability density as a function of time after PM

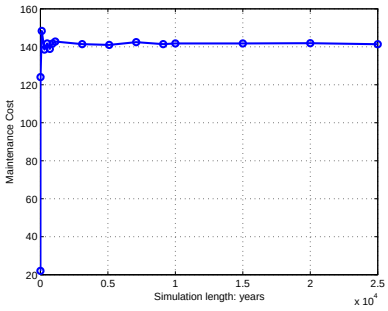
Figure 5.12: Survival time after PMs

The effect of preventive maintenance for stochastic process is not a constant, it follows a normal distribution. We assume the best situation after PM appears if the state after PM is restored to 0.5, the survival distribution according to 4.16 can be seen as the dash curve in Figure 5.12a. Another curve shows the distribution of the virtual age after the preventive maintenance is 300 days. These two distributions have different density distributions, the probability density function for the failure occurrences of the two different distribution are shown in figure 5.12b. We choose the virtual age as 300 days since this age is close to the survival curve of deterioration model but it shows that its preventive maintenance effect is better than the one in deterioration model. Thus the lifetime model with virtual age v_{age} = 300 days will have less failures than the deterioration model. The parameters of the lifetime model are shown in Table 5.2.

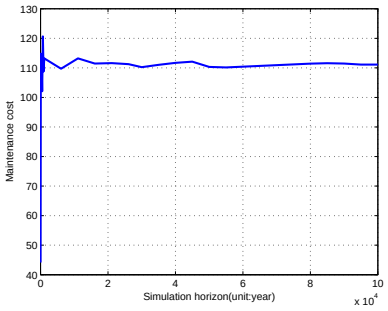
[2]Same inspection costs are set for the three maintenance policies in this chapter.

Table 5.2: Parameters of the model

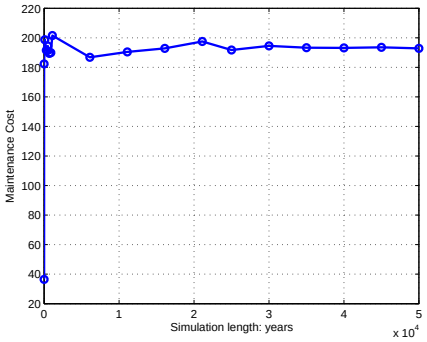
Function	Parameters
Component state after PM(Lifetime Model)	$V_n = y = 300$ days,$n = 1, 2...$
Inspection cost C_{insp}(euro/km) [2]	100
standard intervention cost C_{std} (euro/km)	9,000
Major intervention cost C_{Maj} (euro/km)	900,000



(a) Convergence for Gamma process model with condition-based maintenance



(b) Convergence for Gamma process with periodic preventive maintenance



(c) Convergence for lifetime model with periodic preventive maintenance

Figure 5.13: Convergences of the simulations

5.4.2 Simulation convergence

Monte Carlo simulations are needed to estimate the number of inspection and maintenances. It is important to determine the horizontal length of one simulation or the number of short-term simulations, since we need the converged results. Thus we need to run simulations to find the convergence [].

The convergence of simulation results (maintenance cost) is illustrated in Figure 5.13. Figure 5.13a shows the convergence for Gamma process when $\theta = 7$ and $\delta_{II} = 0.6$; Figure 5.13b shows the simulation for Gamma process model with periodic preventive maintenance policy ($\theta = 7$ and $\theta_{PM} = 240$) and Figure 5.13c shows the convergence of lifetime model when $\theta = 7$ and $\theta_{PM} = 35$. The average maintenance cost of condition-based main-

tenance for Gamma process converges at 7,000 years, the maintenance cost of periodic preventive maintenance for Gamma process is around 80,000 years and the maintenance cost of lifetime model converges at 30,000 years.

5.4.3 Simulation results of deterioration process model

Simulations are carried out to evaluate both of maintenance policies for Gamma process according to parameters in Table 5.1.

5.4.3.1 Simulation results of condition-based maintenance of Gamma process

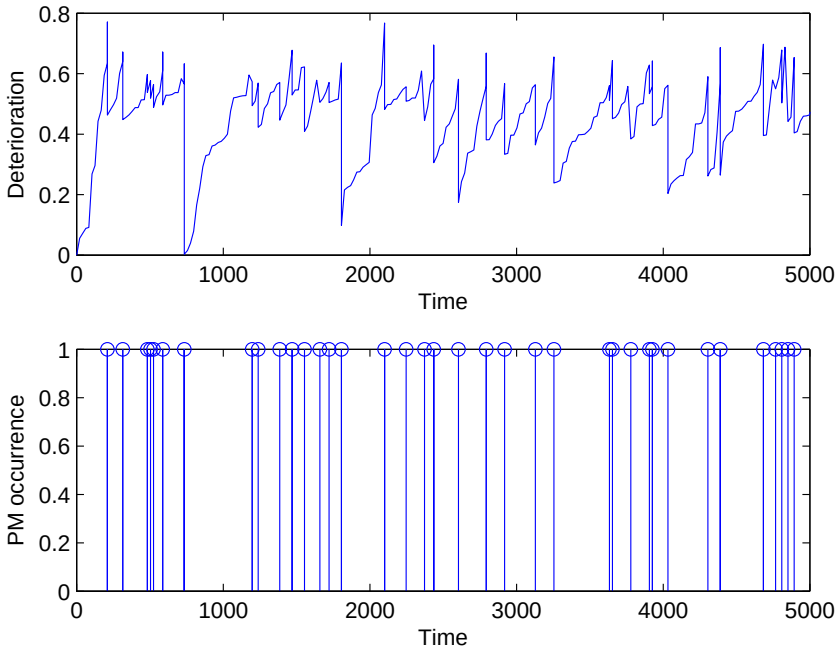


Figure 5.14: An example of deterioration evolution and the corresponding preventive maintenance for period $t \in [0, 5000]$ days

According to the convergence results, simulations for stochastic process are run for a period of 10,000 years. In order to show the component deterioration evolution and maintenance behaviours, Figure 5.14 illustrates the evolution of the component deterioration based on time (top figure) and the occurrences of preventive maintenance for the period $t \in [0, 5000]$ days (the bottom figure). PMs fix the states to random imperfect states and the preventive maintenance is scheduled non-periodically.

Figure 5.15 shows the average maintenance cost against preventive maintenance threshold δ_{PM} and the inspection interval θ_{insp}. It shows explicitly the minimum maintenance cost with the optimized preventive threshold $\delta_{II} = 0.95$ and the optimized inspection interval $\theta_{insp} = 21$ days.

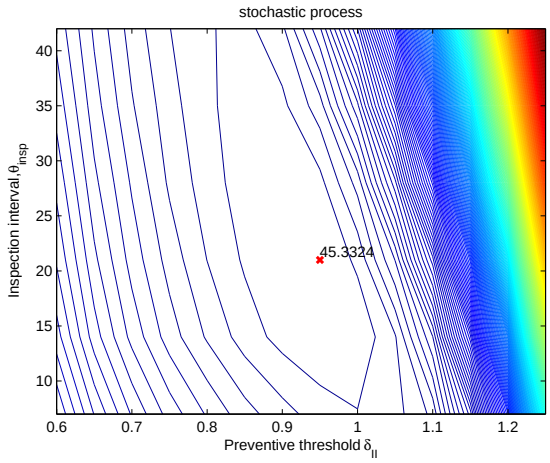
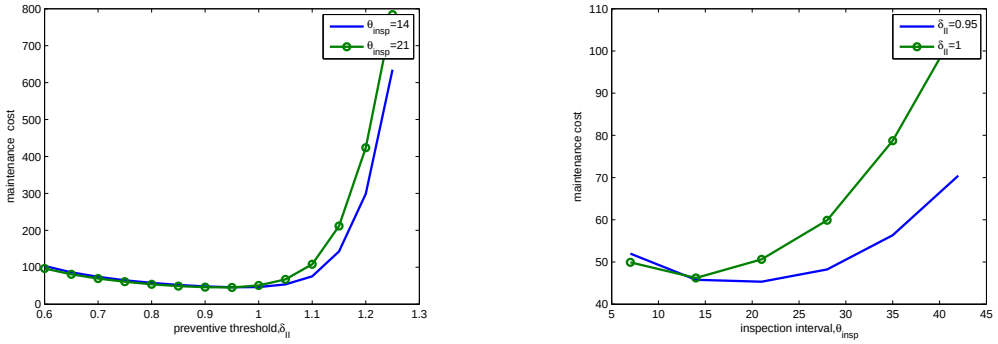


Figure 5.15: Maintenance cost surface as a function of the preventive maintenance threshold δ_{II} and inspection intreval θ_{insp}



(a) $\mathbb{E}C_\infty$ against δ_{II}

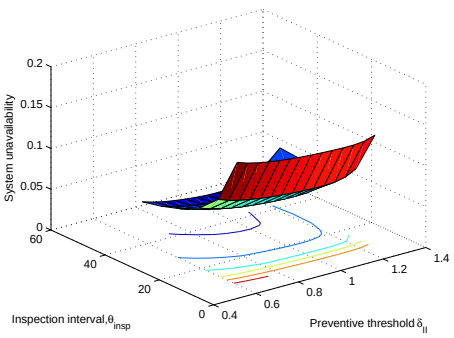
(b) $\mathbb{E}C_\infty$ against θ_{insp}

Figure 5.16: Plot of average maintenance cost $\mathbb{E}C_\infty$ for Gamma process deterioration model with condition-based maintenance policy

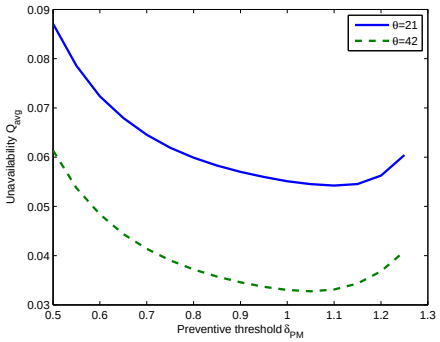
The maintenance cost for the periodic inspection policy is shown in Figure 5.16. Figure 5.16a illustrates the cost against preventive threshold for inspection $\theta = 21, 42$ days. Figure 5.16b shows the maintenance cost against inspection intervals. They show that both preventive threshold δ_{II} and inspection interval θ_{insp} can be optimized to obtain the minimum maintenance cost.

If we know the downtime for the PMs and CMs, the unavailability of the component can be estimated according to Equation5.5 since the maintanence down time is not considered in the CPN simulation time. Figure 5.17a shows the plot of the unavailability against the preventive threshold and inspection interval.

We can have the optimized preventive maintenance threshold to get the lowest unavailability, as shown in Figure 5.17b. For the given $\theta_{insp} = 21$ or 42 days, the optimal unavailability exhibits at $\delta_{II} = 1.05$.



(a) Mesh plot of unavailability against δ_{II} and θ_{insp}



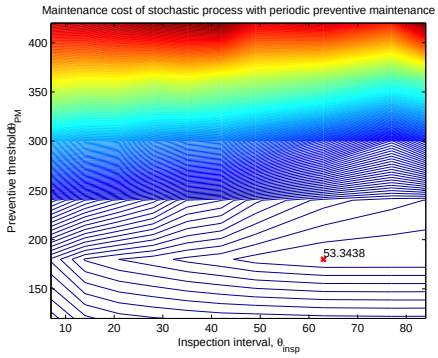
(b) Plot of the unavailability against δ_{II}

Figure 5.17: System unavailability of condition-based maintenance for Gamma process deterioration model

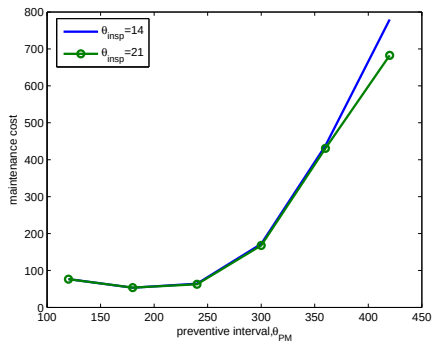
5.4.3.2 Simulation results of periodic preventive maintenance for Gamma process deterioration model

According to the convergence results for the periodic preventive maintenance for Gamma process deterioration model in Figure 5.13b, simulation converges around 80,000 years; in order to get a more converged results, simulations of 100,000 years are carried out for estimate the average maintenance cost and system unavailability of periodic preventive maintenance policy for Gamma process.

Figure 5.18 shows the maintenance cost of the periodic maintenance for Gamma process deterioration model. The optimal maintenance cost is around 53.34 when $\theta_{insp} = 63$ days and $\theta_{PM} = 180$ days as shown in Figure 5.18a. Figure 5.18b shows the average maintenance cost against preventive interval θ_{PM}.



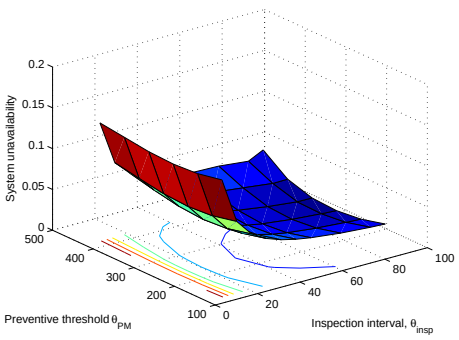
(a) Maintenance cost against PM interval and inspection interval



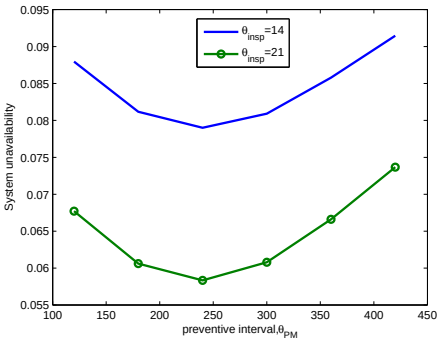
(b) Maintenance cost against intervention interval

Figure 5.18: Maintenance cost of periodic preventive maintenance for Gamma process deterioration model

For the given inspection interval θ_{insp} = 14 or 21 days, the optimal maintenance cost can be obtained at θ_{PM} = 180 days.



(a) System unavailability as a function of the PM interval θ_{pm} and the inspection interval θ_{insp}



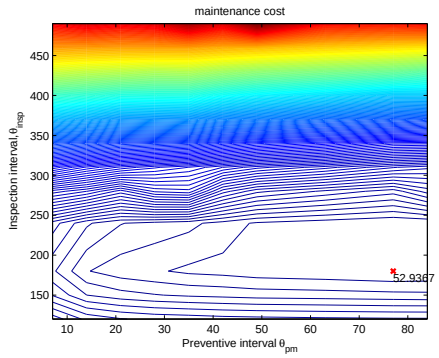
(b) System unavailability against the PM interval θ_{pm}

Figure 5.19: System unavailability of periodic preventive maintenance for Gamma process deterioration model

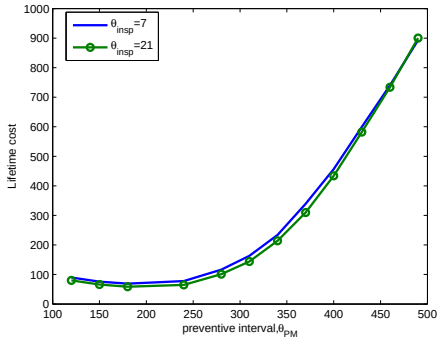
Figure 5.19 illustrates the system unavailability of periodic preventive maintenance for Gamma process and Figure 5.19b shows the unavailability against preventive interval θ_{PM}. For the given inspection interval, the lowest system unavailability is explicitly shown at θ_{PM} = 240 days.

5.4.4 Simulation results of lifetime model

Simulations of the lifetime model converge at around 30,000 years, in order to get a more converged result, we run simulations for the length of 50,000 years.



(a) Maintenance cost as a function of θ_{pm} and θ_{insp}

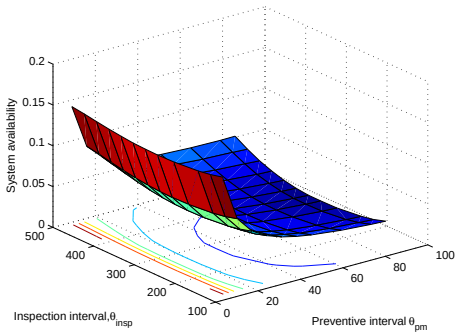


(b) Maintenance cost against preventive maintenance interval θ_{pm}

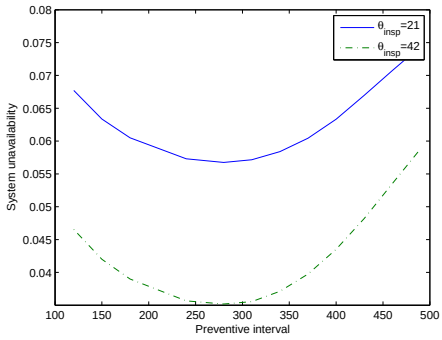
Figure 5.20: Maintenance cost for lifetime model

Figure 5.20a shows the maintenance cost against the preventive maintenance interval

and the maintenance cost, the relationship between the PM interval and the inspection interval. The optimal maintenance cost ($C = 52.93$) is explicitly shown at $\theta_{PM} = 180$ and $\theta_{insp} = 77$. Figure 5.20b plots the maintenance cost against the interval of preventive maintenance for the given inspection intervals.



(a) System unavailability against θ_{pm} and θ_{insp}



(b) Unavailability against preventive maintenance interval θ_{pm}

Figure 5.21: System unavailability for lifetime model

Besides, the unavailability against the preventive maintenance interval is shown in figure 5.21a and Figure 5.21b the system unavailability against preventive interval given the inspection intervals. It shows that the optimized preventive maintenance interval can be $\theta_{pm} = 240$ days.

5.4.5 Comparison of lifetime model and deterioration model

In Section 5.4.3 and 5.4.4, the optimal maintenance cost for the two failure models are shown explicitly in Figure 5.15, 5.18 and 5.20a. We want to compare these results in this section.

Firstly, we assume that the cost parameters for these models are the same (See Table 5.2); in addition, the effect of preventive maintenance in lifetime model is better than the effect in gradual deterioration model. Table 5.3 shows the comparison of the simulations results for the failure models and their maintenance policies. The optimal maintenance cost of periodic preventive maintenance for lifetime model is obtained when $\theta_{insp} = 77$ and $\theta_{pm} = 180$; the optimized maintenance configuration of periodic preventive maintenance for Gamma process is $\theta_{insp} = 63$ and $\theta_{pm} = 180$. The condition-based maintenance for Gamma process is better than both of the periodic preventive maintenance policies when the optimized maintenance configuration is $\theta_{insp} = 21$ and $\delta_{II} = 0.95$.

We also show that for the given inspection interval $\theta_{insp} = 21$, maintenance cost of lifetime model has an optimal value at $\theta_{pm} = 180$ days in Table 5.3. Given the same maintenance price, working with a deterioration model with condition-based maintenance has lower maintenance cost than working with a lifetime model which has a better preventive maintenance effect, since the lifetime model performs more preventive maintenance than the deterioration model.

Table 5.3: Result comparison

	Lifetime model		Deterioration model		
	Periodic PM		Condition-based	Periodic PM	
Configuration	$\theta_{insp} = 77$ $\theta_{pm} = 180$	$\theta_{insp} = 21$ $\theta_{pm} = 180$	$\theta_{insp} = 21$ $\delta_{II} = 0.95$	$\theta_{insp} = 63$ $\theta_{pm} = 180$	$\theta_{insp} = 21$ $\theta_{pm} = 180$
Cost C	52.93	58.43	45.33	53.34	62.82
Unavailability Q	0.0289	0.0605	0.056	0.0316	0.0606

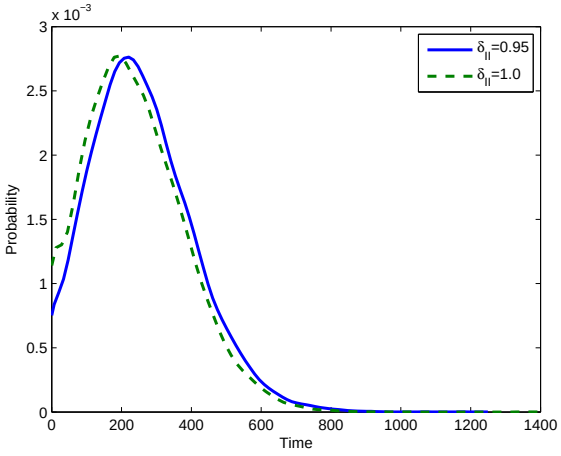


Figure 5.22: Density distribution of time between two PMs of condition-based maintenance for Gamma process

Figure 5.22 plots the density distribution of time between two PMs for $\theta_{insp} = 21$ days and $\delta_{II} = 0.95$ and 1. It shows for the given preventive threshold, the time between two PMs in the deterioration model is around 200 days, which is less than $\theta_{pm} = 240$ of the periodic preventive maintenance policies for both failure models.

5.5 Conclusion for the comparison of failure models

In this chapter, we want to compare component failure models to investigate the effect of inspection capacities on maintenance optimization. Two failure models are considered: one describes the failure process as a gradual deterioration evolution, and another one considers only the time to failures. Since the preventive maintenance is imperfect in the assumption, we assume a virtual age for the lifetime model which underestimate the failures than the stochastic process. For the deterioration model, condition-based maintenance and periodic preventive maintenance policies are taken into account; for the lifetime model, we assume periodic preventive maintenance is planned for the component.

Comparing the maintenance policies for these two kinds of failure models, the results show that the precise inspection can have a better results for the maintenance cost and the component availability since the precise inspection can lead to the non-periodic preventive

maintenance. However, the different inspection prices are not considered in the results in this chapter. Such comparison results could then be used to determine whether it can be worthwhile to invest in a monitoring system with better performance.

CHAPTER 6

Delayed repair for railway track maintenance

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6.1 Introduction

Railway network is a large-scale network which carries thousands of trains and passengers every day. Maintenance machines are allocated in several depots and they need to travel to the locations of the defective assets and the machines and crews are not always available for the maintenance. Once there is a identified asset defect, if it is not critical and does not exceed the extreme threshold, the railway section keeps open to allow trains passing.

Therefore, preventive maintenance for the railway asset cannot be performed immediately after the defects are detected. During the waiting time for preventive repairs, the railway section still allows the traffic and hence suffers to the same deterioration process which possibly results in the asset degrading to a critical state which leads to a corrective maintenance even to an accident.

Castro et al discuss the repair policies for a single unit component which allows repair performing in a repair window [37]. The component works for period T and a continues inspection works for the component. If defects are detected during the repair window, the component is repaired; otherwise, no repair is scheduled and the component is down if the component state reaches N. System reward is the performance evaluation and the length of the repair window is the maintenance decision variable. They calculate the system rewards based on the alternative renewal process [37]. Meier-Hirmer et al. [114] describes the track deterioration as a Gamma process $\Gamma(\alpha,\beta)$, a periodic inspection is scheduled to measure the deterioration details. The preventive maintenance are assumed to arrive in a delay time which may be longer than the periodic inspection interval; during the delay time, component keep deteriorates. They propose a Markov Chain to estimate the maintenance cost.

In this chapter, we want to assess the effect of the delay on the maintenance performance to see if it is necessary to take this delay into account in the decision procedure to make a better maintenance strategy for the track system. A maintenance model is needed to solve the problem. Since the system state not only depends on the last observed state but also more previous states according to the length of the delays, the deterioration process is not a Markov chain. Instead of constructing a Markov Chain introduced in [114], we propose a model based on Coloured Petri Net to estimate the long-term average maintenance cost.

The model in this chapter is presented in conference Safeprocess 2015 [173].

This chapter is organized as followed: Section 6.2 lists the assumptions of track deterioration and maintenance. Section 6.3 illustrates the Colored Petri Net model for the assumptions. Section 6.4 shows the simulation results and section 6.5 give a brief conclusion.

6.2 Track maintenance modelling assumptions

In this chapter, the component deterioration is assumed to be a Gamma process: $X_{\tau+\Delta\tau} - X_\tau \sim \Gamma(\alpha\Delta\tau,\beta)$. Delayed repairs for condition based maintenance and periodic inspection are modeled. The preventive maintenance threshold, inspection interval and the repair delays are optimized to get the minimum maintenance cost.

6.2.1 Modelling assumptions

The delayed maintenance policies considers a single unit component. Track top fault (described in Chapter 2), the vertical geometry fault of track is assumed to be the failure. Tamping is assumed to be the preventive maintenance method and the stoneblowering is the corrective maintenance. Track condition information, .i.e. standard deviation for 35m long is collected by track recording car.

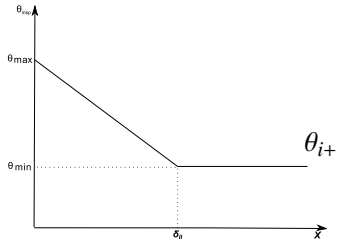
The assumptions of the model in this work are as follows:

- The component is assumed to be a track of 1 kilometre long.

- The track component deteriorates following a Gamma process, X_τ is the component state at time τ and $X_{\Delta\tau}$ represents the deterioration increment over $\Delta\tau$, $X_{\Delta\tau} \sim \Gamma(\alpha\Delta\tau, \beta)$.

- The component states are measured by the inspection, which is arranged to be either periodic or condition based. We compare these two different inspection schemes:

  - **Periodic inspection**: The inspection is carried out periodically and the interval is equal to θ_{insp}.
  - **Condition-based inspection**: After the ith inspection, the interval θ_{i+1} until the $(i+1)$th inspection is based on the observed component state X_i which is inspected by the ith inspection. θ_{i+1} is decided by preventive threshold δ_{II} as shown in Equation 6.1:



$$\theta_{i+1} = \begin{cases} \theta_{max} - \dfrac{X_i(\theta_{max} - \theta_{min})}{\delta_{\text{II}}}, & X_i \in (0, \delta_{\text{II}}) \\ \theta_{min}, & X_i \in [\delta_{\text{II}}, \infty) \end{cases} \tag{6.1}$$

    If the state exceeds preventive threshold, that is $X_i \leq \delta_{\text{II}}$, the inspection interval equals the minimum inspection interval,i.e. $\theta_{insp} = \theta_{min}$; otherwise the $(i+1)$th inspection is $\theta_{i+1} \in (\theta_{min}, \theta_{max}]$.
  - For periodic inspection, there are two decision variables to be optimized: θ_{insp} and δ_{II}.
  - For the condition based inspection, θ_{min} and δ_{II} are the two decision variables to be optimized.

- Two types of maintenances are arranged regarding to two maintenance thresholds: a major maintenance threshold δ_{DL} and a preventive maintenance threshold δ_{II}.

  - If $X_i \geq \delta_{\text{DL}}$, a major maintenance is carried out within a delay t_D. δ_{DL} is given by the maintenance rules.
  - If $\delta_{DL} \geq X_i \geq \delta_{\text{II}}$, a preventive intervention is carried out within a delay t_d.
  - Both interventions are imperfect. A linear regression model is adopted for the repair gains, which is $G = c + mX + \varepsilon, \varepsilon \sim N(0, \sigma)$, X is the component state when repair is arrived. The parameters of the gains can be seen in [114].

- Repair delays t_d and t_D are not decision variables, they are set by the maintenance rules or practice. Upon an inspection, depending on the given t_d and t_D, there are different possible maintenance scenarios:

  - If $t_d \leq \theta_{insp}$ **or** $t_d \leq \theta_{min}$: As shown in Figure 6.1, if the observed state exceeds δ_{II}, a preventive maintenance is arranged in a delay time t_d. The maintenance

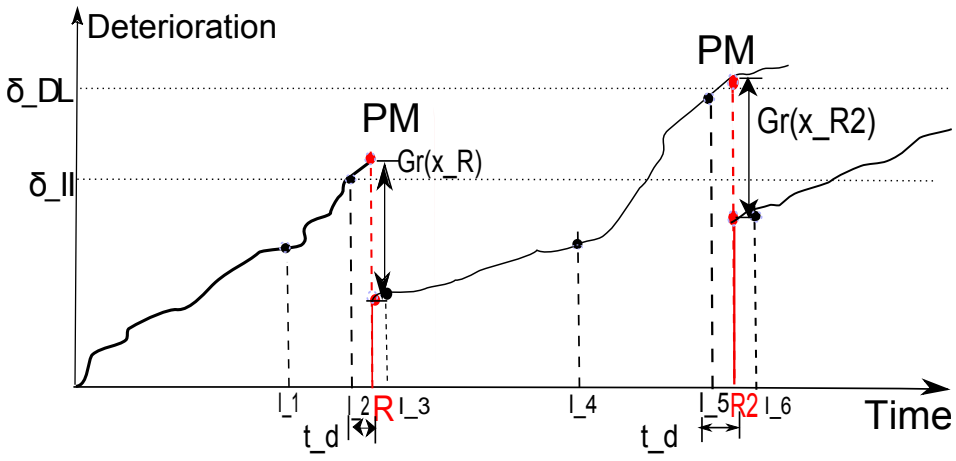


Figure 6.1: Maintenance process for the situation $td \leq \theta_{min}$

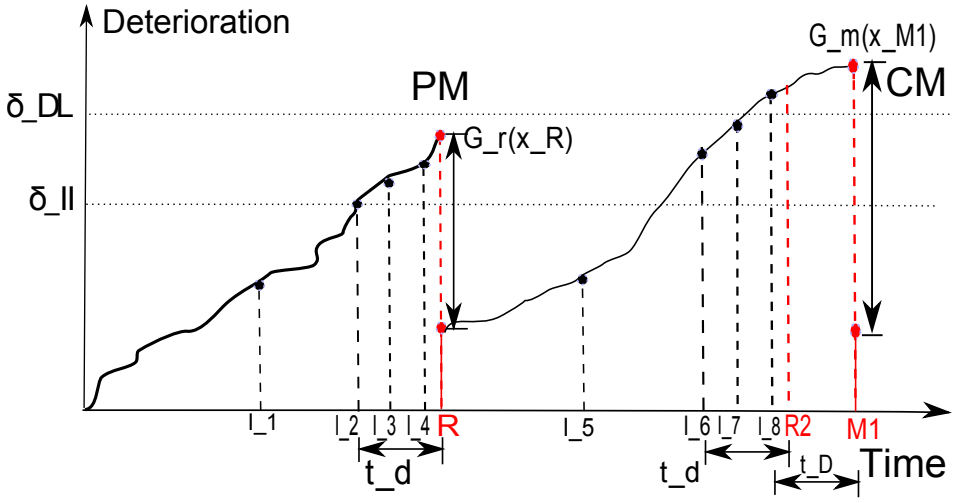


Figure 6.2: Maintenance process for the situation $td \geq \theta_{min}$

type is not updated even though the track state exceeds δ_{DL} during t_d. $G_r(x_R)$ represents the preventive maintenance gain depending on the state X_R at time R. When $X_{I_5} > \delta_{\mathrm{II}}$, a preventive maintenance is planned at R2, it is carried out even though the track state exceeds δ_{DL} before R2.

– If $t_d \geq \theta_{\mathbf{insp}}$ **or** $t_d \geq \theta_{min}$: As shown in Figure 6.2, there are two possible situations as shown in Figure 6.2.

  ◇ If the observed states *never* exceed δ_{DL}, inspection does not change preventive maintenance decision. Inspection I_2 arranges a preventive maintenance at R. I_3 and I_4 show the states stay $\delta_{II} \geq x_{I4} \geq \delta_{\mathrm{DL}}$ so they do not change the maintenance decision, PM is performed at time R in Figure 6.2.

◇ The inspections detect states $x \geq \delta_{\mathrm{DL}}$, so they update the maintenance type. Inspection I_6 detects $X_{I_6} > \delta_{\mathrm{II}}$ so that a preventive maintenance is scheduled at R2, but I_8 updates the preventive maintenance to be major maintenance since $X_{I_8} > \delta_{\mathrm{DL}}$, then the preventive maintenance at R2 is cancelled and the major maintenance arrives at $M1 = I_8 + t_D$. $G_m(x_M1)$ represents the major maintenance gain depending on the state X_{M1} at time M1.

6.2.2 Performance evaluation

In order to assess the effects of repair delays and optimize the maintenance decision variables, average maintenance cost C_{avg} is adopted to evaluate the maintenance strategies.

$$C_{avg} = \lim_{\tau \to \infty} \left(\frac{C_{total}(\tau)}{\tau}\right) \tag{6.2}$$

$$C_{total}(\tau) = \quad N_{std}(\tau)c_{std} + N_{maj}(\tau)c_{maj} + N_{insp}(\tau)c_{insp}$$

Sometimes, the maintenance cost over a finite time horizon is more practical for the engineering. In this chapter, we also consider the maintenance cost rate over a finite time, i.e. 100 years. The short-term maintenance cost rate is estimated by Equation 6.3:

$$\mathbb{E}C_{T^*} = \frac{\mathbb{E}[C_{total}(T^*)]}{T^*} \tag{6.3}$$

C_{avg}	average maintenance cost.
C_{total}	total maintenance cost during time period τ.
c_{std}	cost for each preventive maintenance.
c_{maj}	cost for each major maintenance.
c_{insp}	cost for each inspection.
$N_{std}(\tau)$,$N_{maj}(\tau)$ and $N_{insp}(\tau)$	number of preventive maintenance, major maintenance and inspection during time τ.

6.3 Track CPN models

The CPN model consists of three parts: deterioration, inspection and maintenance. In this section, we show the CPN model of inspection and delayed maintenance.

6.3.1 Deterioration part of CPN model

According to the assumption, the deterioration CPN needs to model the deterioration increments in several cases when the repair delay $t_d < \theta$:

- if the last observed state $x_{(i-1)\theta} < \delta_{II}$, the deterioration increment between the $i-1$th inspection and the ith inspection equals $Pr(x_{i-1}, dx) = f_{\alpha\theta,\beta}(x - x_{i-1})dx$

- If the last observed state $x_{i-1} \geq \delta_{II}$, a preventive maintenance is scheduled before $t_d < \theta$ then the distribution of the increment between two inspections equals $Pr(x_{i-1}, dx) = f_{\alpha(\theta-t_d),\beta}(x - x_{t_d})dx$
- If the last observed state forces a corrective maintenance, the increment equals $Pr(x_{i-1}, dx) = f_{\alpha(\theta-t_D),\beta}(x - x_{t_D})dx$

If the repair delay $k\theta < t_d < (k+1)\theta$, the deterioration between the $(i-1)$th inspection and the ith inspection not only depends on the state at time $(i-1)$ but also depends on the state at time $(i-2)$... time $[i-(k+1)]$. If $k = 1$, the increment can be:

$$\begin{aligned} Pr(x_{i-2}, x_{i-1}, dx) =& f_{\alpha\theta,\beta}(x - x_{i-1})I_{(x_{i-1}\leq x<\delta_{II})\bigcup(x_{i-2}<\delta_{II}\bigcap\delta_{II}\leq x_{i-1}\leq\delta_{DL})} \\ &+ f_{\alpha t_d,\beta}(u - x)g(t)f_{\alpha(2\theta-t_d),\beta}(x - u + v)I_{x_{i-2}\leq x_{i-1}<\delta_{II}} \\ &+ f_{\alpha t_D,\beta}(u - x)g_1(t)f_{\alpha(2\theta-t_D),\beta}(x - u + v)I_{x_{i-1}\geq\delta_{DL}}dx \end{aligned}$$

The complexity of the calculation for the probability density for the ith inspection increases if we have larger k.

In the Colored Petri Net model, we describe the increments between two inspection considering whether there is a maintenance between the inspections:

1. There is no maintenance action between two inspections, as shown in Figure 6.3.

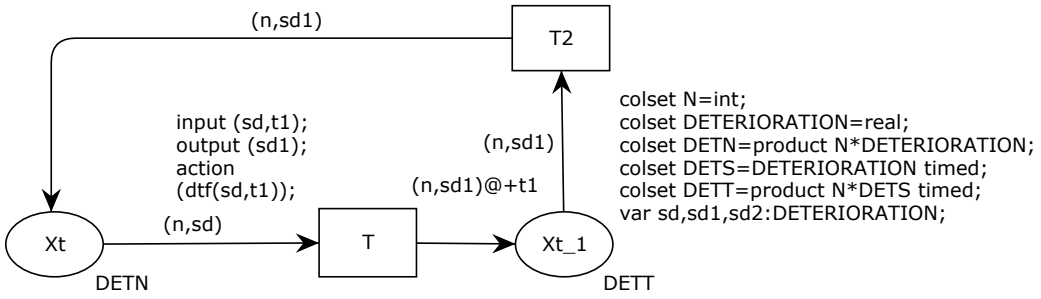


Figure 6.3: CPN model for Deterioration process

Coloured set 'DETERIORATION' represents component state and coloured set 'DETS' has the same meaning as 'DETERIORATION' but it is a timed coloured set. Coloured set 'DETN' consists of the index of deterioration process and the state, 'DETT' is the timed coloured set of 'DETN'. Variables $sd, sd1 \in$ DETERIORATION, they transfer the observed track state to the other places. The place 'Xt' represents the current deterioration value. The initial marking is $M_0(Xt) = 1$'0.0, which means the component is new. place 'xt_1' represents the state during $\tau \in [\tau, \tau + 1)$, place'xt_next' represents the next track state. If transition 'T' fires, it performs function 'dtf(sd)' to get the value for 'sd1', so we have: $M_1(Xt) = \Phi_{MS}$, $M_1(xt_1) = sd$, $M_1(xt_next) = sd1 = sd + \Gamma(\alpha \times t_1, \beta)$. After 1 unit time, 'T2' fires and sends $sd1$ to place 'Xt', which means at time $\tau = t_1$, $Xt = sd1$.

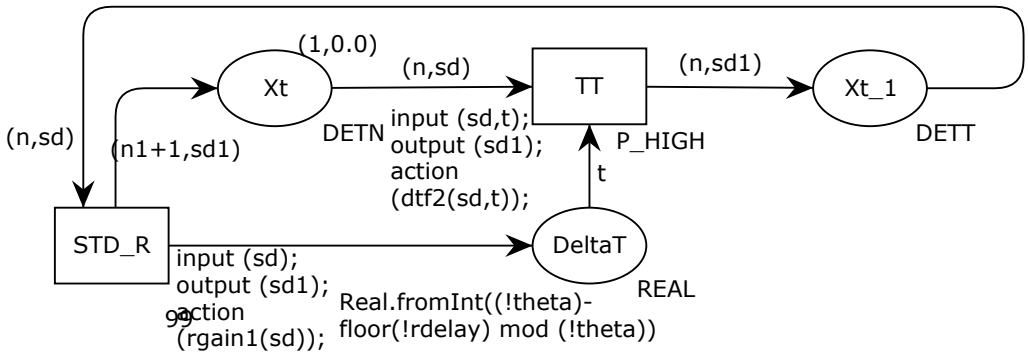


Figure 6.4: CPN model for Deterioration process after PM

2. There is a maintenance action between two inspections, as shown in Figure 6.4.

   The repairs are delayed, which will affect the deterioration increments during the inspection interval. According to the definition of the Gamma process, the time between the intervention and its following inspection determines the increments. In Figure 6.4, transition STD_R takes the states without intervention in place 'xt_1' and transition 'TT' updates the state to place 'xt_1' according to the current state shown in place 'Xt' and the time in place 'DeltaT'.

6.3.2 CPN model of inspection schemes

The inspection CPN is shown in Figure 6.5. Place 'INP_TYPE' controls the inspection schemes which is set by global reference *inptype*. When transition "ARRIVE" fires, function "action()" firstly checks the inspection type and then decides inspection interval: If $inptype := P$, the periodic inspection is adopted, otherwise the function 'CBINSP(sd1)' and updates the inspection interval $t1$ based on $sd1$ as shown in Equation 6.1, thus $t1 = \theta_{insp} = \text{CBINSP}(sd1)$.

'xt_1' represents the current component state, if the token in place 'INSP' is enabled, transition 'Detection' has higher priority than transition 'LEAVE', it fires and updates the observed state in place 'Xt_obs'. The guide function 'sd<>sd1' is used to control the transition 'Detection' to fire once while there is a inspection arrives.

The number of inspections $N_{\text{INSP}}(\tau)$ is collected by monitoring transition 'LEAVE' in figure 6.5.

6.3.3 CPN model of delayed maintenance

The delayed preventive maintenance and corrective maintenance are assumed to arrive in delay times.

Figure 6.6 and 6.7 illustrate the maintenances of the track component. In Figure 6.6, transition 'STD_R' is controlled by guard function "$sd1 >= (!II)$ andalso $sd1 > (!DL)$", global reference "!II" represents δ_{II} and "!DL" is for δ_{DL}. If transition 'STD_R' fires, a

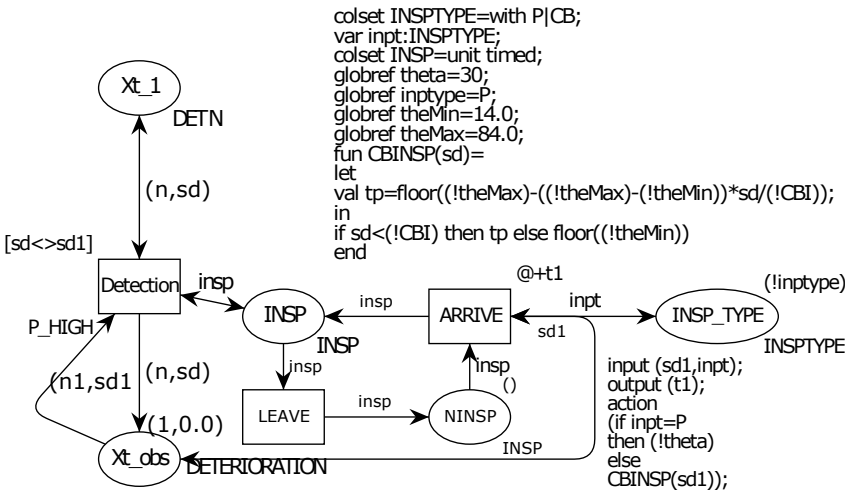


Figure 6.5: CPN model for Inspection configuration

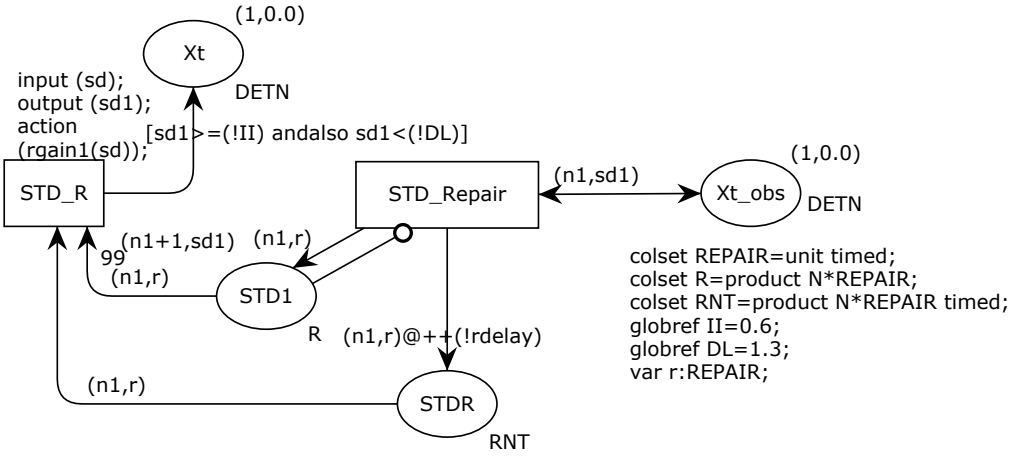


Figure 6.6: CPN for preventive Maintenance

preventive repair is scheduled. The different repair delays are set to the waiting maintenance place place 'STDR'. Global reference "!rdelay" represents preventive repair delay t_d. If transition 'STD_R' fires, function $rgain1(sd)$ is carried out to obtain the preventive repair gains, function $rgain1(sd)$ is defined according to the assumptions.

If $t_d \geq \theta$, at time t_1 the defect is observed and transition 'STD_Repair' fires; the markings of 'STD1' and 'STDR' are $M(STD1, t1) = (n_1, ())$, $M(STDR, t1) = (n_1, ())@(t1 + (!rdelay))$. At time $t_1 + \theta$, the observed state indicates the preventive maintenance is still needed, but there is a token in place 'STD1' which does not allow transition 'STD_Repair' firing at time $t_1 + \theta$. This part represents the preventive maintenance decision does not change if the component requires preventive maintenance until the PM arrives.

Figure 6.7 shows the CPN model of corrective maintenance. 'Maj_Repair' makes a decision of CM, if the guard function $sd1 >= (!DL)$ is satisfied, transition 'Maj_Repair'

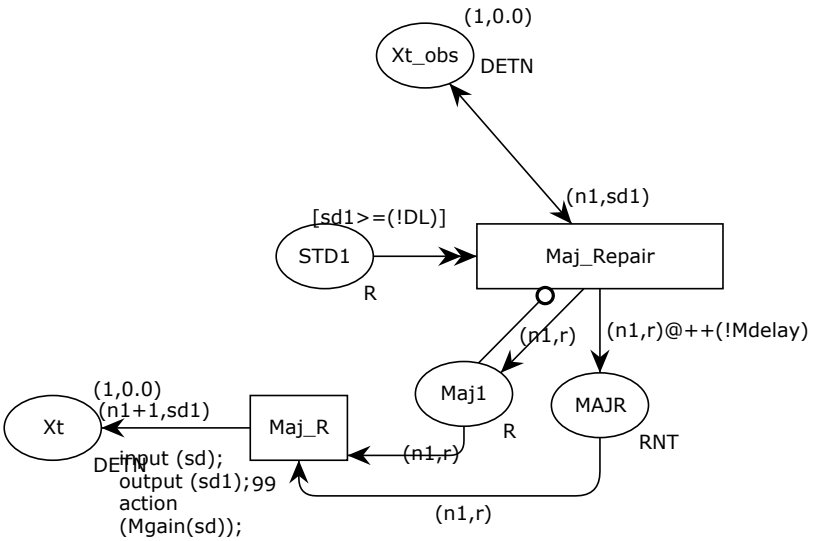


Figure 6.7: CPN for corrective maintenance

fires, a token is sent to place 'Maj1' which means the component needs CM and a token is sent to place 'MAJR' which stores the repair arrival time sampled by function $Mgain(sd)$. Similar to transition 'STD_R' , transition 'Maj_R' fires if token in 'MAJR' is enabled. If PM delay is larger than inspection interval and a major maintenance is needed during the delay time. This maintenance updating process is realized by the reset arc from 'STD1' to transition 'Maj_Repair'.

The number of preventive maintenance actions $N_{\mathrm{STD}}(\tau)$ is collected by monitoring the transition 'STD_R', the number of major maintenance actions $N_{\mathrm{MAJ}}(\tau)$ is collected by monitoring the transition 'Maj_R'.

6.4 Numerical results

Monte Carlo Simulations are needed to:

- investigate how the delay t_d affects the maintenance performance;
- find the optimal maintenance decision value for delayed maintenance strategies.

Simulations are carried out according to the maintenance cost parameters as shown in Table 6.1. The maintenance price is not exactly the real price used in the real railway system; in some researches, the preventive maintenance action price is assumed to be several thousand euros and the corrective maintenance or the renewal price is assumed to be several hundred thousand euros.

6.4.1 Simulation convergence

We run simulations for one maintenance configuration to find the simulation convergence. The simulation are configured as: $\theta_{insp} = 15$, $\delta_{II} = 0.6$,$t_d = 1.0$.

Table 6.1: Simulation parameters

Parameter	Value	Parameter	Value	Parameter	Value	Parameter	Value
α	0.034	β	20.96	θ_{max}	84	t_d	14
C_{cm}	800,000	C_{pm}	8,000	C_{insp}	100	δ_{DL}	1.3

6.4.1.1 Converged simulation time

We run simulations for different lengths of period, Figure 6.8 shows that the maintenance cost converges when the simulation length is longer than 5,000 years for the simulation in CPN tool, the average maintenance cost for the maintenance configuration is around 92.5.

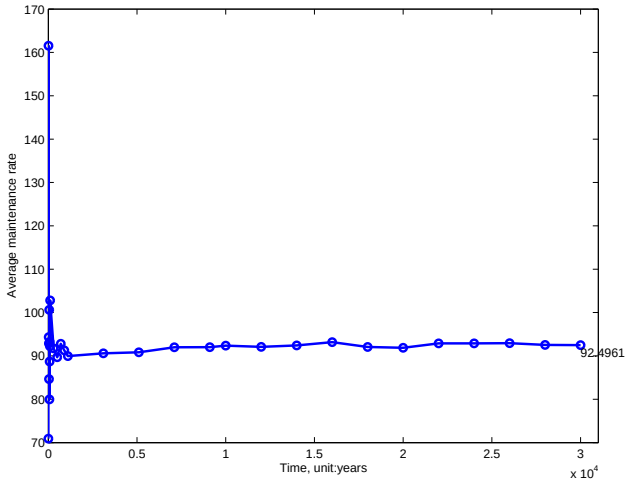


Figure 6.8: Convergence of the simulation period

According to the renewal cycle or semi-regenerative properties[71], the average maintenance cost rate calculated in Equation 6.2 can be written as:

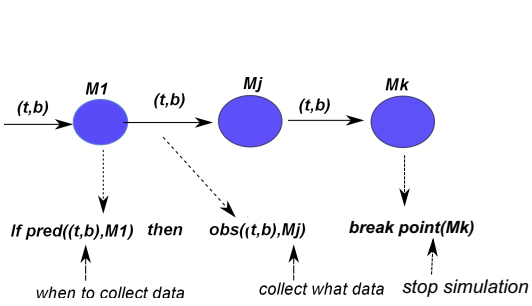
$$C_{avg} = \lim_{\tau \to \infty} \left(\frac{\mathbb{E}C_{total}(\tau)}{\tau} \right) = \frac{\mathbb{E}(C(T_s))}{\mathbb{E}(T_s)} \tag{6.4}$$

T_s is the renewal cycle.Equation 6.4 can be used to estimate the long run maintenance cost rate over an infinite time horizon. The maintenance cost for a renewal cycle $(kT_s, (k+1)T_s]$ equals:

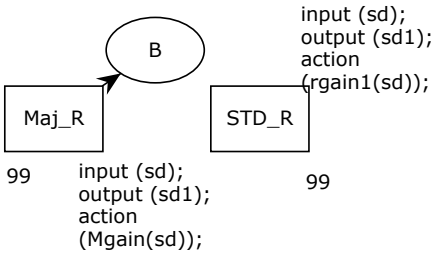
$$C(T_s) = c_{cm} + c_{pm}N_{pm}(T_s) + c_{insp}N_{insp}(T_s) \tag{6.5}$$

Simulations are carried out within a renewal cycle T_s to estimate the maintenance cost. In the CPN tool, we set the monitor to count the number of possible maintenance actions and inspections between two CMs, shown in Figure 6.9.

Figure 6.9a is the general monitoring process in CPN tool. Function 'pred(bindelem)' is used to decide when to collect data, (t, b) represents the transition and bind elements , the marking after (t, b) is $M1$, they are input of function pred(); and then the function 'obs()' is



(a) Monitoring process for renewal cycle



(b) The monitor for corrective maintenance cycle

Figure 6.9: The monitor of renewal cycle

used to collect data when marking Mj appears. When the break point marking Mk occurs, the simulation stops.

Figure 6.9b shows the transitions and places of a monitor which collects the number of PMs $N_{pm}(T_s)$ in a renewal cycle T_s. 'Maj_R' represents the corrective maintenance happens, transition 'STD_R' represents that the preventive maintenance is performed and place 'B' is introduced to indicate the number of corrective maintenance N_{cm}. When there is one token in place 'B', the function 'pred()' enables the monitor. If the bind elements transition STD_R fires and the marking of place B $M(B) = 1$'() appears, function obs() counts the number of PMs. If there are two tokens in place 'B', which means the second corrective maintenance happens, and then the break point stops. In order to obtain the renewal cycle as soon as quickly, the simulation assumes the initial state exceeding corrective maintenance threshold δ_{DL}.

The function "pred()" is shown in Table 6.2, "size(New_Page'B_1_mark)>=1" means the marking of place B is larger than 1 and it turns on the monitor; if not (i.e. "$|obsBindElem_ =\sim 1$"), the monitor is off.

Table 6.2: Function pred() definition

	The Predicate function:
fun	$pred(bindelem, New_Page'B_1_mark : UNITms) =$
let	
fun	$predBindElem(New_Page'STD_R(1,n,n1,r,sd,sd1))$
	$= size(New_Page'B_1_mark) >= 1$
	$\|predBindElem_ = false$
in	
	predBindElem bindelem
end	

Besides the number of preventive maintenance, we need to collect the number of inspections N_{insp} and the time between the first corrective maintenance and the second maintenance T_s. The number of inspections between two corrective maintenances N_{insp} is collected by monitoring the place 'B' and transition 'LEAVE' in the similar way. We collect

the time $Tcm1$ of the first corrective maintenance is performed once there is a token in place 'B', and the time $Tcm2$ of the second corrective maintenance when the break point happens. The time between two corrective maintenance $T_s = Tcm2 - Tcm1$.

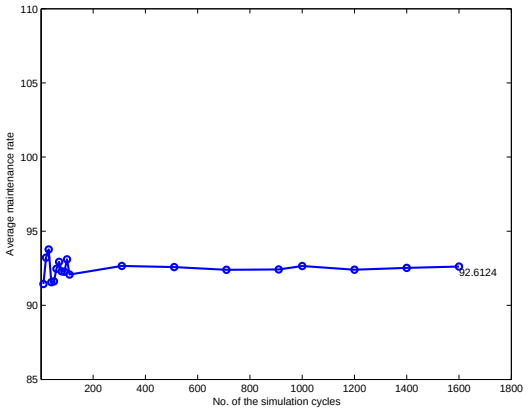
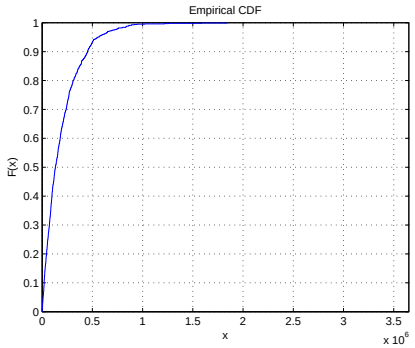
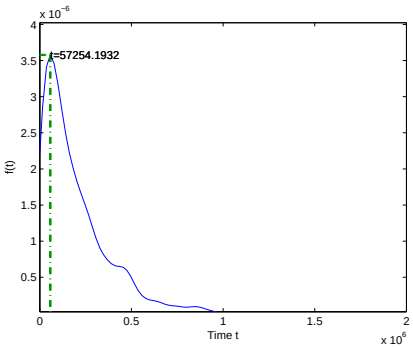


Figure 6.10: The convergence of the renewal cycle

Figure 6.10 shows the convergence of the renewal cycle between two corrective maintenances. The simulation convergence is obtained if more than 1000 simulations are carried out, the average maintenance cost obtained is 92.6.



(a) Empirical cumulative distribution function(cdf) of corrective maintenance



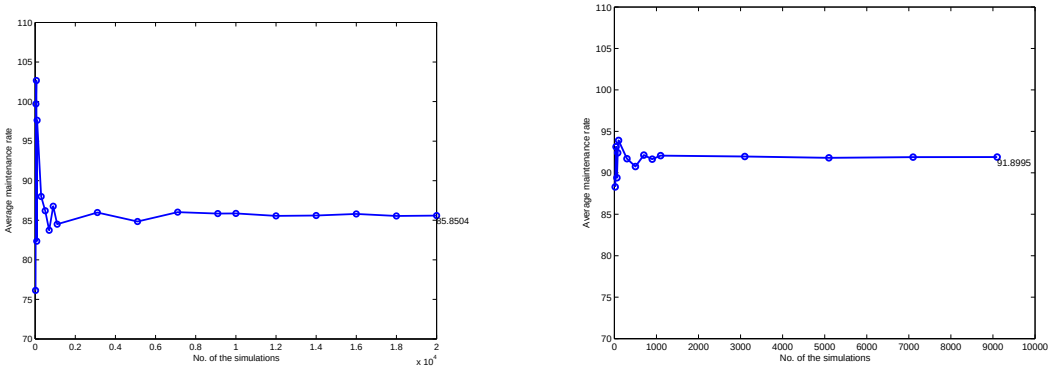
(b) Empirical probability density function(pdf) of corrective maintenance

Figure 6.11: Distribution of corrective maintenance

Figure 6.11 shows the pdf and cdf of the corrective maintenance obtained from the renewal cycle simulations. According to Figure 6.10 and Figure 6.8, maintenance average cost over a long time is 92.5 the cost over the renewal cycle is 92.6. These figures show that the different simulation methods for the average maintenance cost rate over the infinite time horizon are the same. It takes 20 minutes for 5000 simulations of the renewal cycle while it takes 3 minutes to run the simulation of 10,000 years. In addition, the simulations for 10,000 years can be easily implemented with less memory, so we choose to simulate for the time long enough technically to get the estimated results.

6.4.1.2 Number of simulations for a finite simulation time

If the length of simulation period is a finite period, we need to find the number of simulations for the finite time to get a converged result. Thus, we run the simulations with different simulations number for the period of 3,650 days and 36,500 days



(a) Length of 3650 days (b) Length of 36500 days

Figure 6.12: Convergence of the finite period simulations

Figure 6.12a shows the convergence of 10 year simulation is around 7,000 and Figure 6.12b shows the simulations for period of 100 years (36,500 days) is around 1,000 simulations. Figure 6.12 shows the average maintenance cost for 10 years and the maintenance cost for 100 years are different, i.e. $\mathbb{E}C(3650) = 85.85$ and $\mathbb{E}C(36500) = 91.90$. According to the convergence, $\mathbb{E}C(3650) < \mathbb{E}C(36500) < \mathbb{E}C_\infty$. The reason of the differences is the distribution of the corrective maintenance. Figure 6.13 shows the density distribution of the time between corrective maintenance, $t \in [0, 2 \times 10^5]$.

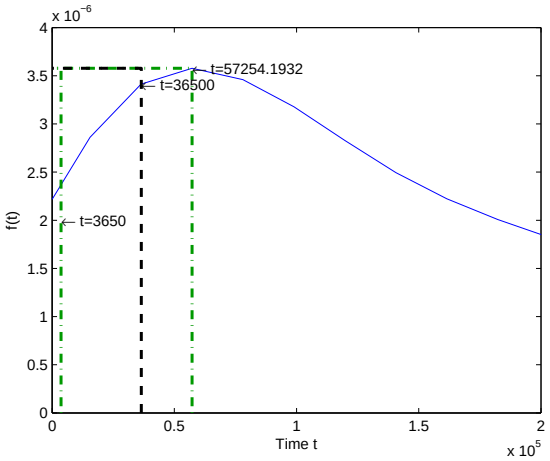
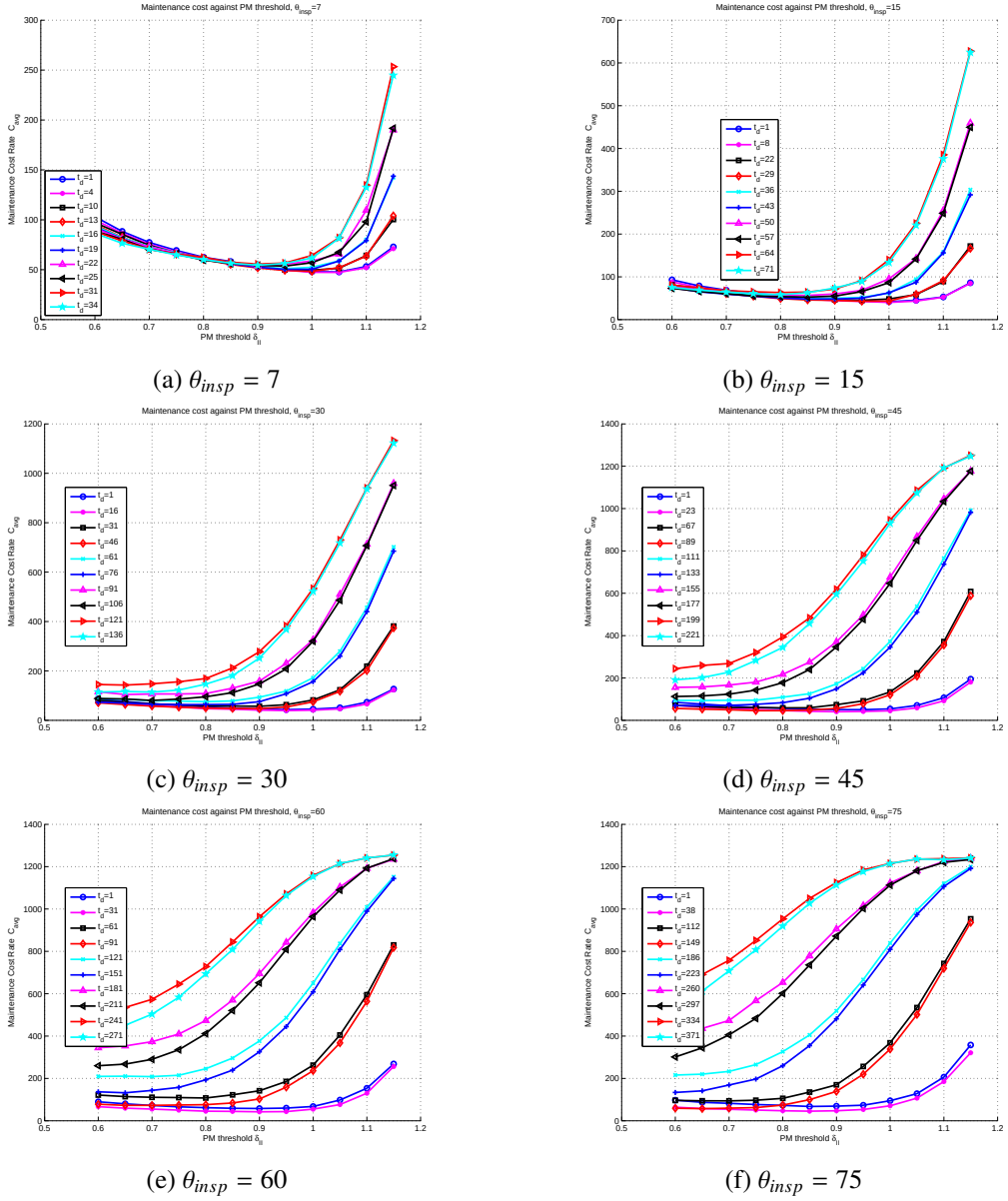


Figure 6.13: Empirical PDF of corrective maintenance

6.4.2 Repair delay for periodic inspection

We run simulations with the CPN model instead of the Markov chain proposed by Meier-Hirmer to investigate the effect of PM delays for period inspection policy. The simulations are carried out with the parameters in Table 6.1. Inspection interval θ_{insp} and PM threshold δ_{II} are the maintenance decision variables, long-term average maintenance cost and short-term average maintenance cost (10 years and 100 years)are estimated.



(a) $\theta_{insp} = 7$

(b) $\theta_{insp} = 15$

(c) $\theta_{insp} = 30$

(d) $\theta_{insp} = 45$

(e) $\theta_{insp} = 60$

(f) $\theta_{insp} = 75$

Figure 6.14: The repair delays for the periodic inspection policies

6.4.2.1 Long-term average maintenance cost for periodic inspection

According to the simulation convergence, the length of simulations for long-term maintenance cost are set to be 10,000 years, Figure 6.14 shows the maintenance cost against preventive maintenance thresholds, they illustrate that the ratio of repair delay and inspection interval has influence on the long-term average maintenance cost.

Different repair delays are set for the inspection intervals: Figure 6.14a shows the maintenance cost of 10 delays for $\theta_{insp} = 7$, which fall in 5 major areas. They are separated by the ratio of delays and inspection interval, r:

$$r = \lfloor \frac{t_d}{\theta_{insp}} \rfloor \tag{6.6}$$

Notation $\lfloor \rfloor$ is floor function to get the greatest integer and hence r is the integer part of $\frac{t_d}{\theta_{insp}}$.

Similarly, the plots of maintenance cost for the delay maintenance policies when $\theta_{insp} = 15, 30, 45, 60, 75$ also fall into 5 major areas as shown in Figure 6.14b to 6.14f.

Besides the ratio of the preventive maintenance and the inspection interval, the preventive repair delays given the same ratio is investigate: for the given ratio, the longer repair delays has lower maintenance cost because the corrective maintenance decreases as shown in Figure 6.15.

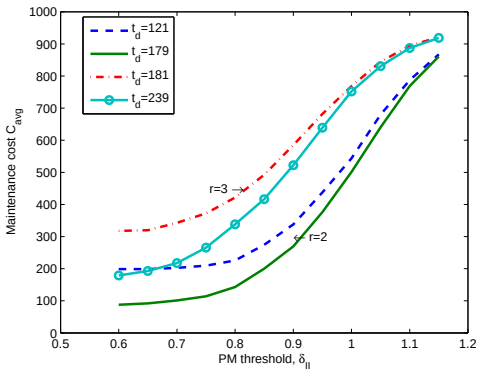
Figure 6.15a shows the maintenance cost for $r = 2, 3$ when $\theta_{insp} = 60$ and $\delta_{II} = 0.6$. The maintenance cost when $r = 3$ is higher than the cost when $r = 2$; however, for the given ratio r, the longer PM delays has the lower maintenance cost: given $r = 2$, the cost when $t_d = 121$ is higher than $t_d = 179$. The number of corrective maintenance and the preventive maintenance against PM threshold are shown in Figure 6.15b and 6.15c. The corrective maintenance plays the important role in the maintenance cost since the number of preventive maintenance per unit time decreases when the repair delay increases. The shorter time to the next inspection, the lower the maintenance we can obtain.

Even though the maintenance cost falls into several areas depending on the ratio 'r', the time between the PM and the next inspection also has the effect on the maintenance cost. We run simulations for different ratios and the time after PM to the next inspection are set to be same. Figure 6.16 shows the plot of the maintenance cost for periodic inspection and the optimal maintenance costs for different ratio r is exhibit.

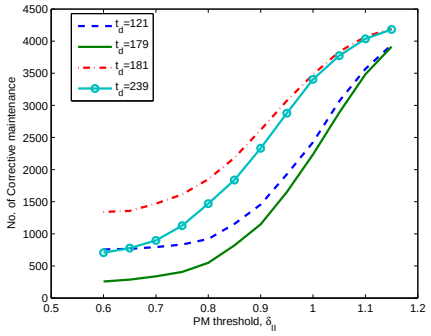
Figure 6.17 shows the cost against the inspection interval for the given δ_{II}. Figure 6.17a is a maintenance cost curve given that $r = 0$ and $\delta_{II} = 1.0$, the optimized inspection interval is $\theta_{insp} = 30$. Figure 6.17b plots the maintenance cost for different 'r', the effect of 'r' is larger for the longer inspection interval. The optimized inspection interval is smaller for the higher ratio 'r' which means if a longer repair delays is scheduled, the inspection interval needs to be shorter.

6.4.2.2 Short-term average maintenance cost for periodic inspection

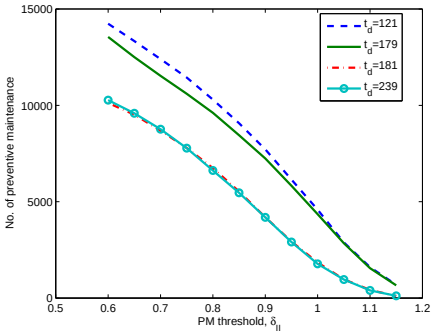
In Section 6.4.2.1, maintenance cost over infinite time horizon is estimated. We need to consider the average maintenance cost over a finite period. In this section, we run simulations for 100 years and 10 years to show the maintenance cost over a finite time horizon.



(a) Maintenance cost for $r = 2, 3$



(b) No. of corrective maintenance



(c) No. of preventive maintenance

Figure 6.15: Average maintenance cost and the number of maintenance for $r = 2, 3$, $\theta_{insp} = 60$, $\delta_{II} = 0.6$

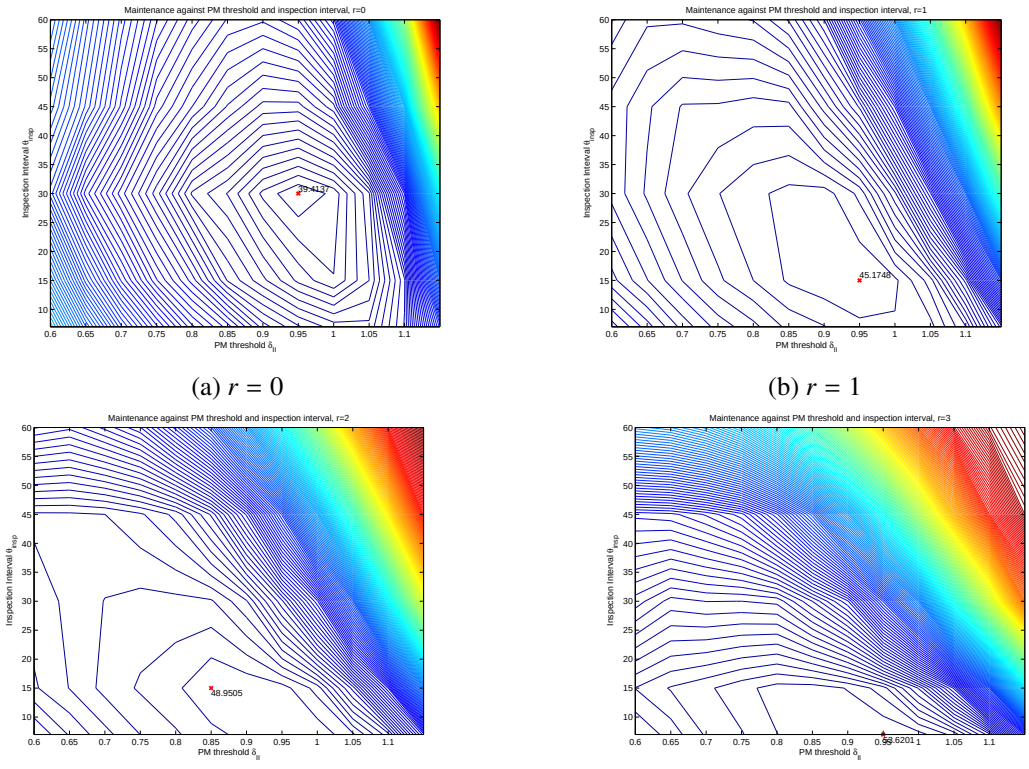
For the simulation period of 3650 days, the number of simulations are set to be 5,000; and 10,000 simulations are carried out for the simulation period of 36,500 days.

Figure 6.18a and 6.18c show the maintenance cost for 36500 days (100 years) for different ratios; Figure 6.18b and 6.18d show the maintenance cost for simulation period of 3650 days (10 years).

The maintenance cost for 36,500 days are higher than the cost for 3,650 days as shown in Figure 6.18, since the shorter simulation time can have less probability to have a corrective maintenance.

6.4.3 Repair delay for condition-based inspection

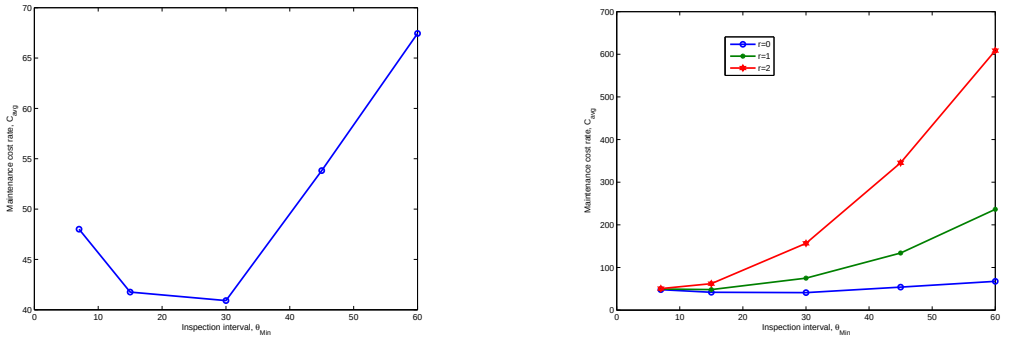
Section 6.4.2 investigates the effect of repair delay on the periodic inspection. Condition-based Inspection is a non-periodic inspection policy depending on the observed states. The effects of repair delay in condition-based inspection policies are investigated. Long term average maintenance cost is adopted to evaluate the performance of maintenance policies according to the parameters in Table 6.1.



(a) $r = 0$ (b) $r = 1$

(c) $r = 2$ (d) $r = 3$

Figure 6.16: Maintenance cost for the periodic inspection for $r = 0, 1, 2, 3$



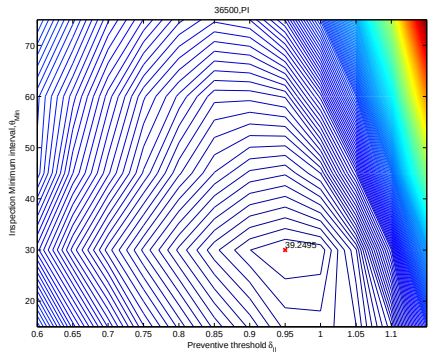
(a) $\delta_{II} = 1.0$,$r = 0$, periodic inspection (b) $\delta_{II} = 1.0$, $r = 0, 1, 2$, periodic inspection

Figure 6.17: Maintenance cost against inspection interval, periodic inspection

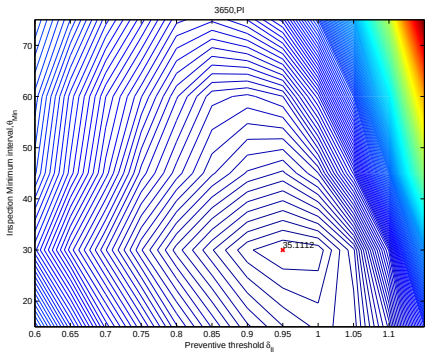
6.4.3.1 Long-term average maintenance cost for Condition-based inspection

The length of simulation time is set to be 3650,000 days (10,000 years) according to the simulation convergence to get the long-term average maintenance cost.

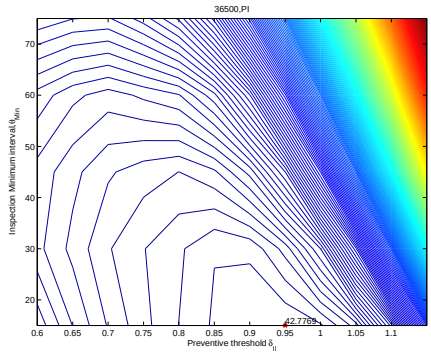
Figure 6.19 shows the average maintenance cost for different minimum inspection interval for conditioned-based inspection policies. The simulation results show that the floor of the ratio of repair delay and minimum inspection interval determines the maintenance



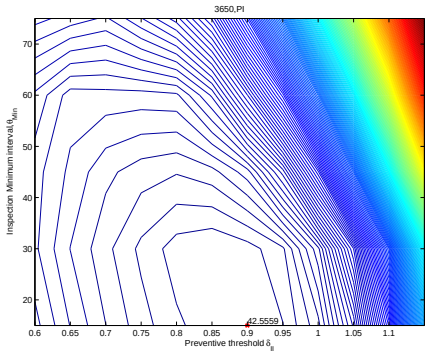
(a) Simulation time: 36500 days,$r = 0$



(b) Simulation time: 3650 days,$r = 0$



(c) Simulation time: 36500 days,$r = 1$



(d) Simulation time: 3650 days,$r = 1$

Figure 6.18: Short term maintenance cost, periodic inspection

cost, the ratio is denoted by r, as shown in Equation 6.7:

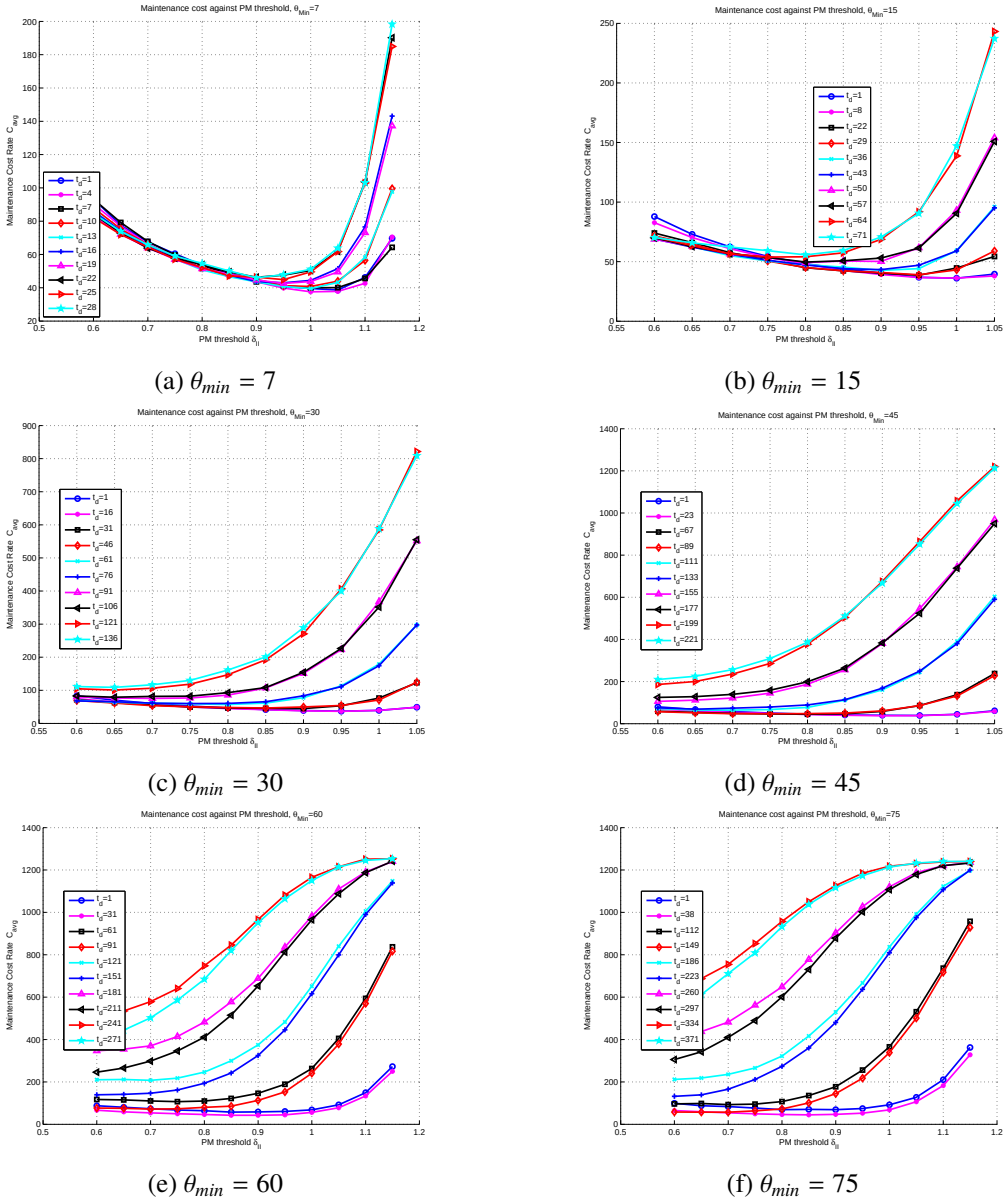
$$r = \lfloor \frac{t_d}{\theta_{min}} \rfloor \tag{6.7}$$

Figure 6.19 illustrates the simulation results for different θ_{min}. In the case that $\theta_{min} = 15$ shown in Figure 6.19b, there are only 5 major areas for 10 repair delay configurations; We find the 5 major areas are $t_d \in (0, \theta_{min})$, $t_d \in [\theta_{min}, 2\theta_{min})$, $t_d \in [2\theta_{min}, 3\theta_{min})$, $t_d \in [3\theta_{min}, 4\theta_{min})$ and $t_d \in [4\theta_{min}, 5\theta_{min})$. Similarly, the other figures shown in Figure 6.19, the maintenance cost for the other θ_{min} also fall into several areas according to the value r.

These results show that the ratio of repair delays and inspection interval determines the maintenance cost of condition based inspection, the effects of the ratio "r" are similar to the delayed maintenances with periodic inspection.

In Figure 6.19d, 6.19e and 6.19f, the maintenance cost curves do not coincide for the smaller preventive maintenance threshold δ_{II} for the same ratio 'r'. This phenomenon also exists in the periodic inspection policies, as shown in Figure 6.14. If the inspection interval θ_{Min} increases, the maintenance cost decreases with the longer repair delay for the given ratio 'r'. The delays lead to the different occurrence of PMs and CMs as shown in Figure 6.20 for the configuration: $\theta_{Min} = 60$, $r = 2, 3$.

As shown in Figure 6.20a and 6.20b, the longer delays can decrease the corrective maintenance and the preventive maintenance at the same time. Comparing $r = 2$ and $r = 3$,



(a) $\theta_{min} = 7$ (b) $\theta_{min} = 15$

(c) $\theta_{min} = 30$ (d) $\theta_{min} = 45$

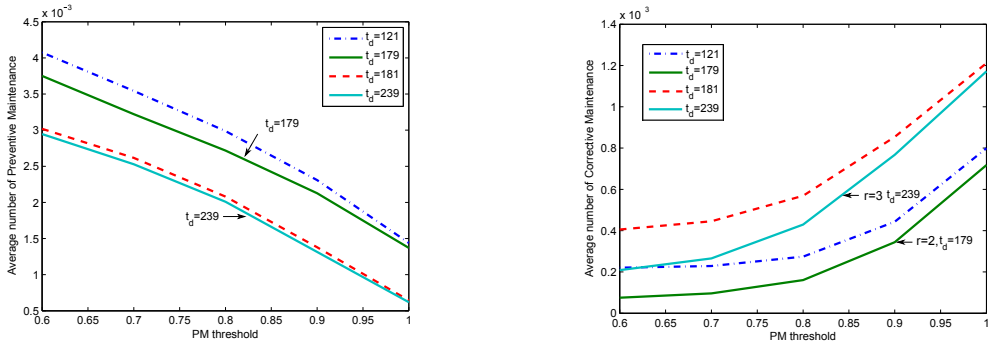
(e) $\theta_{min} = 60$ (f) $\theta_{min} = 75$

Figure 6.19: The repair delays for the CBI policies

the larger r decreases the number of preventive maintenance but increases the number of corrective maintenance.

Figure 6.21 shows the maintenance cost rate of $t_d = 121$ and $t_d = 179$ against k (the rate of corrective maintenance cost and preventive maintenance cost, $k \in [1, 10]$) and PM threshold δ_{II}. It illustrates that the rate of maintenance cost for a given 'r' depends on k. However, the curves in Figure 6.20a and 6.20b which indicates the number of maintenances (N_{pm} and N_{cm}) for $t_d = 179$ and $t_d = 181$ indicates that the ratio 'r' plays a more important role for the delayed repair strategy.

For the given ratio r, Figure 6.22 shows the optimal maintenance cost against inspection



(a) Number of PMs, CBI

(b) Number of CMs, CBI

Figure 6.20: Maintenance number for different time give the ratio

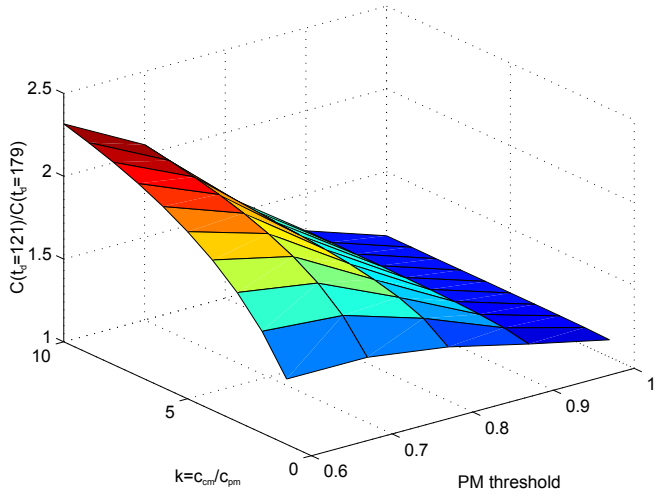


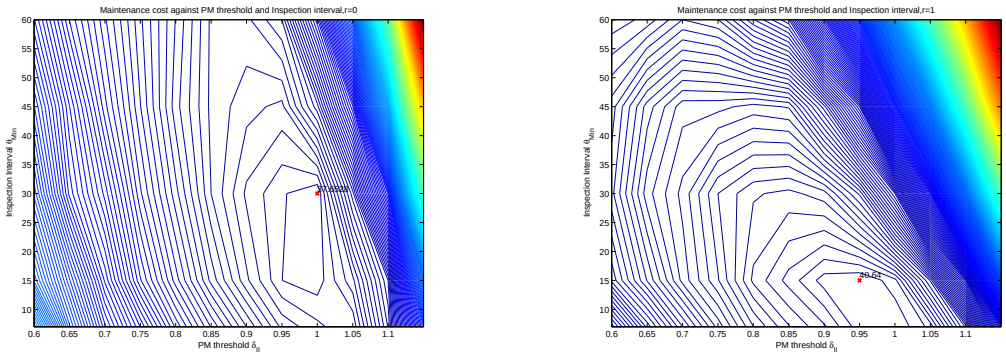
Figure 6.21: The effect of the maintenance prices for a given 'r'

interval θ_{Min} and the PM threshold δ_{II}. When $r = 0$, we can obtain the lowest maintenance cost ($\mathbb{E}C = 37.65$) when $\theta_{Min} = 30$ and $\delta_{II} = 1.0$ in Figure 6.22a. When $r = 1$, the optimal maintenance cost ($\mathbb{E}C = 40.64$) exhibits at $\theta_{Min} = 15$ and $\delta_{II} = 0.95$ in Figure 6.22b. Figure 6.22c and 6.22d are the maintenance cost for $r = 2$ and $r = 3$.

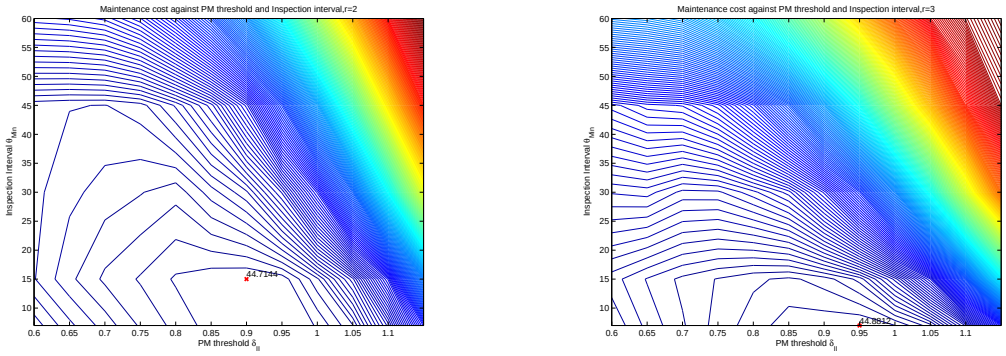
Figure 6.23 shows the cost against inspection interval given that $\delta_{\mathrm{II}} = 1.0$. The curve $r = 0$ exhibits a minimum cost around $\theta_{min} = 30$ as shown in Figure 6.23a; for $r = 1$ the minimum cost is around $\theta_{min} = 15$ and for $r = 2$ is around $\theta_{min} = 7$ as shown in Figure 6.23b. The larger r can get the minimum cost at a smaller inspection interval θ_{min}.

According to the results of Monte Carlo simulations, we find that the larger r leads to more corrective maintenance as shown in Figure 6.24 and more inspections in the CBI policies and hence the higher maintenance cost.

Figure 6.24a shows the probability of the time between two PMs for different r ($r = 14, 29, 44, 59, 74$) when $\theta_{\mathrm{Min}} = 15$. The longer 'r' contributes less number of PMs while

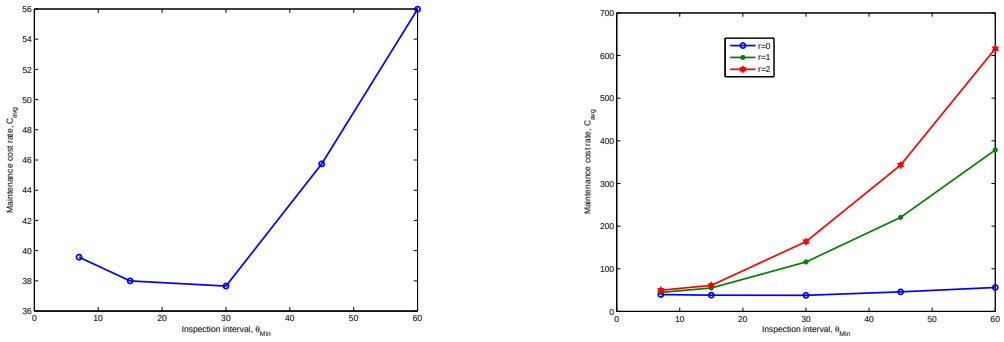


(a) $r = 0$ (b) $r = 1$



(c) $r = 2$ (d) $r = 3$

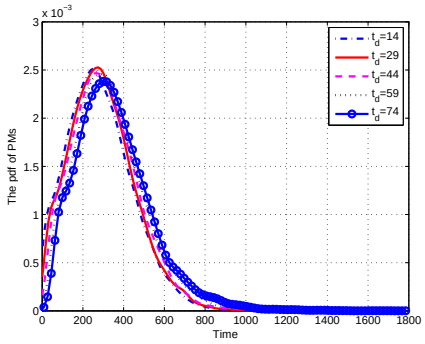
Figure 6.22: Plot of Maintenance against the minimum inspection interval θ_{Min} and preventive maintenance threshold δ_{II} for the CBI



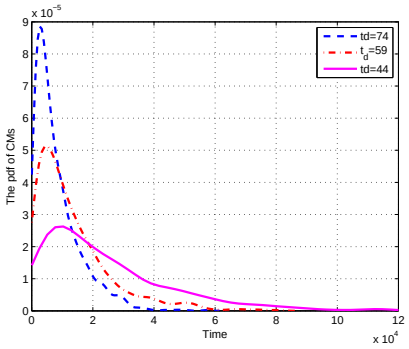
(a) $r = 0$, CBI (b) $r = 0, 1, 2$, CBI

Figure 6.23: The plot of maintenance cost against inspection interval, $\delta_{II} = 1.0$, CBI

the density distributions for different 'r' are not significantly different. Figure 6.24b is the density distribution of corrective maintenance for $r = 44, 59, 74$, it illustrates that the different PM delays lead to the different time between CMs and hence the longer delays has a higher CM probability.

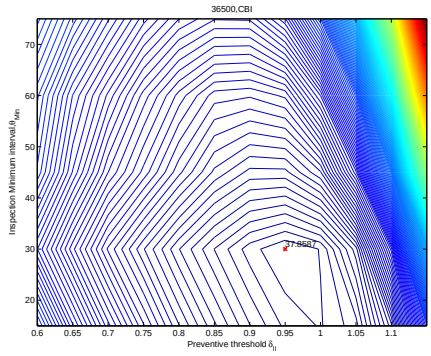


(a) The PM distribution for the maintenance policy: $t_d = 14$,$t_d = 29$,$t_d = 44$,$t_d = 59$,$t_d = 74$

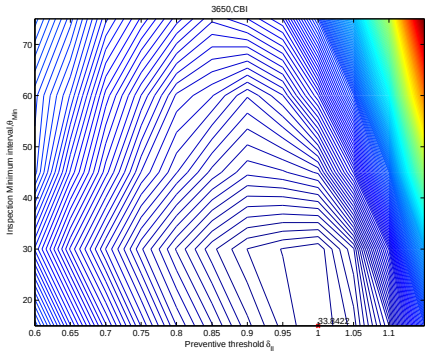


(b) The CM distribution for the maintenance policy:$t_d = 44$,$t_d = 59$,$t_d = 74$

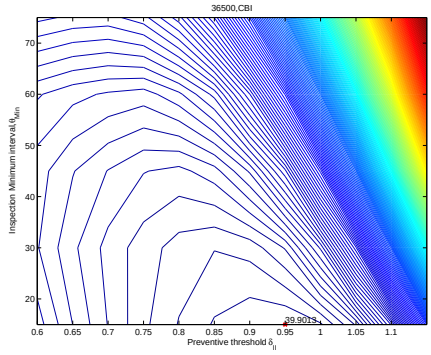
Figure 6.24: The pdf of maintenances: $\theta_{Min} = 15$



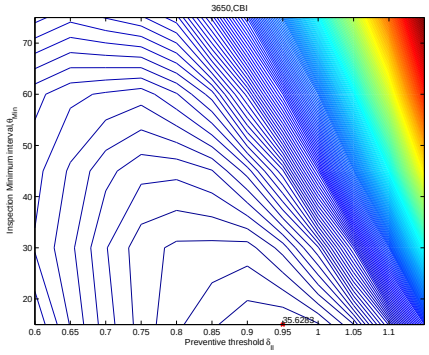
(a) Simulation time: 36500 days,$r = 0$



(b) Simulation time: 3650 days,$r = 0$



(c) Simulation time: 36500 days,$r = 1$



(d) Simulation time: 3650 days,$r = 1$

Figure 6.25: Short term maintenance cost for CBI

6.4.3.2 Short-term maintenance cost for condition-based inspection

We consider the maintenance cost for a period of 10 years and 100 years. According to the convergence results in section 6.4.1, 5,000 simulations for the period of 100 years are

carried out to estimate the average maintenance cost in 100 years. The maintenance cost for 10 years are estimated by 10,000 simulations.

Figure 6.25 shows the maintenance cost for the condition-based maintenance with different PM delays. They have the similar results as the maintenance cost for periodic inspection. The smaller the ratio has the lower maintenance cost.

6.4.4 Comparison of inspection policies

Periodic inspection policies and condition based inspection policies are compared according to the simulation results for $r = 0$, $r = 1$ and $r = 2$. Periodic inspection and condition based inspection policies are compared considering different intervals θ, ratios r and preventive thresholds δ_{II}.

Table 6.3: Values of optimal maintenance cost for inspection policies with delayed repair

	Periodic		CBI	
$r = \lfloor \frac{t_d}{\theta_{\text{Min}}} \rfloor$	θ_{insp}	C_{avg}	θ_{Min}	C_{avg}
$r = 0$	7	47.75	7	38.61
	15	41.76	15	37.99
	30	**39.41**	30	**37.65**
	45	50.32	45	48.91
	60	57.84	60	57.57
	75	67.44	75	69.05
$r = 1$	7	49.51	7	**39.51**
	15	**45.17**	15	40.64
	30	47.13	30	48.64
	45	58.75	45	58.38
	60	72.66	60	71.59
	75	93.96	75	92.59
$r = 2$	7	50.34	7	**44.40**
	15	**48.95**	15	44.71
	30	63.53	30	59.40
	45	69.49	45	70.71
	60	132.09	60	139.39
	75	215.76	75	211.97

Table 6.3 lists the minimum cost for different r and θ_{insp} (or θ_{min}). The optimized result for periodic inspection is obtained when $\theta = 60$ and $r = 0$, the minimum cost is 39.79; the optimized result for the condition based inspection appears when $\theta_{min} = 15$ and $r = 0$, the minimum cost is 36.14. Therefore the condition based inspection is better than the periodic inspection.

If $r = 1$, the minimum cost for periodic inspection is 48.58 while the cost for CBI is 38.15; the cost for both inspection schemes when $r = 2$ is more than $r = 0$ and $r = 1$, therefore the maintenance of a smaller r performs better.

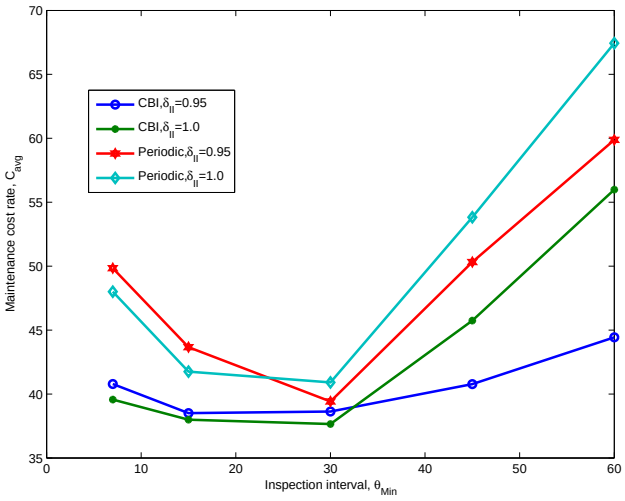
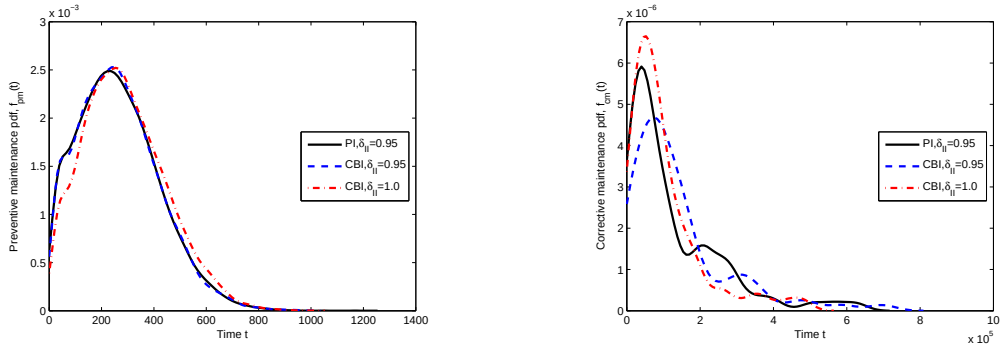


Figure 6.26: The plot of maintenance cost against inspection interval given that $\delta_{II} = 0.95$ for periodic inspection $\delta_{II} = 1.0$ for CBM inspection and $r = 0$

To see the relationship between inspection interval and maintenance cost, Figure 6.26 shows that the maintenance cost against inspection interval given that $r = 0$, it shows the results of $\delta_{\mathrm{II}} = 0.95$ and $\delta_{\mathrm{II}} = 1.0$ for both inspection schemes.

The optimized maintenance configurations in periodic inspection and CBI policies are investigated , i.e. for periodic inspection, $\theta_{insp} = 30$, $\delta_{II} = 0.95$ and for CBI, $\theta_{Min} = 30$, $\delta_{II} = 1.0$.

The time between two PMs in periodic inspection policy and condition-based inspection policy are compared. Figure 6.27 shows the pdf of CMs and PMs for the optimized maintenance configurations. They indicate that the periodic inspection policy have more CMs during the simulation time.



(a) Preventive Maintenance, pdf

(b) Corrective Maintenance, pdf

Figure 6.27: The comparison of the maintenance density distribution

6.5 Conclusions for the delayed repairs

Delayed repair is a specific problem in railway maintenance. The delays may eventually lead to accidents and hence cost much more money in maintenance. In order to make a better maintenance decision, it is necessary to take these delays into account for track maintenance.

The deterioration process with the delayed repair cannot be modeled by a simple Markov Chain, even though we can construct a Markov Chain for the delayed repair model proposed in the literature.

Therefore we propose a timed Coloured Petri Net model which can assess the maintenance strategies and optimize the maintenance decision. The CPN model adopts the coloured sets and their corresponding variables to describe the component states; the marking process can represent the possible deterioration evolution. The deterioration process between two inspection is considered and modelled for three scenarios: whithout maintenance, within PM and within CM. Either periodic inspection strategies or condition-based inspection strategies is performed to collect the component states for maintenance decisions.

Monte Carlo simulations are carried out to estimate the maintenance performance. According to the simulation results, the ratio of repair delays and minimum inspection interval affects the cost of condition-based inspection, which is similar to the delayed maintenance with periodic inspection. The smaller r, the better is the performance of condition-based inspection strategies. For a given ratio r, the longer repair delay leads to more corrective maintenance but the ratio 'r' still plays an important role. We can optimize θ_{insp} and δ_{II} for both inspection schemes to obtain the optimal maintenance cost. Periodic inspection is compared to CBI policies: the results indicate that CBI inspection is better than the periodic inspection for a given ratio r.

Short-term maintenance cost for 10 years and 100 years are estimated from simulations, the maintenance cost is lower than the maintenance cost over the infinite time horizon, since the short time cannot include the corrective maintenance when the time between them is longer than the short time (i.e. 10 years and 100 years).

Part IV

MAINTENANCE MODELLING FOR A RAILWAY SECTION

Chapter 7

Maintenance modelling for a railway section: limited maintenance resources

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7.1 Introduction

Railway system can be seen a large scale network which consists of regions and components. When making maintenance decisions for the railway network, it is necessary to build a model for the entire multi-component system to estimate the maintenance cost, the total downtime and analyse the risk since the component failures and maintenance may depend on the states of the region, the states of the other components and the maintenance ability of the network [146]. The limitation of maintenance resources, such as the limited number of maintenance machines and the limited maintenance teams, which has effect on the maintenance decision making and hence the system performance, are needed to be taken into account in railway network maintenance modelling.

The CPN model built in Section 4.3.5 is a model for single-unit system, the failure process of the system is divided into several stages. The model shows how the CPN tool

model the maintenance and inspection process for the component. However, if the system consists of several components, we need to build another CPN model for the system.

In this chapter, we want to assess the effect of maintenance on a multi-component network where the maintenance resources are limited. We introduce a multi-component system model using CPN tool for a railway network to estimate the number of maintenance and the total days for the traffic control. A hierarchical CPN model is built, which divided the model into smaller modules to make the model more readable.

The chapter is organised as follows: Section 7.2 describes the assumptions for component failure process, maintenance and inspection in the network. Section 7.3 introduces the modelling framework for the system, the CPN models for the track, the maintenances, the region and the network. Section 7.4 shows some simulation results and Section 7.5 gives the conclusion.

7.2 Modelling assumptions

The modelling assumptions are based on the assumptions in Prescott's paper[146].

7.2.1 Assumptions for the component

A track component is defined to be 1/8 mile long (200m). The failure process of a track component is illustrated as shown in Figure 7.1:

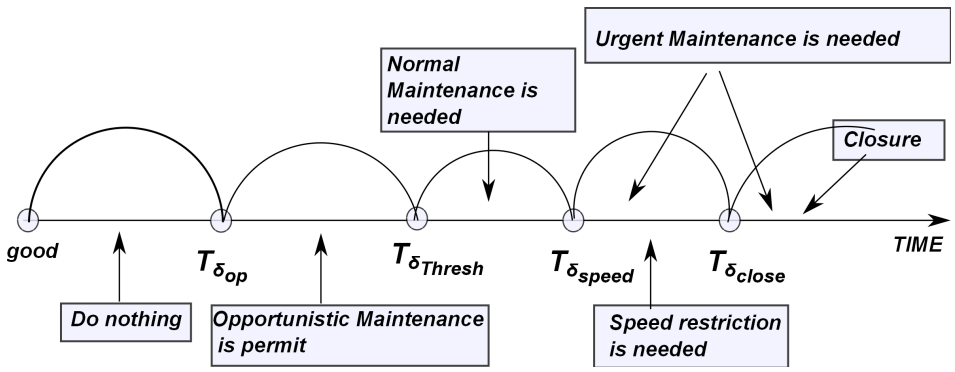


Figure 7.1: Failure process of track

- Track has a multiple stage failure process as shown in Fgiure 7.1 . There are 5 track states: Good, track defect permitting opportunistic maintenance($SD > \delta_{op}$), track defects needing maintenance ($SD > \delta_{Thresh}$), track defect needing temporary speed restriction (TSR)($SD > \delta_{speed}$) and failure needing line closure ($SD > \delta_{close}$).

- The time between two levels is assumed to follow a Weibull distribution, $T_\delta \sim Weibull(\alpha(N_{tmp}, N_{stbl}), \beta(N_{tmp}, N_{stbl})$ which depends on the number of tampings (N_{tmp}) and the number of stoneblowings (N_{stbl}) taken before. If there are more intervention taken before, the sojourn time between two states are shorter.

- There is a periodic inspection with inspection interval θ to identify track states, the inspection takes ε time. If there is a maintenance for the component, inspection is carried out after the maintenance.
- There are two maintenance priorities: normal maintenance requirement and urgent maintenance requirement:
  - If track deterioration exceeds δ_{Thresh}, the track component needs a normal maintenance.
  - If track deterioration exceeds δ_{speed} or δ_{close}, the track component needs an urgent maintenance.
  - The urgent maintenance requirement has a higher priority than normal maintenance requirement and hence the maintenance task is carried out for the track component needing urgent maintenance prior to the others.

Two kinds of maintenance are considered in this chapter: Tamping and stoneblowering. Tampers and stoneblowers can be used respectively for the maintenance.

- Tamping is preferable to stoneblowering. If a stoneblower is used for the track component, a tamper can no longer be used.
- Stoneblower can be used for the track component if T_{limit} has passed since maintenance is required for the track; or there is an urgent maintenance requirement for the component.
- Both of the maintenances can restore track state to be as good as new.
- The machine (both of tampers and stoneblowers) arriving time is assumed to follow Normal distribution $\tau \sim N(\theta, \delta)$.

7.2.2 Region and network assumptions

In a region, there are N_t track components, the maintenance procedure in the region are set as follows:

- If there are urgent maintenances needed in the region, the urgent maintenance is performed firstly.
- The available machines are allowed to work for the defective tracks in the region at the same time.

The network has N_r regions and each region has N_t track components, the maintenance rules for the network are as follows:

- There are M_{tamper} tampers and $M_{stoneblower}$ stoneblowers in this network.
- Maintenance performed by one machine can only be performed within a region. The maintenance machines are allocated randomly for the regions which have the same maintenance priority.

- The urgent regions always have the highest priority, tampers need to fix all the urgent track components firstly even though they are located in different regions.
- Similar to the tampers, stoneblowers need to fix all the urgent tasks in the network, and then it can perform the normal maintenance task.

7.3 CPN model for the railway network

The entire model is a hierarchical CPN model considering the maintenance assignments for the network.

7.3.1 Modelling framework

Figure 7.2 illustrates the CPN model framework for the whole network. There are three levels in the framework.

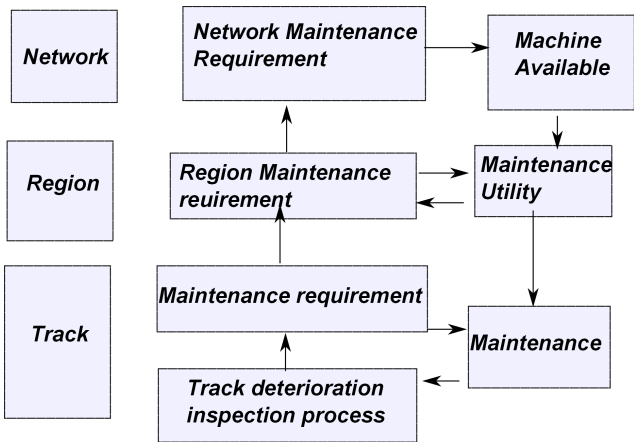


Figure 7.2: Modelling Framework

The bottom level is the track model: the model describes the track failure process and the inspection process, it identifies the maintenance type and the maintenance priority. The track deterioration with inspection module outputs the detected states to track maintenance requirement module; the maintenance requirement module identifies the maintenance type and maintenance machine used in this track component.

The region model checks the available machines and assigns the maintenance task for the machines according to its maintenance requirements. The region maintenance module collects the maintenance requirements of all track components in the region and outputs to the network module.

The top level model is the railway network, it identifies all the urgent tasks in the network, including the urgent tamping tasks and urgent tamping tasks and hence it requires the machines to implement the urgent tasks firstly. Furthermore, the available machines are identified in the network model.

7.3.2 Track component CPN model

Track component CPN model consists of three major parts: Track deterioration and inspection process model, track maintenance requirement model and track maintenance model.

7.3.2.1 Track deterioration and inspection process model

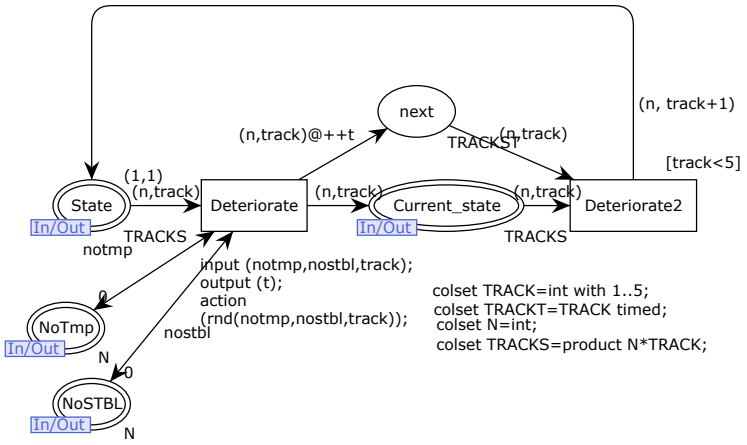


Figure 7.3: CPN model for track failure

Figure 7.3 describes the track deterioration. Colored set $TRACK$ describes the track deterioration level and it is an untimed colored set. $TRACKS$ is the timed colored set product $TRACK$ with integer colored set N. The token in place *next* represents the time when the track deterioration exceeds the thresholds δ. The variable *track* is used to represent the track states from 1 to 5 to represents the good state to the closure state as shown in Figure 7.1. Function $rnd(notmp, nostbl, track)$ is used to calculate the life time of each states. The life time depends on the number of tamping *notmp* and the number of stoneblowing *nostbl*. Place 'NoTmp' and 'NoSTBL' restores the number of tamping and stoneblowering performed in this track before, the initial marking of these two place is 0, which means there has been no intervention before.

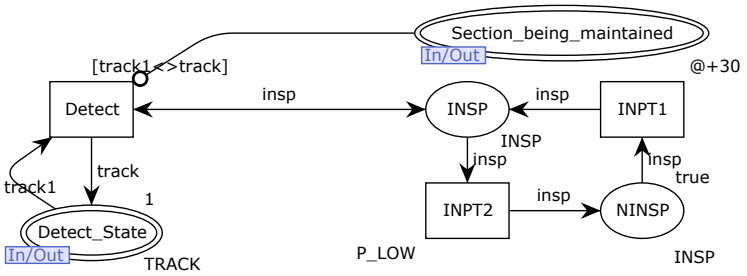


Figure 7.4: Track inspection process

Figure 7.4 shows the inspection CPN model. Coloured set 'INSP' indicates the in-

spection state. When there is an inspection, transition *Detect* updates the detected state, the initial marking of place *Detected_State* is assumed to be 1 which means that the track state is considered to be good at the beginning.

7.3.2.2 Track component maintenance requirement

The maintenance of each track component needs to identify whether the track needs urgent maintenance and which kinds of machines can be used on the track.

Figure 7.5 shows that the tamping can be carried out according to the detected track state, including the normal tamping requirement and the urgent tamping requirement.

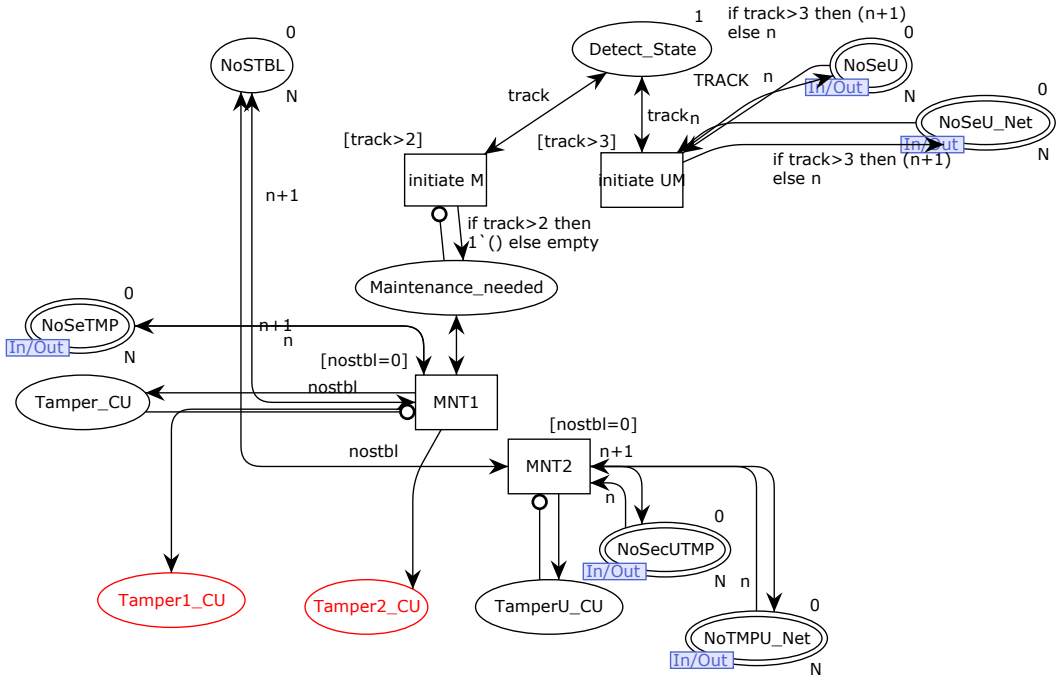


Figure 7.5: CPN model for tamping requirement and authority

The tamping requirement for the track depends on the detected state *Detect_State* and the number of stoneblowing *nostbl*. If $track > 2$ (2 represents that $SD > \delta_{Tresh}$), the track needs maintenance, a token is put in place *Maintenance_needed*, and then if there was no stoneblowing before ($nostbl = 0$), transition $MNT1$ fires to indicate that tampers can be used on the track (place $Tamper1_CU$ and $Tamper2_CU$); if $track > 3$, transitions $initiateM$ and $initiateUM$ fire and put a token to *Maintenance_needed* and $UrgM_needed$ which means urgent maintenance is needed and the tampers can be used on the track. If the track has the labels in place $Tamper_CU$ and $TamperU_CU$, the corresponding transitions cannot fire again. According to the maintenance priority, the model gives labels for the track for the maintenance arrangement in the network and region. Transition *initiate_UM* collects the number of urgent maintenance in the network in place $NoSEU_{Net}$ and the number of urgent maintenance in the region in place $NoSeU$. Transition $MNT1$ counts the

number of tamping in the region in place $NoSeTMP$; transition $MNT2$ counts the urgent tamping for the region $NoSeUTMP$ and the network $NoSeUTMP_Net$.

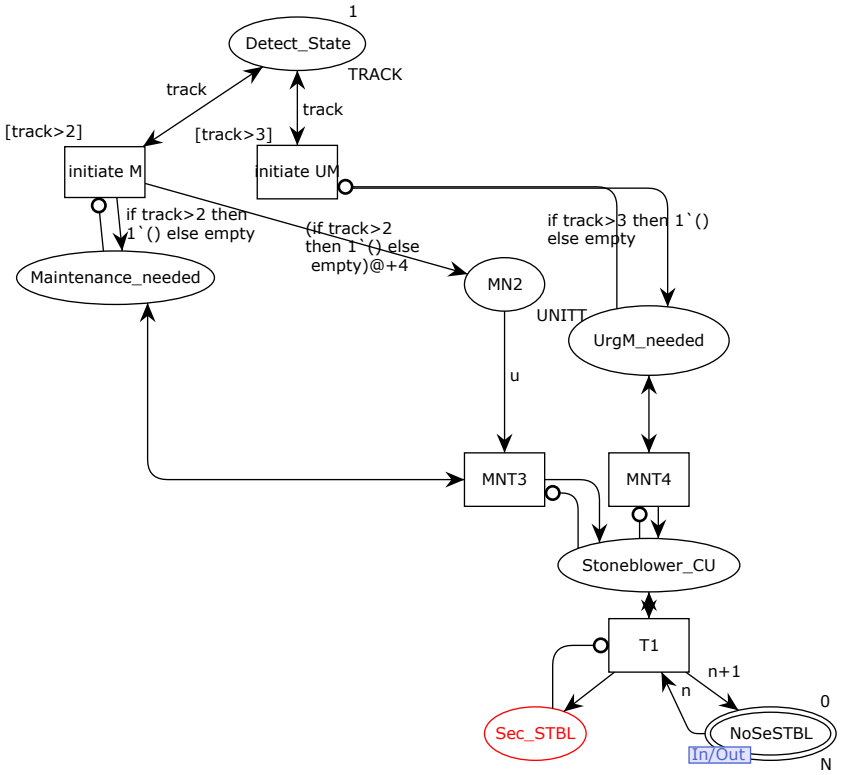


Figure 7.6: Track component maintenance requirement

Figure 7.6 illustrates the situation in which the stoneblower can be used: the normal maintenance or the urgent maintenance is needed. Place $MN2$ belongs to timed colored set UNITT. This place enables transition $MNT3$ if $T_{limit} = 4$ days passes since place $Maintenance_needed$ has been marked, which is required in the model assumption. If urgent maintenance is needed, i.e. a token in place $UrgM_needed$, transition $MNT4$ fires and then transition $T1$ counts the number of stoneblowers can be used for the region in place $NoSeSTBL$. Place sec_STBL represents that the track allows stoneblowers.

7.3.2.3 Tamper maintenance model

Figure 7.7 shows the tamper 1 maintenance model for the urgent task. If tamper 1 can be used in the track component ($Tamper1_CU$ is marked) and tamper 1 is in the region due to work ($TMP1_due_Work$), maintenance can be carried out by tamper 1 on this track (transition $TMP1_M$); then a token in place $Tamper1_busy$ represents that the tamper 1 is working. The maintenance work will be completed in rnd2() time. If there is a token in place $UrgM_needed$ which means that the urgent tamping task is needed, Transition $updateT2$ updates the track state to be good (empty $Current_state$ and send 1 to place

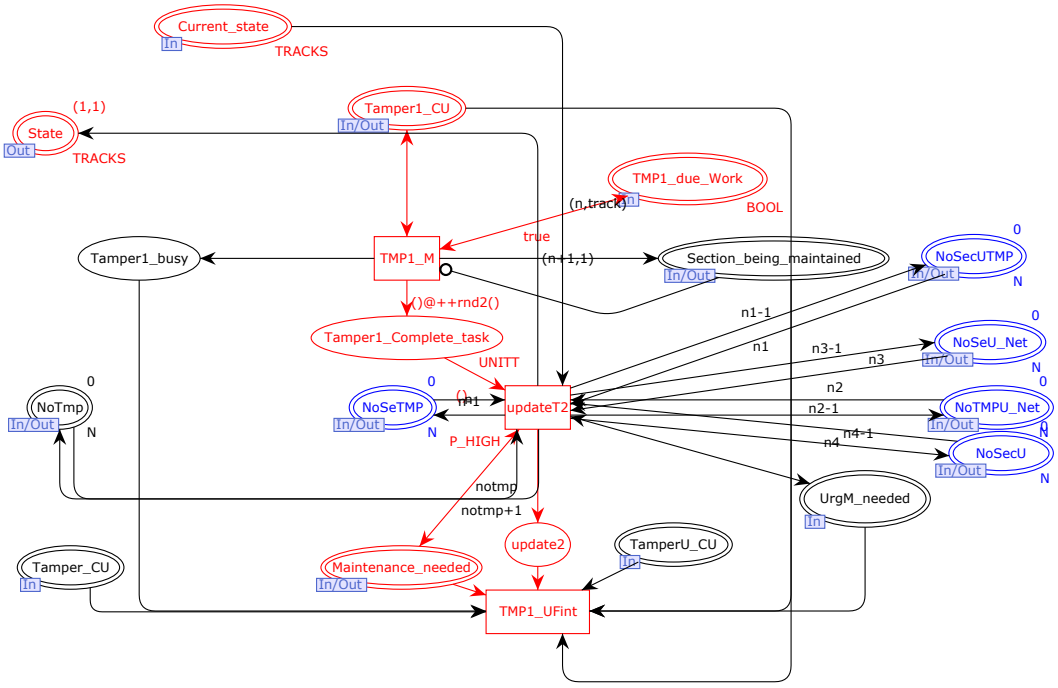


Figure 7.7: Tamper1 maintenance model for urgent task

State). At the same time, the number of tamping on the track is counted in place *NoTmp*.

After the track state is updated, the number of track components in the current job need to minus 1 and the component does not need maintenance (no token in place *Maintenance_needed*). The maintenance process updates the number of track components in the places *NoSeU_Net*, *NoTMPU_Net*,*NoseTMP*, *NoseU* and *NoSecUTMP*.

If there is no token in place *UrgM_needed*, the tamper performs a normal maintenance task. The transition *updateTransition* fires instead of *update*2, which fixes the track state to be 1. Transition *TMP*1_*FinT* represents that the tamping is finished. The maintenance process is similar to the urgent task, but the normal task does not need to updates the number in the places *NoSeU_Net*, *NoTMPU_Net*,*NoseTMP*, *NoseU* and *NoSecUTMP*.

7.3.2.4 Stoneblower maintenance model

Figure 7.9 shows the stoneblower maintenance model, the normal maintenance task and the urgent maintenance task are carried out by different transitions. The difference between tamping CPN model in Figure 7.7 and Figure 7.9 is the places representing the number of components which need maintenance, including *NoSeU*, *NoSeU_Net*, *NoSeSTBL* and *NoSTBL*.

7.3.3 Region CPN model

As shown in Figure 7.2, the region model will identify the available machines in the network and the machine tasks in the region. Figure 7.10 shows the region level model, in this

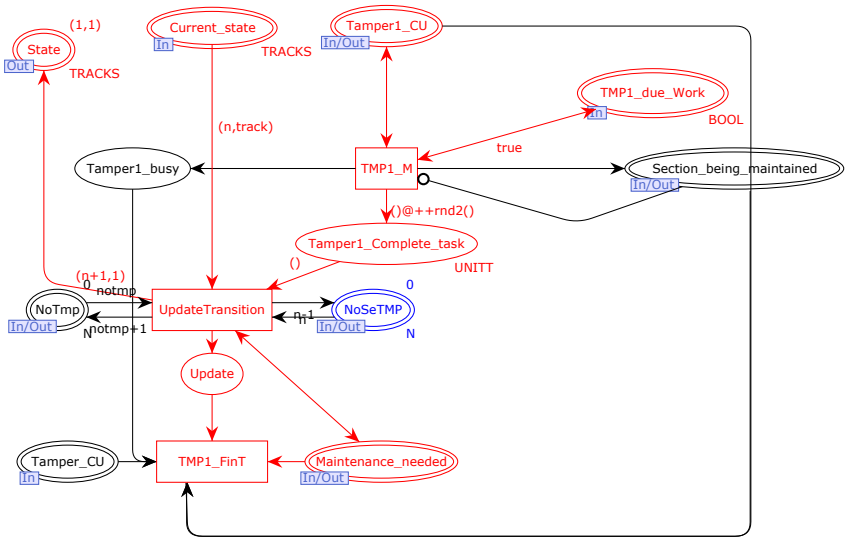


Figure 7.8: Tamper1 maintenance model for normal maintenance task

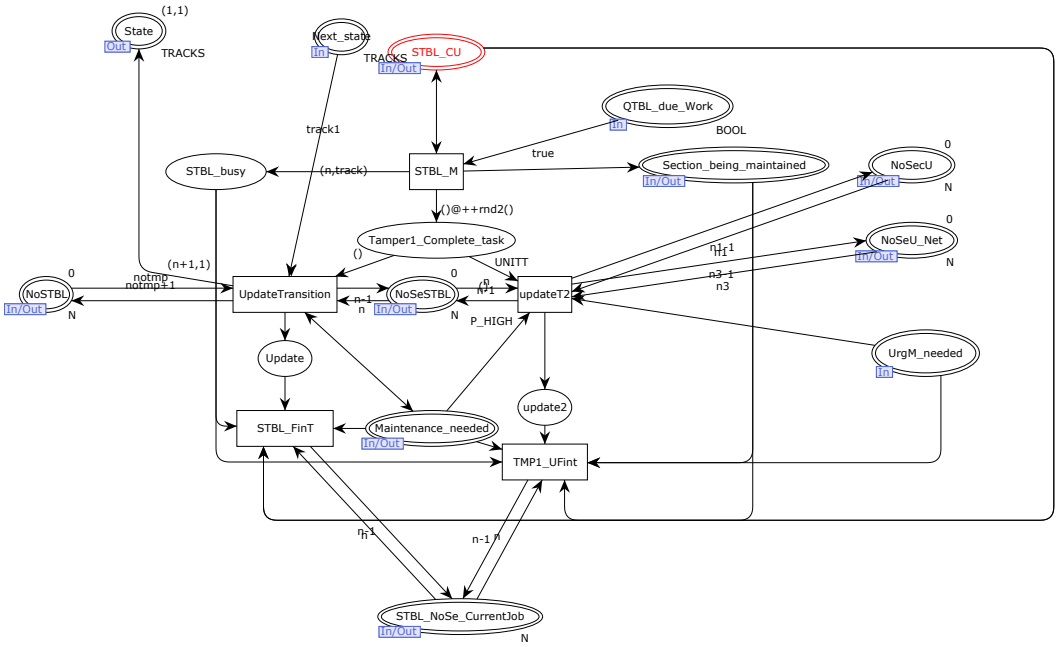


Figure 7.9: Stoneblower maintenance model

model, substitution transition *TRACK* contains the models presented in Figure 7.5, 7.6, 4.12 and 7.9.

Substitution transition *TMP1_Utility* and *STBL_Utility* are used to model two tampers and stoneblowers working tasks in the region. The substitution transition can be seen in Figure 7.11. The region model sends information to the network, i.e. the number of

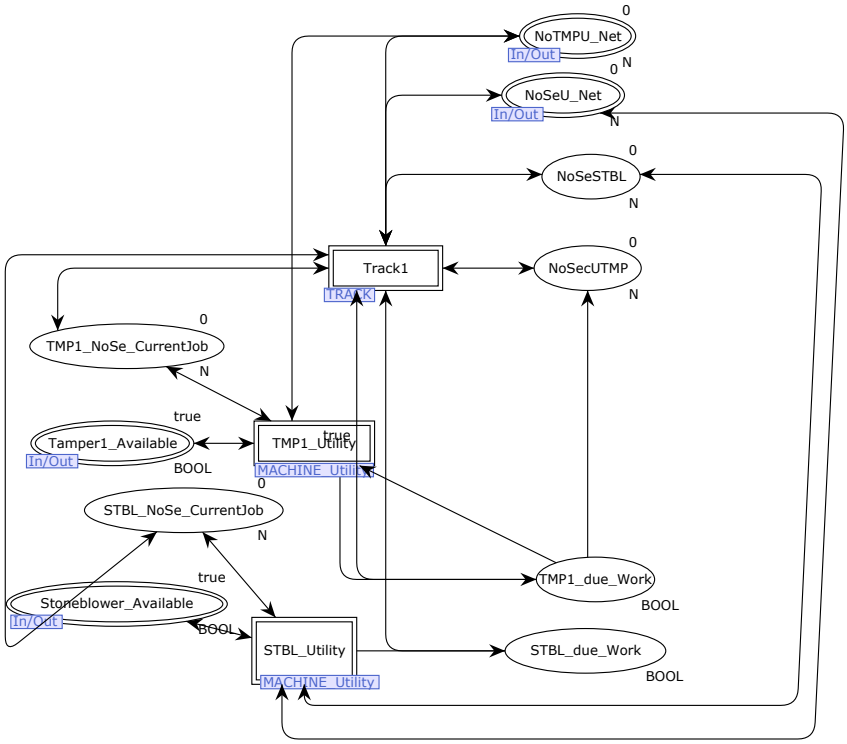


Figure 7.10: Region model

track components which need urgent tamping ($NoTMPU_Net$) and the number of track components which need urgent maintenance $NoSeU_Net$.

Figure 7.10 only contains 1 track component, 1 tamper and 1 stoneblowers in the Region Model. If there are N_t track, we just need to add the substitution transition $TRACK1$ and link it to the corresponding places. Similarly, if there are several tampers and several stoneblowers, we need to add the substitution transition $TMP1_Utility$ and $STBL_Utinility$ for the region model.

7.3.3.1 Machine utility model

The tamper and stoneblower need to be available in the region so that they can carried out the maintenance. Figure 7.11 and 7.12 illustrate the model which describes the tamper (stoneblower) machine availability.

Figure 7.11 models the machine arriving process. Places $NoSecUTMP$ and $NoSeTMP$ enable transition $MArr_delay$ and then they mark place $Tamper_Required$, which means the region need the machine. If there is a token in place $Tamper1_Available$, transition TMP_inT fires and marks place $Tamp1_inR$ which means the tamper is in the region. Then transition Tmp_inT2 marks place $Tamper1_in_NTMP$ which means the tamper machine is in the region but it is not tamping.

Figure 7.12 describes the task setting in the region for the machine. Transition $Dec1$ makes decision for normal tamping task, it fires if there are some components in the region

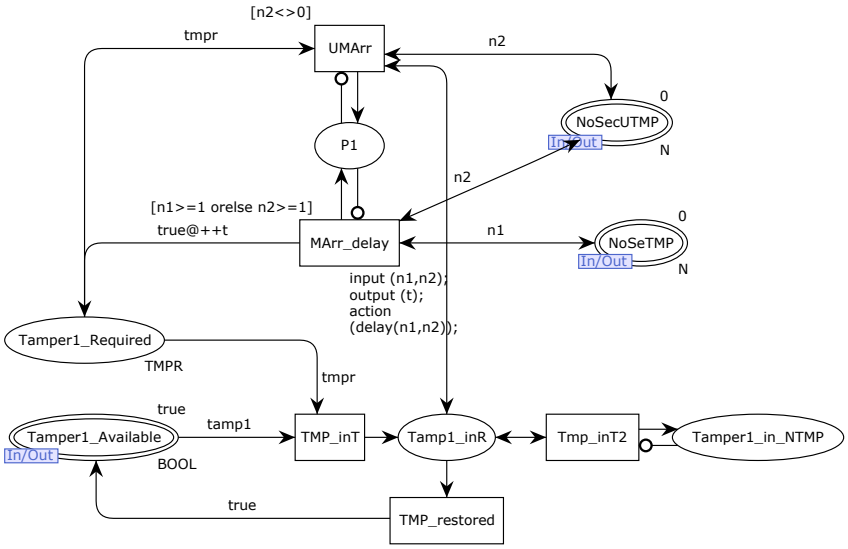


Figure 7.11: Tamper1 arrives in the region

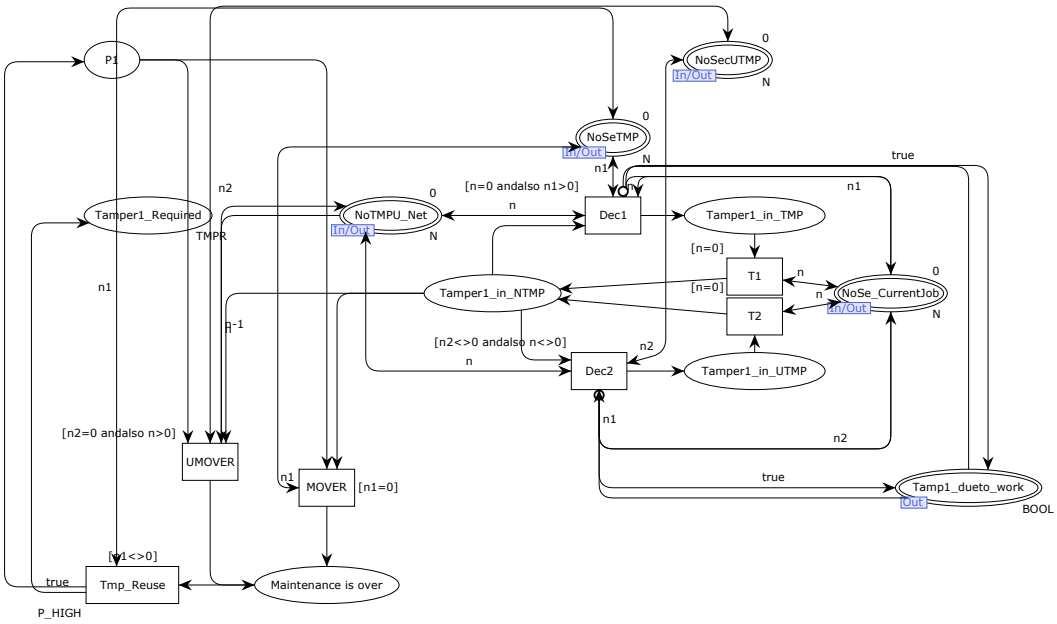


Figure 7.12: Tamper1 working task setting

needing maintenance (the variable $n1$ of the place $NoSeTMP$) and there is no urgent maintenance task in other region (n of place $NoSeU_Net$ is 0). $Dec1$ will send the number of components needing maintenance ($n1$) to the place $NoSe_CurrentJob$ and marks the place $Tamp1_dueto_work$. Transition $Dec2$ makes decisions for the urgent tamping tasks in the region. It sends the number of components which need urgent tamping ($n2$ of place $NoSecUTMP$) to the place $NoSe_CurrentJob$ and marks the place $Tamp1_dueto_work$.

If variable n of $NoSe_CurrentJob$ is 0, it enables transition $T1$ or $T2$. If the token in place $NoSeTMP$ becomes to be 0, which means there is no track needing maintenance in this region, so transition $MOVER$ marks place $Maintenanceisover$, the similar process to transition $UMOVER$. At the end, transition $TMP_restored$ marks place $Tamper1_Available$.

7.3.4 Network CPN model

The top level model can be seen in Figure 7.13. It shows a network model consisting of 6 regions, 2 tampers and 1 stoneblower in the network. We can change the number of region by the substitution transition *Region*, and the number of tampers and stoneblowers can be changed by adding the places $TAMPER_Available$ and $Stoneblower_Available$.

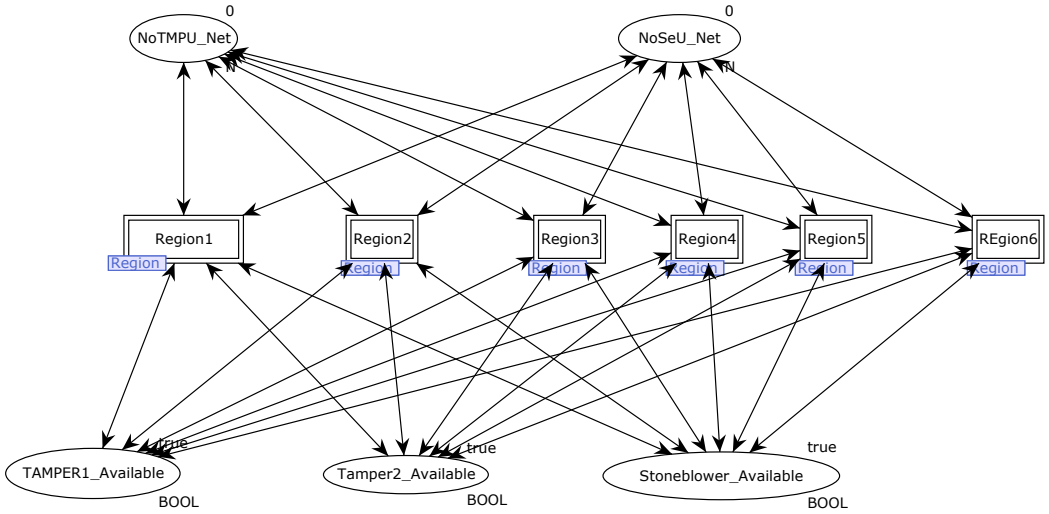


Figure 7.13: Network model

The number of the track components needing urgent tamping (the value of variable n in place $NoTNPU_Net$) and the number of components needing urgent maintenance(the value of variable n in place $NoSeU_Net$) are needed to decide whether the tamper or the stoneblower need to go to another region when they complete the urgent maintenance work in the region.

7.4 Simulation results

In this section, simulations for a CPN model which represents a system consisting of 6 regions and each region contains 2 track components. 2 tampers and 1 stoneblower are waiting for the maintenance task in the network as shown in Figure 7.13.

Table 7.1 shows the functions used in the CPN model. We define function $rnd(n1, n2, n)$ to model the component degradation and define function $delay(a1, a2)$ to model the repair delay time. Function $rnd(n1, n2)$ generates the time between two states, $n1$ is the number

of tampings and $n2$ is the number of stoneblowerings. Function *delay*() represents the machine arrival time, $a1$ is the number of track components needed tamping in the region, $a2$ is the number of urgent tamping needed in the region.

Table 7.1: Transition function configuration

Function Name	Function setting			
	$n2 < 5$			$n2 \geq 5$
	n	$n1 > 10$	$n1 \geq 10$	
rnd(n1,n2,n)	1	weibull(1000.0,1.4)	weibull(900.0,1.4)	weibull(800.0,1.4)
	2	weibull(900.0,1.9)	weibull(800.0,1.9)	weibull(700.0,1.9)
	3	weibull(800,2.4)	weibull(700,2.4)	weibull(600,2.4)
	4	weibull(700,2.9)	weibull(600,2.9)	weibull(500,2.9)
	a2>0		a2=0	
delay(a1,a2)	a1		a1>0	a1=0
	normal(4.0,1.0)		normal(10.0,1.0)	normal(48.0,1.0)

The convergence of the number of urgent tampings is shown in Figure 7.14. The number of urgent tampings are counted by the simulations with the period of 100 years. At least 10,000 simulations are needed to collect the converged number of urgent tamping.

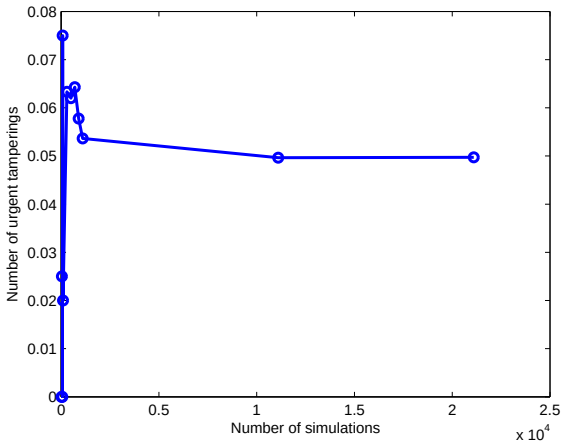


Figure 7.14: The convergence of the period of 100 years

Then we run 20,000 simulations for the network with 5 regions to estimate the number of normal tampings n_{tmp} or stoneblowering n_{stbl}, the number of urgent tampings n_{utmp} or stonblowerings n_{ustbl} , the number of closure n_{cl} and the number of temporary speed restriction (TSR) needed n_{tsr}. The total days with TSR (T_{tsr}) and the total days with maintenance (T_m) can be estimated by the model.

Table 7.2 shows some results of the network model for 200 years simulation according to the configurations in Table 7.1. It shows that we need to carry out more tampings than

the stoneblowerings. We can estimate the maintenance cost and the system unavailability with the results in this table.

Table 7.2: Some simulation results of the network model for 200 years lifetime

Event	Average	Event	Average
No.TMP ($\mathbb{E}n_{tmp}$)	14.318	No. UTMP ($\mathbb{E}n_u tmp$)	0.0507
No. STBL ($\mathbb{E}n_s tbl$)	0.02	No. USTBL ($\mathbb{E}n_{stbl}$)	0.0039
No of closure ($\mathbb{E}n_{cl}$)	6.1634	No of TSR ($\mathbb{E}n_{tsr}$)	6.2751
Total days needed maintenance ($\mathbb{E}T_m$)	69.927	Total days with TSR ($\mathbb{E}T_{tsr}$)	14.829

7.5 Conclusion for the limited resource maintenance

Railway system is a large scale network consisting of regions and components.

Stochastic Petri Nets have been used to model the maintenance limitation in a railway network [146], but the SPN model is a little bit complex for the complex system since it does not modularize the system model. Hierarchical Coloured Petri Nets are more readable for the system modelling with the substitution transitions. Ports and socks places are used to connect two different substitution transitions to send information and states among different modules.

For the Network maintenance modelling, the network are divided into several regions and the maintenance can only be carried out in the region. The model in the chapter gives an idea for network modelling, the region in the paper can be one signal block section in practice. This model focus on the limited maintenance capacity in a railway network. The links between network level model and region level are the number of components needed maintenance and the machine availability. This model can help to estimate the maintenance cost of the network via the simulation results. It can be used to optimize the inspection interval to get a minimum maintenance cost.

But there is a obvious drawbacks of this model: the number of machines and the number of track components or regions may be the decision variables for the optimization; while we want to change the number of machines and the number of components, it needs a lot of works in the modelling. For example, if we want to estimate the maintenance cost for this network with 3 tampers and 1 stoneblower, we need to change the model: at the system level, the 3rd tamper available place is needed; In the region model, substitution transition representing the tamper 3's utility are needed and corresponding places such as TMP3_NoSe_CurrentJob and TMP3_due_work are required; finally, a module represented the working of tamper 3 is needed in the model.

CHAPTER 8

Maintenance of a railway section: two-level inspection policies

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8.1 Introduction

The failures of a repairable component can be classified in revealed (or self-announcing) and unrevealed. Track faults in railway system are non-revealed: we need to carry out the inspections to make sure that the component is good enough for the train passage. The maintenance and corresponding traffic control are planned according to the inspection results in order to avoid a railway accident.

The inspection ability influences the maintenance planning and hence have effect on the maintenance cost, system unavailability and so on. In order to describe the inspection ability in failure process, Christer et al propose the “Delayed time" concept [41] ; Wang proposes an inspection model for a component which suffers from two kinds of defects and two inspection methods are set to the two defects separately [195]. Another similar model

"P-F" failure process has been introduced for reliability centred maintenance (RCM)[117], Podofillini et.al propose a Markov model for the rail breakage assuming there are two levels inspection for the failure process[144].

Gauge spread, a kind of track fault, can be classified to be static gauge spread or dynamic gauge spread as described in Section 2.4.1.2. Two kinds of inspection measurements are set for these two kinds of gauge spread. We assume that the visual inspection can inspect the track and identify the static gauge spread whereas the train recording car can identify the loaded (dynamic) gauge spread. This chapter aims to propose a CPN model for the maintenance policy with a two-level inspection procedure to investigate the inspection planning.[1]

The structure of the chapter is as follows: Section 8.2 describe the system, including the deterioration process, maintenance rules, operation and risk condition. Section 8.3 introduces the CPN model for the system, the framework and the details of the CPN models according to the framework. The simulation results are shown in Section 8.4 to show that the effect of the inspection policy. Section 8.5 gives a brief conclusion.

8.2 Modelling assumptions

In this study, we work on a plain line section consisting of 8 track components. These track components suffer from gauge spread. The study concerns about the system maintenance cost and the availability, as well as the derailment frequency.

8.2.1 Component assumptions

At the component level, component degradation and its maintenance strategy with inspection policies are presented in this section.

8.2.1.1 Component degradation and maintenance

In this chapter, a multi-stage deterioration model is adopted to describe the process of gauge spread. The deterioration distribution for each stage is assumed to follow a exponential distribution $Exp(\lambda_i)$. Corresponding repairs are carried out for each observed deterioration stages.

The model of maintained component is shown in Figure 8.1. The component degradation process is divided into k stages, this process is shown in the grey rectangle area in Figure 8.1. The time distribution of each level is assumed to be an exponential distribution with rate λ_i, when the component deteriorates to level k, it may cause an accident.

Each level can be identified by inspections $INSPi$, then the component state is observed and a corresponding repair Mi controls the observed deterioration. Unfortunately, the repair arrives in a delay time and the component keeps degrading when this defective component is waiting for the repairs, hence the arriving repair may not fix the defects. The component deterioration and the corresponding maintenance and control methods are assumed as shown in Table 8.1. At the component level, derailments may happen due to the

[1] The work in this chapter has been presented in ESREL2014 [172]

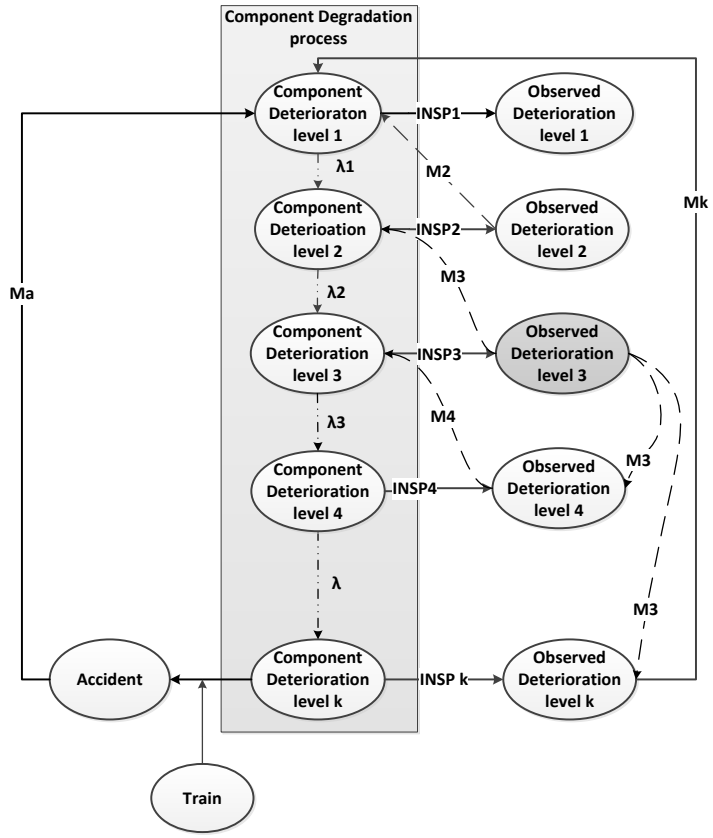


Figure 8.1: The Maintained Component Model

Table 8.1: Repair assumption for different component states (VI:visual inspection; TRV: train recording vehicle; TSR: temporary speed restriction)

State	Inspection	Repair	Effect	Waiting time	Duration
Level 1	-	N/A	-	-	-
Level 2	VI	Refastening	Level 1	τ_{f2}	μ_{f2}
Level 3	VI	Tie bar	Level2	τ_{f3}	μ_{f3}
Level 4	VI/TRV	Tie bar & TSR	Level 3 (TSR)	τ_{f4}	μ_{f4}
Level 5	TRV	Re-sleepering	Level 1	τ_{f5}	μ_{f5}
Accident	-	Renewal	Level1	τ_{f6}	μ_A

repair delays. Figure 8.2 shows an example of these situations. Level 5 is assumed to be the failure state in this example. When level 3 arrives and it is identified by the i-th inspection, there is a waiting time for the repairs R_i. Before the i-th repair R_i arrives, the level 3 defect may degrade to be level 5, in this case, a derailment accident may happen. If R_i arrives

between T_{l4} and T_{l5}, level 4 may be observed. Therefore, the dash arrows from 'observed deterioration level 3' in Figure 8.1 show the possible situations that the repair waiting time exceeds deterioration time to the other stages.

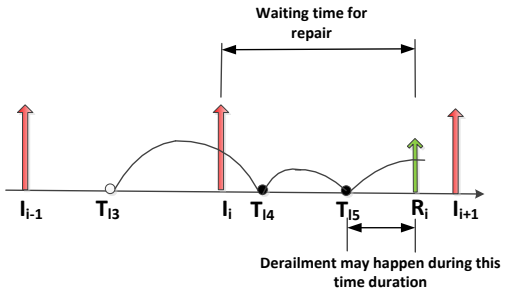


Figure 8.2: Repair waiting time exceeds deterioration time

8.2.1.2 Component working model

The component working model is used to model a component having the different working states. In the chosen section, track component working states include 'available', 'being inspected', 'being maintained' and 'occupied by train'. Figure 8.3 shows the relationship of these working states. For example the track is being inspected if an inspection arrives when the track is available and track becomes available once inspection leaves.

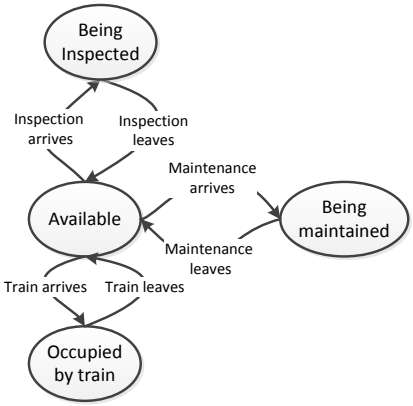


Figure 8.3: Track component working status model

8.2.2 System operation and accident assumptions

In this study, maintenance for the railway section depends on the maintenance for each components. We do not consider maintenance grouping or opportunistic maintenance in this model.

System operation model describes railway section behaviors. There are two operation modes for the chosen section. Normally, trains may pass the section with normal speed; if

there is a defect, train may be required to pass the section with a speed restriction; if there is an identified failure, an inspection or a maintenance, the railway line is closed.

An accident will occurs when a train passes a failed track with normal speed or speed restriction.

8.2.3 Performance evaluation

In this study, we consider the short-term system performances. The system performance indices 'Scheduled line availability A_{sch}', 'Line availability A_{uns}', 'Line Scheduled cost C_{sch}', 'Total cost C_{uns}' and 'The number of derailments $N_{derailment}$' are used to compare the maintenance or inspection policies. 'Scheduled line availability' considers the downtime due to the scheduled maintenances, 'line availability' considers the downtime due to both of the scheduled maintenance and accidents which are considered to be unscheduled.

$N_{derailment}$ is counted by monitoring transition D in Accident model. The scheduled availability A_{sch} and the line availability A_{uns} are obtained by monitoring transition T_D and T_i_E according to Equation 8.1 and Equation 8.2. $T_{available}$ is the line available time, T_{total} is the total time, DT_{uns} is the unscheduled down time due to accident.

$$A_{sch} = \frac{\mathbb{E}T_{available}}{\mathbb{E}[T_{total} - DT_{uns}]} \tag{8.1}$$

$$A_{uns} = \frac{\mathbb{E}T_{available}}{T_{total}} \tag{8.2}$$

C_{sch} and C_{uns} are calculated by Equation 8.3 and 8.4. C_M is maintenance cost, C_{trv} is the cost of each track recording car, C_{vi} is the cost of each visual inspection and $C_{Accident}$ is the cost of each accident. The number of track recording cars N_{trv}, the number of Visual Inspections N_{vi} are counted by monitoring the transition $INSP_TRV$ and transition $INSP_INT$. The number of maintenances N_M are obtained by monitoring transition Tmms(refastening), TMMs (tie bar) and TMMs (re-sleepering) in the CPN model.

$$C_{sch} = \frac{\mathbb{E}[C_M N_M(T_{total}) + C_{trv} N_{trv}(T_{total}) + C_{vi} N_{vi}(T_{total})]}{T_{total}} \tag{8.3}$$

$$C_{uns} = \frac{\mathbb{E}[C_{sch}] + C_{Accident}\mathbb{E}[N_{derailment}(T_{total})]}{T_{total}} \tag{8.4}$$

The following statistics are needed for railway line performance evaluation:

- The number of accident happened in the system $N_{derailment}$.
- The available time ($T_{available}$)
- The unscheduled down time (DT_{uns}).
- The number of maintenances (N_M);
- The number of inspections (N_{trv} and N_{vi})

8.3 CPN model for the railway section

A plain line block section is modelled in this study to evaluate inspection and maintenance strategies. According to the above modelling framework, a hierarchical CPN model is built to estimate derailment frequency, system availability and maintenance cost. The CPN model contains several parts: component deterioration model, component working model, operation and accident model.

The CPN model evaluates two inspection schemes:

- Visual inspection and Train Recording Vehicle for gauge spread are taken periodically;
- Visual inspection is carried out periodically, Train Recording Vehicle has a maximum planned interval but its interval decreases if the number of identified defects increases.

8.3.1 Modelling framework

A modeling framework for the chosen section is proposed to combine risk modeling and track deterioration modeling. The framework can be described as shown in Figure 8.4, including three levels: Component level, System level and Operation level.

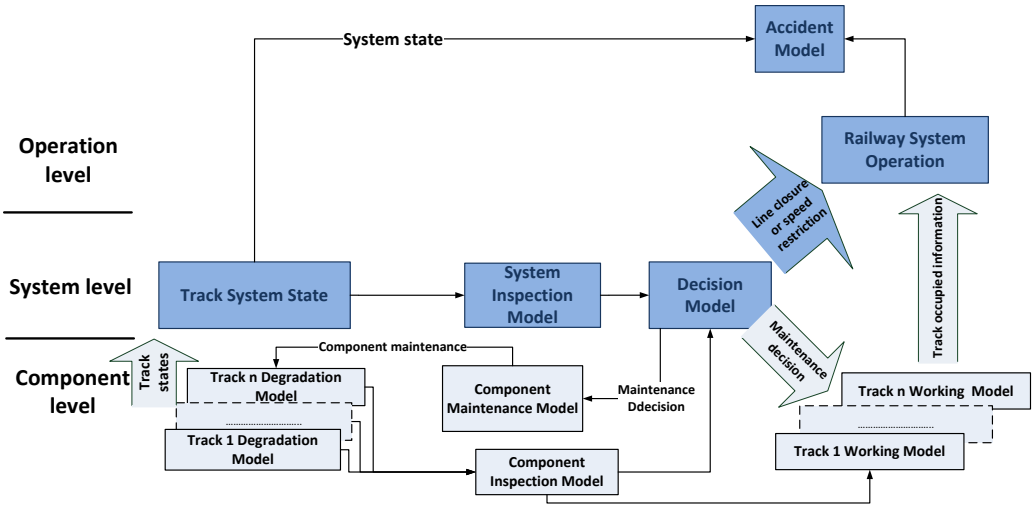


Figure 8.4: Modeling Framework

The component level describes track component deterioration and component working status. Inspection is needed to detect the unrevealed track degradation, then maintenance activities are carried out for the defective components. At component level, component working status contains: being inspected, being maintained, occupied by train, available.

The system level consists of the system state, the system inspection and the decision model. System state depends on track component deterioration and system structure. System is considered to be a series system, thus any component failure will lead to system

failure state. A system inspection is carried out for the entire chosen section, then the decision making model decides maintenance activities according to system and component inspection results.

Operation level contains “Railway System Operation" model and “Accident model". Railway System Operation model describes two system statuses: available and unavailable. When there is a train, an inspection or a repair, the system is unavailable for a waiting train; otherwise it is available. Accident model describes possible event sequences which might lead to derailment.

8.3.2 Component CPN model

The component CPN model contains the CPN model of component working states and the CPN model of inspection and maintenance.

8.3.2.1 Component deterioration CPN Model

According to the deterioration process in Figure 8.1, a component deterioration model is built as shown in Figure 8.5.

Place ‘state’ represents the initial state, place ‘state_current’ represents the current track state. Variable *comp* represents the defect level, there are *k* component deterioration levels. Transition T1 samples deterioration time to next state by function *lambda*() and it assigns the deterioration time to ‘next state’ by variable *at* in arc inscription, place ‘next state’ records the next state arriving time in its token time stamp. Once the token in ‘next state’ is valid, transition T2 fires, the component state degrades.

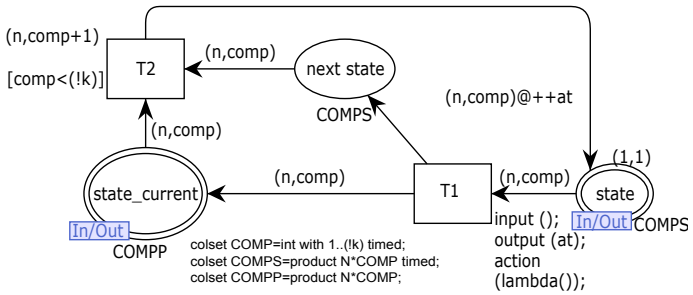


Figure 8.5: CPN component deterioration model for track component 1

8.3.2.2 Component working CPN Model

Figure 8.6 shows the CPN model, which describes the component working process.

The working model considers existence of a train and its presence on the section, inspection and maintenance. The place $TR1_busy$ represents a track occupied by train, the place $TR1_idl$ represents the component being available. Transition T_D means that a train enters this track component. T_E represents train leaving. Substitution transitions $TRV1$ and $VI1$ represent the inspection arrivals. Substitution transition $C1$ combines the component deteriorations and the maintenances.

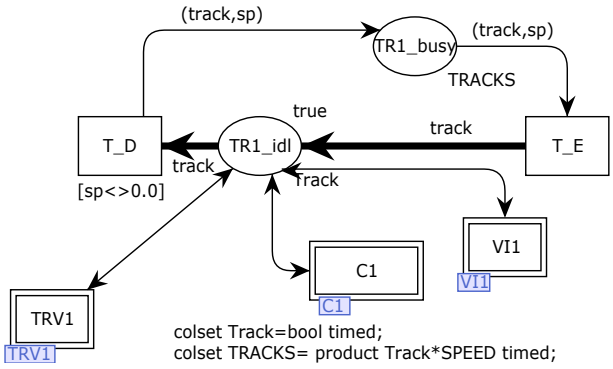


Figure 8.6: CPN component working model for track 1

8.3.2.3 Component inspection CPN Model

Visual inspection is considered to be the component level inspection, it is assumed to be taken periodically.

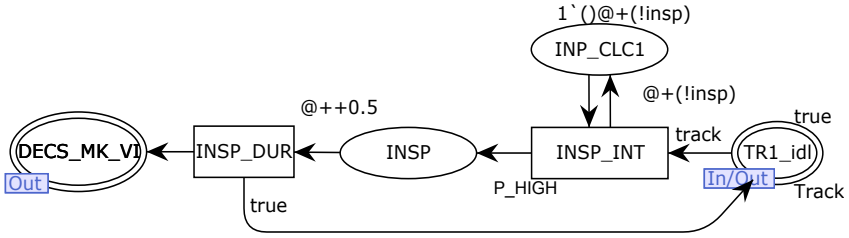


Figure 8.7: Visual Inspection Model

The substitution transition 'VI1' in Figure 8.6 is extended as shown in Figure 8.7. When a track is available (the token in Place 'TR1_idl' is valid) and the cycled inspection time arrives (token in place 'INP_CLC1' is valid), a visual inspection takes place (transition *INP_INT* fires). In Figure 8.6 there may be the conflicts among substitution transition TRV1, C1 and VI1 if they are enabled at the same time. In this study the inspections are assumed to have a higher priority, therefore the priority of transition 'INSP_INT' is set to be 'P_HIGH' (high priority). The inspection lasts 0.5 hour and the transition INSP_DUR assigns the inspection duration and represents a finished inspection; then a decision is made (the place 'DECS_MK_VI') and the track becomes available (TR1_idl).

The CPN model of TRV is a system inspection which is presented in Section 8.3.3.

8.3.2.4 Component maintenance CPN Model

Maintenances are carried out according to the visual inspection result. Table 8.1 lists the repair activities for the identified component degradation levels, these degradation levels are defined by global reference values $!j = 2$, $!m = 3$, $!l = 4$ and $!k = 5$. There are four repair activities for identified track gauge spread: refastening, tie bar, re-sleepering and renewal. These repair processes for level '!k','!l' and '!m' are described in substitution transition $C1$.

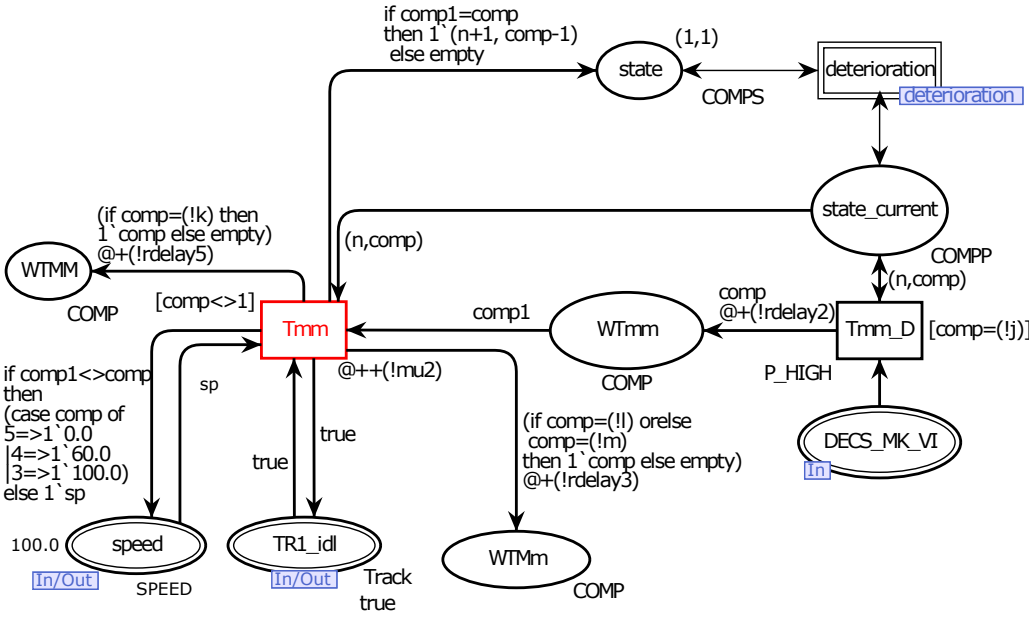


Figure 8.8: Repair model of observed level '!j' for track component 1

Figure 8.8 illustrates the repair CPN model for the observed component deterioration level !j. Substitution transition deterioration describes the deterioration process, which is shown in Figure 8.5.

1. When visual inspection is completed at time t, token in place DECS_MK_VI is valid. At this moment, the value of the token in place 'state_current' is level j, according to this state, transition 'Tmm_D' fires.

2. After 'rdelay2' time, the token in place 'WTmm' is valid, which means the planned repair arrives.

3. Transition Tmm fires which means repair for level !j is carried out, according to the maintained model in Figure 8.1:

   - if the current state is the same as the observed state, repair maintains track state to be '$comp - 1$ in place 'state', the repair takes '!mu2' hours;
   - if the current state degrades to be the failure state !k, a token is put in place 'WTMM' which means waiting for maintenance for level !k.

4. If the current state is !l or !m, a token is put in place 'WTMm' and the track component will wait for another level repair (repair for level !l and !m).

8.3.3 System inspection CPN model

A Train Recording Vehicle inspection campaign can be carried out once there is no train, no maintenance and visual inspections in the section.

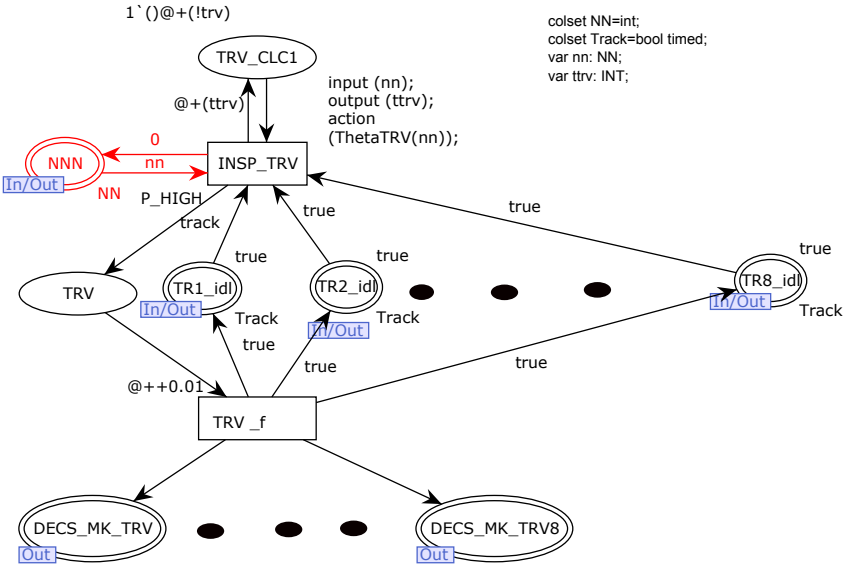


Figure 8.9: Track Recording Car Inspection Model

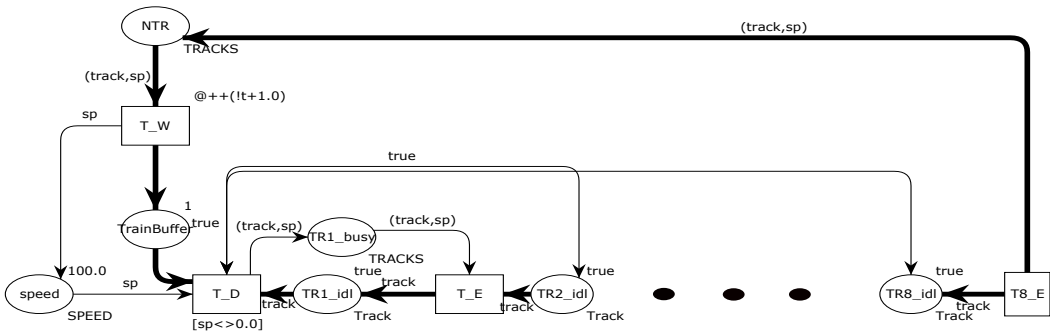


Figure 8.10: System Operation model

A CPN model of the track recording car is shown in Figure 8.9. If all of the places 'TR*i*_idl' have a token when it is time for TRV (a token at place 'TRV_CLC1' is enabled), transition 'INSP_TRV' fires and a token arrives at place 'TRV' and the decisions for track components (places 'DECS_MK_TRVi') are made.

The TRV CPN can model two inspection schemes using function $ThetaTRV(nn)$. Function $ThetaTRV(nn)$ controls the interval of track recording car by variables *ttrv*. If TRV is periodic, function $ThetaTRV(nn) = !trv$, where $!trv$ is defined as the planned maximum TRV interval. If TRV depends on the number of observed defects, place NNN collects the number of defects in the section, then function $ThetaTRV$ defines 'ttrv' according to 'nn'.

8.3.4 System operation and accident CPN model

The track system operation model is shown in Figure 8.10. Place TrainBuffer represents a waiting train at the entry of the section. Place 'Speed' controls train operation modes

due to the track gauge spread. Train can pass the section normally with speed 100, or in a degraded mode with speed 60; if the extreme failure exists, traffic must be stopped (speed is 0). Transition 'T_D' describes a train entering the section; it fires if all of the places 'TR*i*_idl' have tokens and variable *sp* of place 'Speed' is not zero. 'T_D' fires and it takes token from place 'TR*i*_idl' to 'TR*i*_busy', which means that track component is occupied by train, thus 'T_D' is not enabled and another train is not allowed to enter.

Figure 8.11 shows the derailment model: a derailment happens (transition D fires) when train is passing along the component (the place 'TRi_busy' has a token), where a track failure exists (place 'state current' has a value 5). After the accident, a renewal ('TMM' fires) is carried out and the track is restored (the variable *track* is 1 in place 'state') in '!MU' time (μ_A in Table 8.1).

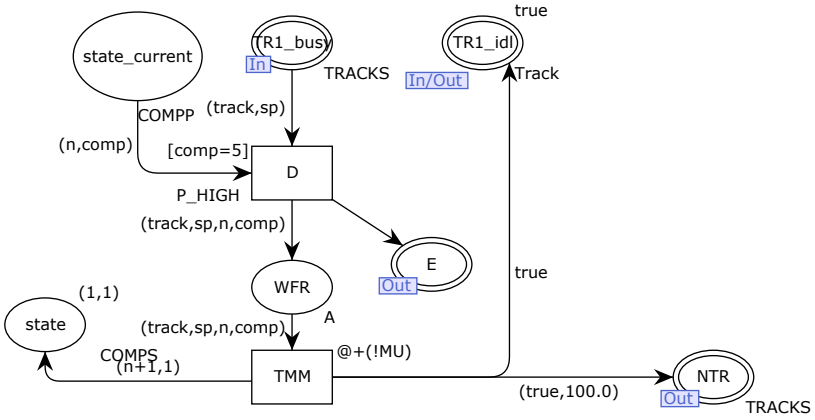


Figure 8.11: Accident Model at track component 1

8.4 Simulation results

The CPN model can be used to evaluate different inspection policies of the two inspection schemes. Four inspection policies are assumed in this chapter:

- Policy 1: two-level periodical inspections, interval of track recording cars θ_{trv} are decision variable for a given Visual Inspection interval which equals $\theta_{vi} = 40$ hours;
- Policy 2: visual Inspection interval is $\theta_{vi} = 40$ hours while track recording cars interval depends on the number of defects.
- Policy 3: two-level periodical inspections, Visual Inspection interval $\theta_{vi} = 50$ hours;
- Policy 4: visual inspection interval is $\theta_{vi} = 50$ hours while track recording cars interval depends on the number of defects.

In this study, we want to estimate the system performance for 1 year (8760 hours) with the inspection policies mention above. For these inspection policies, the planned Train Recording Vehicle (TRV) interval ranges from 5 to 2000 hours. The parameters for maintenance are shown in Table 8.2. Since we have no actual failure data for gauge spread, the parameters in this table are our assumptions.

Table 8.2: Simulation parametres

State	Failure rate	Effect	Waiting time (hours)	Duration (hours)
Level 1	$\lambda_1 = 0.002$	-	-	
Level 2	$\lambda_2 = 0.002$	Level 1	$\tau_{f2} = 15$	$\mu_{f2} = 1$
Level 3	$\lambda_3 = 0.002$	Level2	$\tau_{f3} = 10$	$\mu_{f3} = 4$
Level 4	$\lambda_4 = 0.002$	Level 3 (TSR)	$\tau_{f4} = 5$	$\mu_{f4} = 4$
Level 5	$\lambda_5 = 0.002$	Level 1	$\tau_{f5} = 2$	$\mu_{f5} = 10$
Accident	-	Level1	$\tau_{f6} = 0$	$\mu_A = 70$

8.4.1 Simulation convergence

20000 simulations with a simulation length of 8760 hours (1 year) are carried out to check how many simulations are required to observe a convergence in the results. A plot of the average line availability against the number of simulations is shown in Figure 8.12. The

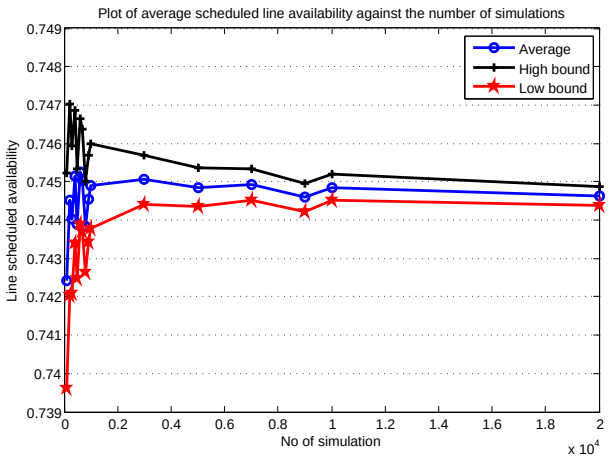


Figure 8.12: The number of simulation against the availability(simulation horizon: 8760 hours (1 year))

middle curve is the average availability result, the curve below it and above it are the 99% confidence results. It shows the simulation converges at around 2000 simulations. If the number of simulations is less than 2000, the results have larger deviations. Therefore, at least 2000 simulations are needed to get the solution of CPN model; in this study, we run 10000 simulations for the simulation length of 8760 hours.

8.4.2 System performance evaluations

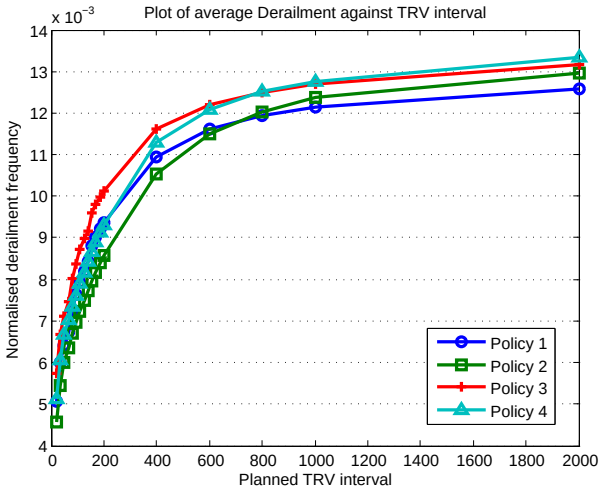
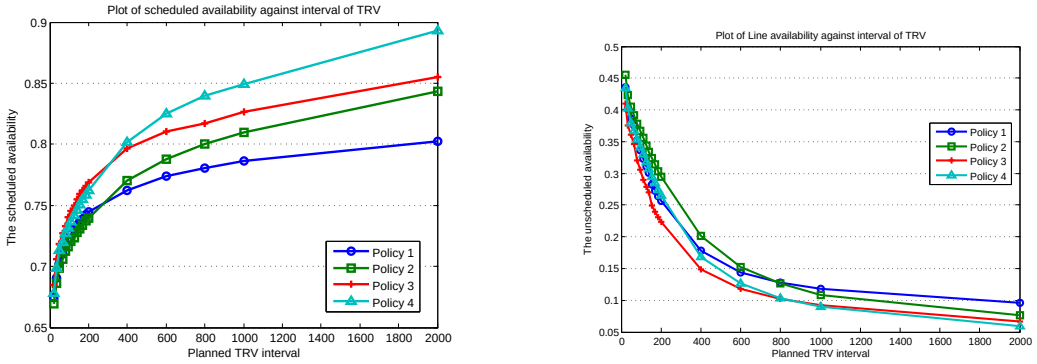


Figure 8.13: The number of derailment against TRV interval in one year

Figure 8.13 shows the normalized number of derailments against TRV interval per year. The derailment frequency increases when either Visual Inspection interval or Train recording Vehicle interval increases.



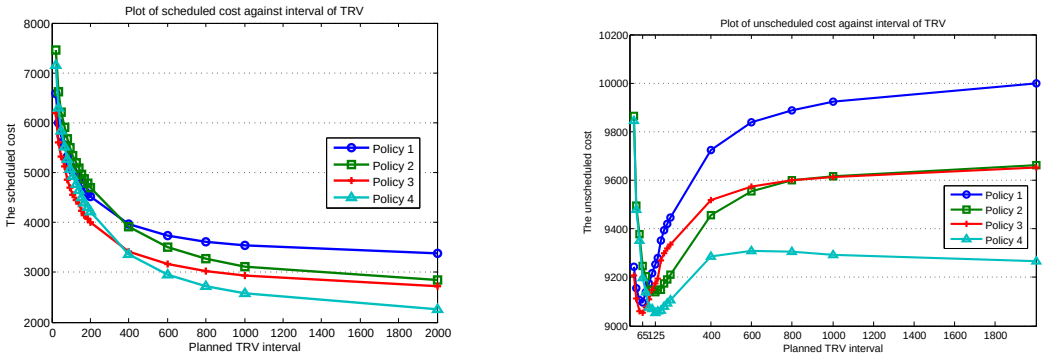
(a) Scheduled availabilities against TRV intervals

(b) Unscheduled availabilities against TRV intervals

Figure 8.14: Plot of system availability

If the track recording cars interval increases, the scheduled availability increases as shown in Figure 8.14a. However, the line availability decreases if TRV interval increases as shown in Figure 8.14b.

The scheduled cost and unscheduled cost are shown in Figure 8.15a and Figure 8.15b. All of the inspection policies have the minimum total cost as shown in Figure 8.15b. For policy 1 and policy 3, the minimum maintenance cost can be obtained for a Train Recording vehicle interval of 65 hours. For policy 2 and policy 4, the minimum total cost can be obtained if the track recording cars interval is 125 hours.



(a) Scheduled cost against TRV intervals

(b) Total cost against TRV intervals

Figure 8.15: Plot of costs against TRV intervals

In the plot of derailment, if TRV interval ranges from 0 to 300 hours, policy 2 and 4 exhibit fewer derailments and a shorter visual inspection interval can lead to a lower number of derailments. If TRV interval is within range from 300 hours to 700 hours, policy 1 and policy 2 are better than policy 3 and policy 4, policy 2 has a lower number of derailments than policy 1; if TRV interval exceeds 700 hours, policy 1 is better than policy 2.

8.5 Conclusion for two-level inspection policies

A modeling framework is presented for a railway plain line. System degradation and system operation are taken into account for the system performance evaluation. A hierarchical CPN model is built according to this framework, which consists of component working model, deterioration model, inspection model and maintenance model. Monte Carlo simulations are carried out to obtain the solutions.

CPN is a flexible modeling tool due to the concept of color set, for example, the track degradation states are defined by color set COMP as shown in Figure 8.5, the preventive maintenance thresholds (the parameter 'k', 'l' and 'm' in Figure 8.8) are defined by global references. In addition, function $ThetaTRV$ can be defined as an input of the CPN model to combine the different inspection schemes.

The model can be used to evaluate the strategies for risk-based maintenance and cost-effective maintenance. It can also evaluate the performance measures according to the practical inspection requirements, that requires visual inspection to be 168 hours and the maximum track recording cars interval to be 3 months. However, these simulations are carried out with some assumed lifetime parameters, if we need to evaluate the inspection strategies for a real section, the collected lifetime data is needed for the simulations.

CHAPTER 9

Maintenance optimization for a railway section: delayed maintenance vs speed restriction

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9.1 Introduction

Track vertical geometry faults due to poor ballast condition can be adjusted by track tamping or stoneblowering. Several researches study on the track failure evolution and they point out that the track quality depends on some factors such as speed, tonnage (MGT), maintenance histories and materials [11, 166, 203, 221].

Speed , one of these factors, plays an important role in railway maintenance and operation. Zio et al [219] discuss the flexibility of speed restrictions to reduce the train delays over the entire network since speed restriction can ensure the railway safety but may cause the delays.

Besides safety and train travelling time, speed restrictions have effects on the maintenance cost and operation benefit since a slower speed decelerates the deterioration evolution, which allows delayed maintenance and reduces the number of maintenances. However, speed restriction also reduces the throughput, and hence the system benefit.In a comparable setup, some researches consider age-based maintenance taking into account variable loads in production industries [204, 180].

Figure 9.1 (top) illustrates the effect of a speed restriction on the track deterioration: a limitation to a slower speed leads to a slower deterioration process and a longer residual time to failure which allows for a longer repair delay. The longer delay before repair can then be used to better organize the maintenance at a reduced preventive maintenance cost. At the same time, Figure 9.1 (bottom) shows that, under speed restriction, the system allows for less passing trains, which causes a loss of system throughput, and hence a lower system profit. On the other hand, the longer repair delay time gives more opportunities to group maintenance activities to save the set-up cost and the down time due to the repairs.

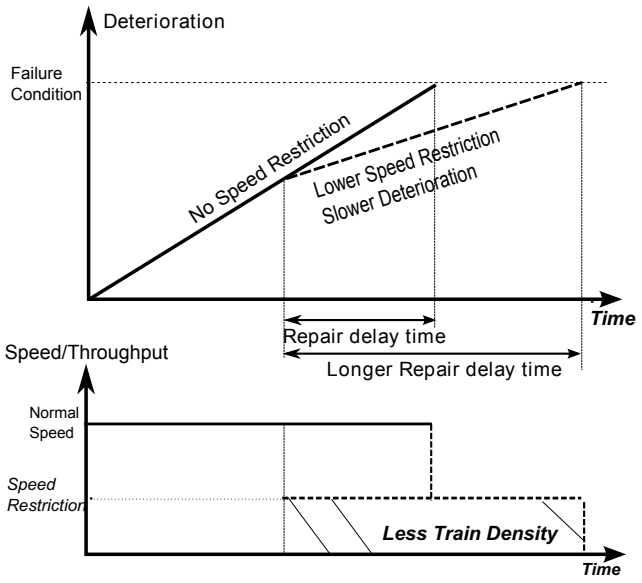


Figure 9.1: Effect of speed restriction on deterioration and throughput

Thus, we work on a maintenance optimization problem, in order to achieve a trade off between speed restriction and the preventive maintenance delay to maximize the system benefit and minimize the system downtime for a plain line railway section, in which the track deterioration depends on the speed and the number of passing trains.[1].

The structure of this chapter is arranged as follows: Section 9.2 presents the track

[1]The model in this chapter is presented in ESREL 2015 [174]

deterioration assumptions and the section maintenance rules. In addition, the performance indices of the section are given in Section 9.3; Section 9.4 describes the CPN models for the section, including the maintenance for the component (with/ without grouping policy), the

9.2 Modelling assumptions

We assume a series section consisting of 5 track components on a plain line. The deterioration of all the components is independent, following the same deterioration process. Train speeds on each component are independent, but train density for the system is determined by the minimum density value among all of the components in the railway series system.

9.2.1 Track component deterioration and maintenance

The track deterioration depends on the number of passing trains and the speed of the trains, as shown in Figure 9.2. X_t represents the track condition at time t; Y_k denotes the deterioration increment of the kth train passage. Two levels of maintenance and three speed options are scheduled for the periodically observed track condition. In Figure 9.2, CM represents the threshold of corrective maintenance and PM is the threshold of preventive maintenance. More arrivals at a higher speed can result in more serious track deterioration.

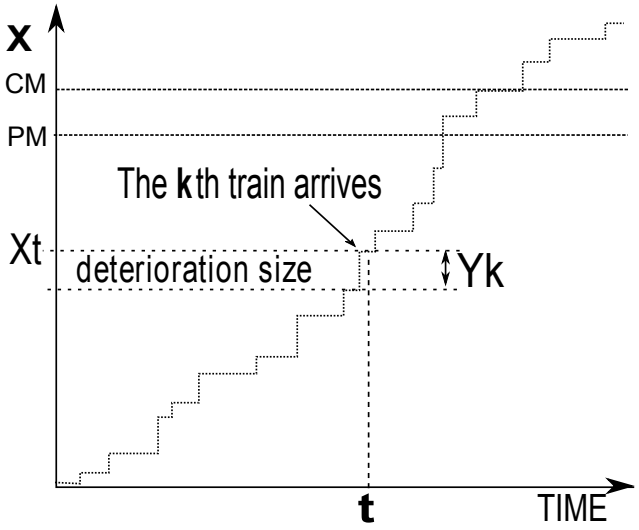


Figure 9.2: Deterioration process of the track component

9.2.1.1 Track deterioration

Train arrival time are assumed to follow a Poisson process with the arrival rate λ [163]. N_t is the number of trains until time t. X_t is the sum of deteriorations, as shown in Equation 9.1. The kth deterioration increment is a random value Y_k when the kth train passes, which

follows a Gamma distribution. The deterioration size Y_k has two parameters $\alpha(v)$ and β, and parameter $\alpha(v)$ depends on the speed v (as shown in Equation 9.2).

$$X_t = \sum_{k=1}^{N_t} Y_k, Y_k \sim \Gamma(\alpha(v), \beta) \tag{9.1}$$

$$\alpha(v) = \alpha_0 e^{a_0 v} \tag{9.2}$$

The deterioration process is a compound Poisson process with the Gamma distributed jump sizes [182]. According to the properties of compound Poisson process, the deterioration increment for a time period Δt equals Equation 9.3:

$$X_{\Delta t} = X_{t+\Delta t} - X_t = \sum_{k=1}^{N_{\Delta t}} Y_k = \Gamma(\alpha(v) N_{\Delta t}, \beta) \tag{9.3}$$

9.2.1.2 Component maintenance

Periodic inspection is scheduled for the track component on operation calendar, the inspection interval is denoted as θ_{insp}. Maintenance strategies based on the condition are widely discussed in the literature [70, 71], in this chapter, maintenances are scheduled based on the track condition: preventive maintenance and corrective maintenance are carried out for the observed defective component j.

- Preventive maintenance threshold is defined to be δ_{II} and the corrective maintenance threshold is δ_{DL}.
- If ith observed state X_{j_i} of component j exceeds corrective threshold δ_{DL} (i.e. $X_{j_i} \geq \delta_{DL}$), a corrective maintenance is carried out, which can fix track to be as good as new. The maintenance is performed in a delay time t_D. During the delay time t_D, the traffic is stopped.
- If $X_{j_i} \geq \delta_{II}$, a preventive maintenance is carried out in a delay time t_d. The preventive maintenance is imperfect, which maintains the component condition to a fixed value.
- The speed after the ith inspection is denoted as v_i, which is set according to the ith detected state.

$$v_i = \begin{cases} v_0, & X_i \in (0, \delta_{\mathrm{II}}) \quad \text{Normal speed} \\ v_{tsr}, & X_i \in [\delta_{\mathrm{II}}, \delta_{\mathrm{DL}}) \quad \text{Limited Speed} \\ 0, & X_i \in [\delta_{\mathrm{DL}}, \infty) \quad \text{No Trains} \end{cases} \tag{9.4}$$

9.2.2 Section maintenance planning

The chosen railway network is a series system. Trains can have different speeds on different track components, but the train densities are the same for all of the components.

The section is inspected periodically by the inspection train, ignoring the traveling time of the inspection train ($I1$ to $I8$ in Figure 9.3).

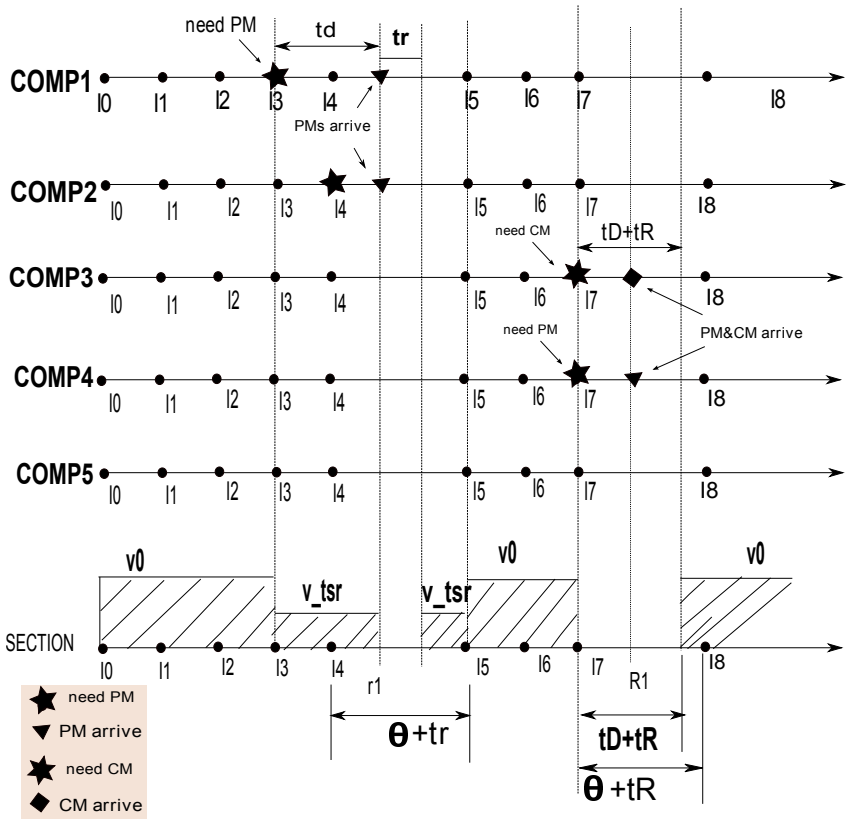


Figure 9.3: Scenarios of maintenance grouping for the section

If any failure state of the components is detected (i.e. $X_{j_i} \geq \delta_{DL}$), a corrective maintenance is set up in a delay time t_D. The corrective maintenance action takes t_R to fix the component. The cost of corrective maintenance consists of two parts: the corrective maintenance setup cost c_{csu} and the corrective maintenance action cost c_{cm}.

- If there are n_m components failed, n_m corrective maintenance actions are carried out at the same time, the section downtime for this pure corrective maintenance group is $t_D + t_R$. They share the corrective maintenance setup cost, the maintenance cost for this group is $c_{csu} + n_m c_{cm}$.

- If some other components need preventive maintenances, i.e. $\delta_{II} \leq X_{l_i} \leq \delta_{DL}, j \neq l$; preventive maintenance is set up at the same time with corrective maintenance. This is a mixed maintenance group. The maintenance cost consists of the corrective setup cost c_{csu}, corrective maintenance action cost c_{cm}, preventive maintenance setup cost c_{psu} and the preventive maintenance actions cost $c_{pm}(t_d)$.

- For the mixed maintenance group, since $t_d < t_D$ and $t_r < t_R$, the section downtime is equal to $t_D + t_R$. In Figure 9.3 inspection $I7$ identifies that component 3 is failed and component 4 needs a preventive repair and these two components are repaired during $t_D + t_R$ when $R1$ arrives.

At time t_i, if $X_{j_i} \geq \delta_{II}$, a preventive maintenance is set up in a delay time t_d. During t_d, if the following inspection only identifies defects but no failures, all the defective components are repaired at time $t_i + t_d$. This is a pure preventive maintenance group, as shown in Figure 9.3, $I3$ identifies component 1 needs preventive maintenance, then a preventive maintenance is scheduled at time $I3 + t_d$, inspection $I4$ identifies that the component 2 also needs a preventive maintenance, thus the preventive maintenance for component 4 is carried out at time $I3 + t_d$ and it does not need to wait for another delay time t_d. Preventive maintenance needs a down time t_r.

The cost of preventive maintenance includes the setup cost c_{psu} and the cost of each preventive maintenance action $c_{pm}(t_d)$. $c_{pm}(t_d)$ depends on the longest repair delay time in the group, that is t_d for component 1 at time $I3$ in Figure 9.3. The longer t_d the lower maintenance cost as shown in Equation 9.5. If $t_d \in (0, T^*)$, the preventive maintenance action cost depends on the repair delay time t_d, if $t_d \geq T^*$, the preventive maintenance action cost equals a minimum repair value $c_{p_{min}}$.

$$c_{pm}(t_d) = \begin{cases} At_d + B & t_d \in (0, T^*) \\ c_{p_{min}} & t_d \in [T^*, \infty) \end{cases} \tag{9.5}$$

There are three traffic density configurations according to the minimum train speed in the section: If all observed states are normal $X_{j_i} \leq \delta_{II}$, the train density is λ_0. If component j is defective ($X_{j_i} \geq \delta_{II}$), during t_d, the speed at j component is $v_j = v_{tsr}$ and the speed for the other normal component equals $v_l = v_0, l \neq j$, the train density for the section is λ_{train} in Equation 9.6 until the following inspection confirms that all the components are normal.

$$\lambda_{train} = \frac{v_{tsr}}{v_0}\lambda_0 \tag{9.6}$$

When the maintenance action is performed, the system is closed, that is $I3$ to $I5$ in Figure 9.3. If component j is failed ($X_{j_i} \geq \delta_{II}$), the section is closed and the density is 0.

9.3 Performance evaluation

In this section, the performance evaluation indices are introduced. For the single objective, we can compare the system benefit or the system unavailability for the evaluation; for the multiple-objectives, we adopt the Pareto front.

9.3.1 Single objective evaluation

System benefit and system unavailability are used to evaluate the system performance. System unavailability is equal to Equation 9.7:

$$Q_{avg} = \lim_{t\to\infty} \frac{[N_{csu}(t) + N_{mix}(t)](t_D + t_R) + N_{psu}(t)t_r}{t} \tag{9.7}$$

System benefit is the system gain minus the system maintenance cost:

$$\mathbb{E}B_\infty = \mathbb{E}G_\infty - \mathbb{E}C_\infty \tag{9.8}$$

The average maintenance cost rate (EC_∞) and system gain rate (EG_∞) per time unit on an infinite time span are:

$$\mathbb{E}C_\infty = \lim_{t\to\infty} \frac{C(t)}{t} \tag{9.9}$$

$$\mathbb{E}G_\infty = \lim_{t\to\infty} \frac{N_{train}(t)c_{train}}{t} \tag{9.10}$$

where c_{train} is the gain for each train passage.

Maintenance cost includes maintenance setup cost and maintenance action cost.

$$\begin{aligned} C(t) = & \underbrace{\sum_{m=1}^{N_{csu}(t)} (c_{csu} + n_m c_{cm})}_{\text{Pure corrective maintenance group}} + \underbrace{\sum_{n=1}^{N_{psu}(t)} (c_{psu} + n_n c_{pm})}_{\text{Pure preventive maintenance group}} \\ & + \underbrace{\sum_{h=1}^{N_{mix}(t)} (c_{csu} + n_{cm_h}c_{cm} + c_{psu} + n_{pm_h}c_{pm})}_{\text{Mix maintenances group}} + N_{insp}(t)c_{insp} \\ = & [N_{csu}(t) + N_{mix}(t)]c_{csu} + (\sum_{n=1}^{N_{psu}(t)} n_n + \sum_{h=1}^{N_{mix}(t)} n_{pm_h})c_{pm} \\ & + [N_{psu}(t) + N_{mix}(t)]c_{psu} + (\sum_{m=1}^{N_{csu}(t)} n_m + \sum_{h=1}^{N_{mix}(t)} n_{cm_h})c_{cm} + N_{insp}(t)c_{insp} \end{aligned} \tag{9.11}$$

In order to evaluate these quantities, we need to build a simulation model to collect the number of trains N_{train}, the number of inspections N_{insp}, the number of maintenance setups (N_{mix}, N_{csu} and N_{psu}), the number of maintenance actions (N_{cm} and N_{pm}).

9.3.2 Multiple-objective evaluation

The multiple objective problem evaluates the system performance considering the system benefit and unavailability at the same time, Pareto front is adopted [30, 122]; we need to find the solution set (v_{tsr}, t_d) to satisfy:

if and only if there is no $(v^*_{tsr}, t^*_d) \in (V, T_d)$

$$B(v_{tsr}, t_d) \geq B(v^*_{tsr}, t^*_d) \tag{9.12}$$

$$Q(v_{tsr}, t_d) \leq Q(v^*_{tsr}, t^*_d) \tag{9.13}$$

The solution set (v_{tsr}, t_d) is called strict Pareto front. If $B(v_{tsr}, t_d) > B(v^*_{tsr}, t^*_d)$ and $Q(v_{tsr}, t_d) < Q(v^*_{tsr}, t^*_d)$, the solution set is called weak Pareto front.

9.4 CPN models

A hierarchical CPN network model is built for the numerical experiment solutions. The framework of the CPN network model, consisting of the system level CPN model and the component level CPN models, is shown as Figure 9.4. The rectangles represent the substitution transition modules and the ellipses represent states link substitution transition modules.

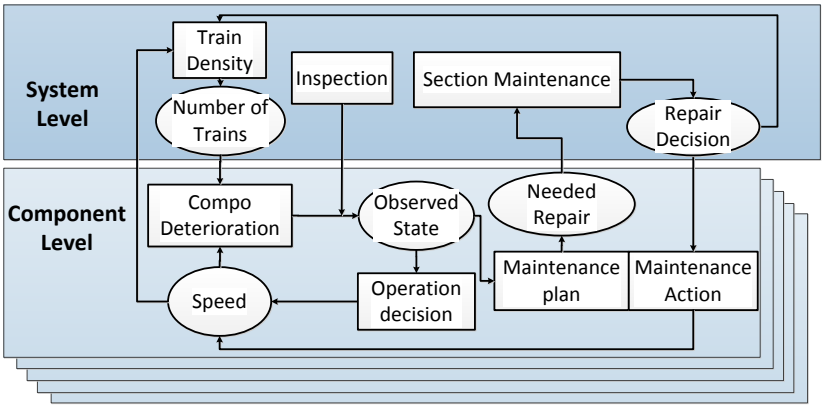


Figure 9.4: Framework of the CPN model

There are three modules in the system level: “Train Density" module controls the number of arriving trains; “Inspection" module is the CPN for the inspection process and the section maintenance decisions are determined in module “Section Maintenance".

9.4.1 CPN model for railway section

Figure 9.5 is the CPN model for the chosen section. It is a hierarchical CPN model, the substitution transition TRACK represents the component level model in Figure 9.4.

Substitution transition Maintenance_Plan_System represents the module section maintenance decision in the frame work. Substitution transition NO_TRAIN models the module Train density and INSPECTION models the inspection module in the framework in Figure 9.4.

Places Scheduled_Speed*i* sends the component own speed to the system module NO_TRAIN, places N_Train_*i* returns the number of trains to each track module TRACK. Places PM_TC*i* are the preventive maintenance decision for *i*th component, places CM_TC_*i* are the corrective maintenance decision for *i*th component. Place PM_Need represents that at least one preventive maintenance is needed in the section, place PM_time is used to manage the preventive maintenance delay time. Place CM_time is used to manage the corrective maintenance waiting time and place CM_Need is used to represent that there is at least one component needing corrective maintenance.

In Figure 9.5, we just show part of the CPN for railway system in which there is only one track for explanation.

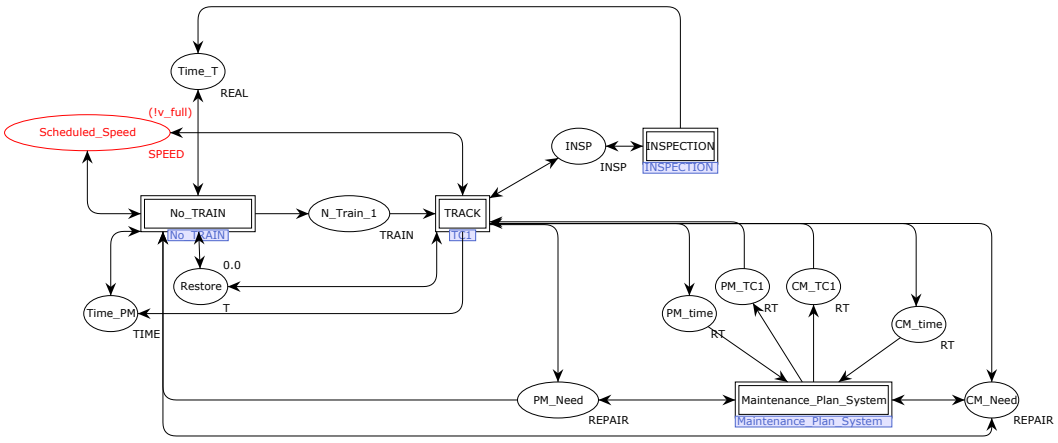


Figure 9.5: CPN model for the railway system with one track component

9.4.2 Component CPN model

Each component is a separated model, they send their own speed and maintenance plans to the system model and perform maintenance decisions. they have three modules: “deterioration" module models the deterioration increment according to the train speed and density; “operation decision" module decides the speed based on the observed state; in the “maintenance" module, “maintenance plan" sends the component repair requirement to system maintenance decision module and then “maintenance action" module performs the maintenance actions. Figure 9.6 illustrates the details of the substitution transition “Track", which represents the “Component Level" in Figure 9.4.

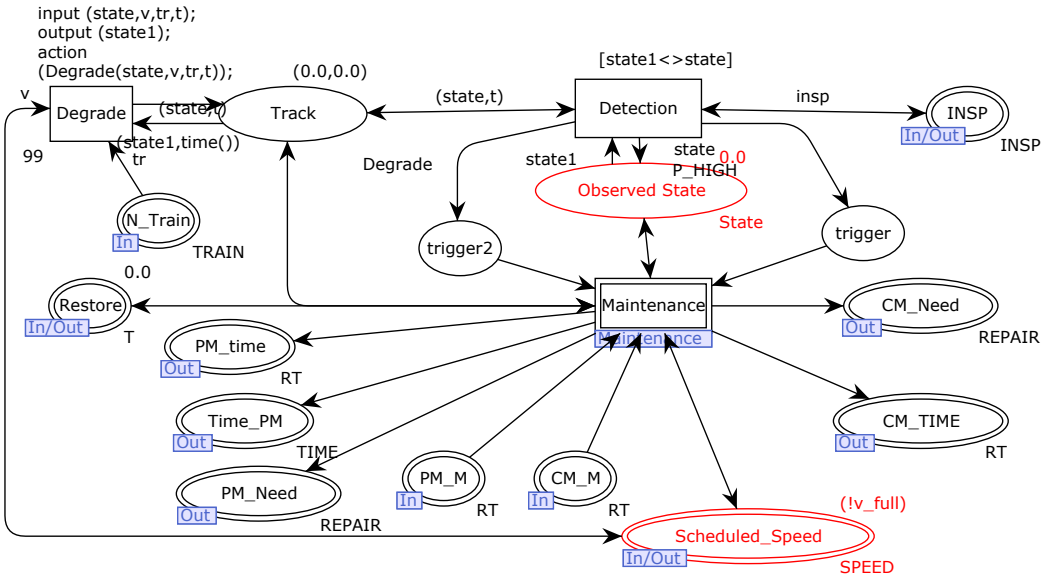


Figure 9.6: Component deterioration CPN model with maintenance substitution transition

Place ‘Track’ represents the track state x at time t, with the initial state (0.0,0.0). If train arrives, tokens in place ‘N_Train’, transition Degrade generate a random state according to the last state in place ‘Track ’ and the number of trains in place ‘N_Train’. Once inspection arrives (tokens in place ‘INSP’), track state is detected and sent to place ‘Observed State’ and triggers the maintenance substitution transition, which sends the maintenance requirements to the places ‘Restore’,‘PM_time’,‘PM_Need’,‘PM_M’,‘CM_M’,‘CM_TIME’ and ‘CM_Need’, which are links to the “Maintenance plan system" CPN model.

9.4.3 Component maintenance CPN model for grouping strategy

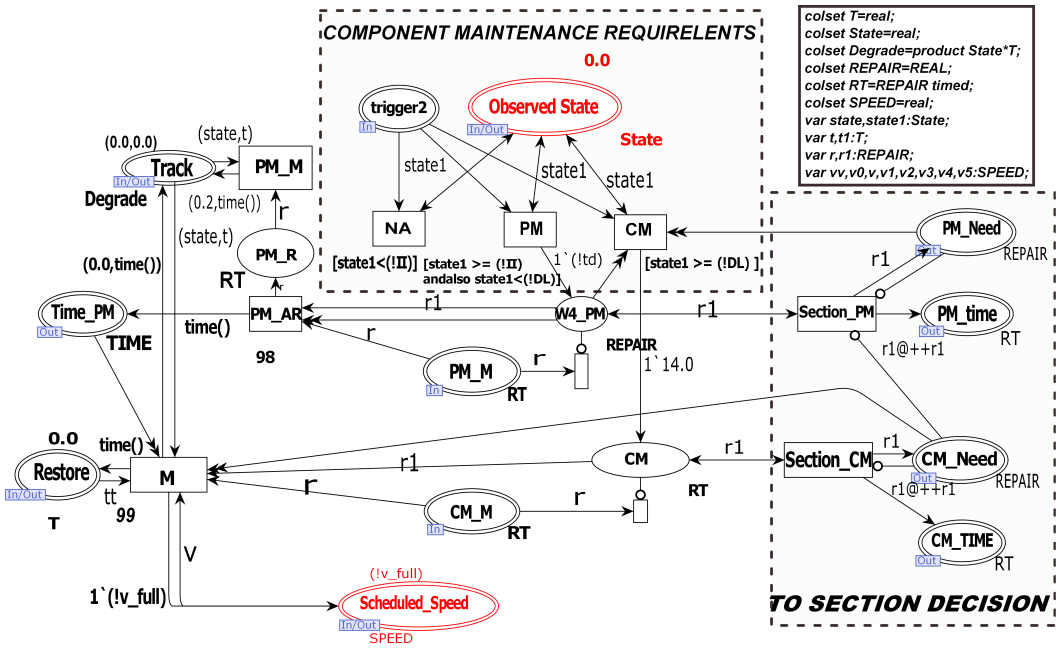


Figure 9.7: Component CPN model for grouping maintenance

Figure 9.7 illustrates the details of the component maintenance module (substitution transition “maintenance" in Figure 9.6), including the maintenance plan and the maintenance action. The component maintenance requirement depends on the token in place ‘Observed State’ which is the result of the inspection; place ‘trigger2’ has a token after an inspection which help to control the component decision transitions. Three transitions (‘NA’, ‘PM’ and ‘CM’) are used for decision making, the transition guards decide the firing condition: ‘!II’ represents the preventive maintenance threshold δ_{II} and ‘!DL’ is the corrective maintenance threshold δ_{DL}.

If the observed state falls between δ_{II} and δ_{DL}, transition ‘PM’ fires and the delay time ‘!td’ is send to place ‘W4_PM’. If this is the first preventive maintenance requirement since last corrective maintenance, transition ‘Section_PM’ fires and it sends a token to place ‘PM_Need’ which indicates the section needs a preventive maintenance, and the preventive maintenance time is set in place ‘PM_time’. If this is not the first preventive maintenance requirement in the section since previous corrective maintenance, which means there was

at least one defect identified before and the section now is waiting for the preventive maintenance, thus the transition 'Section_PM' does not fire. Place 'PM_M' is the preventive maintenance decision from the system level. If there is a valid token in place 'PM_M' and the tokens in place 'W4_PM', transition 'PM_AR' fires and consumes all the tokens in place 'W4_PM'. Transition 'PM_M' fires and recovers the track state to be 0.2.

This model also considers the situation that the repair delay is longer than inspection interval, i.e. $t_d \geq \theta_{insp}$. The inspection results do not change the preventive maintenance time and the reset arc helps to empty the place 'W4_PM'.

If the inspection identifies the failure $X \geq \delta_{DL}$, or the defective state deteriorates to be a failure, transition 'CM' fires and empty the preventive requirement in place 'W4_PM' and 'PM_Need'. At the same time, the section needs corrective maintenance (token in place 'CM_Need' and the maintenance time is controlled by token in place 'CM_TIME'). Place 'CM_M' represents the section decision. Once there are token in both place 'CM' and 'CM_M', transition 'M' fires and recovers the track to be as good as new (i.e. $state = 0.0$).

A monitor of 'M' is set to collect the number of corrective maintenance activities, i.e. $(\sum_{m=1}^{N_{csu}(t)} n_m + \sum_{h=1}^{N_{mix}(t)} n_{cm_h})$. Similarly, a monitor of 'PM_M' is used to collect the number of preventive maintenance activities, i.e. $(\sum_{n=1}^{N_{psu}(t)} n_n + \sum_{h=1}^{N_{mix}(t)} n_{pm_h})$.

9.4.4 Maintenance planning CPN model

When each component model has its own maintenance requirements, we need to make decision for the whole railway system. There are three situations for the system maintenance planning: pure corrective maintenance, pure preventive maintenance and mixed maintenance. Figure 9.8 illustrates the system maintenance planning CPN model.

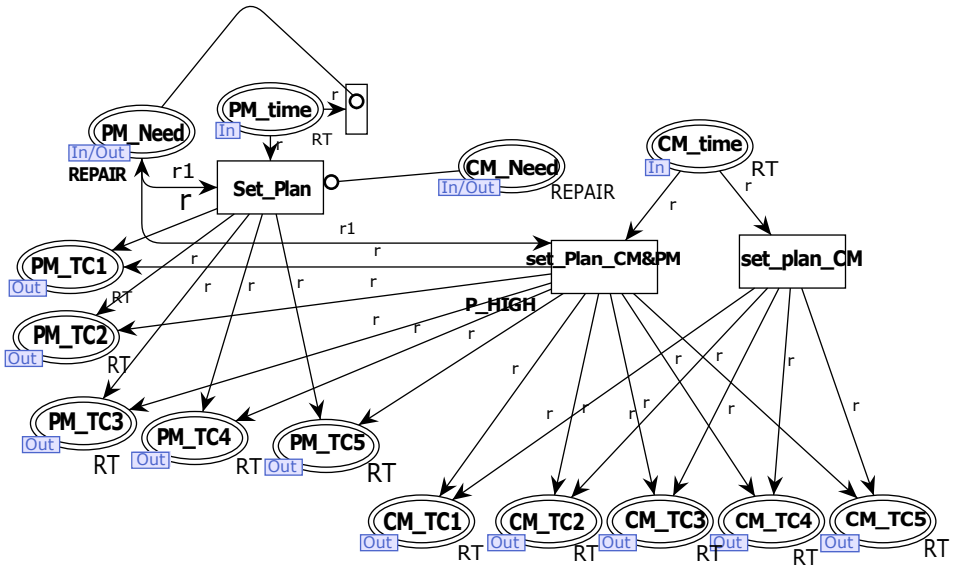


Figure 9.8: Maintenance plan CPN model

Figure 9.8 shows the details of the substitution transition 'Maintenance_Plan_System'

which makes the maintenance decisions for the whole railway section. Transition 'set_Plan' fires when a pure preventive maintenance group is needed, the firing time of which is controlled by the place 'PM_time'. It sends tokens to the place 'PM_TC*i*' which is the preventive maintenance demand connected to the component maintenance modules. Transition 'Set_plan_CM' fires when it is time for the pure corrective maintenance group. Similarly, it sends the corrective maintenance demands (the tokens) to the place 'CM_TC*i*'. Transition 'Set_Plan_CM&PM' fires when a mix group of maintenance is implemented. Since this is a mix maintenance group, the transition sends the maintenance requirements to all the places 'PM_TC*i*'s and 'CM_TC*i*'s. We set the monitors for these three transitions ('set_Plan','Set_plan_CM' and 'Set_Plan_CM&PM') to collect the number of maintenance setups (i.e. $N_{psu}(t)$, $N_{csu}(t)$ and $N_{mix}(t)$) in Equation 9.11.

The other parts of CPN model, such as the train density module, the inspection module are shown in Appendix C.

9.5 Simulation results

In order to estimate the performance indices, Monte Carlo simulations are carried out to collect the number of maintenance actions and the number of maintenance groups. In this section, we show the simulations results for the infinite time horizon, which are obtained by running simulations of 10,000 years. The parameters used in the CPN model are shown in Table 9.1.

Table 9.1: Parameters used in simulations

	Value		Value		Value		Value
δ_{II}	0.9	δ_{DL}	1.2	θ_{insp}	15	A	-183.3
t_D	14	v_0	100	λ_0	12	t_R	6
B	12000	α_0	0.000167	a_0	0.04	t_r	3
β	20.96	$c_{p_{min}}$	1000	C_{cm}	100000	c_{psu}	8000

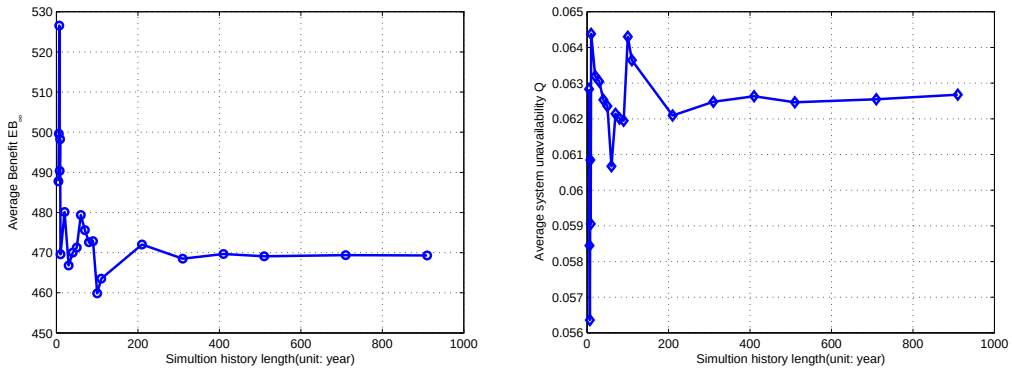
9.5.1 Convergence

Figure 9.9 shows the convergences of the performance. Simulations for the section CPN model are set: $\delta_{II} = 0.9$, $t_d = 14$ and $v_{tsr} = 10$.

Maintenance cost converges at the length of 500 years as shown in Figure 9.9a; Unavailability converges at the length of 700 years as shown in Figure 9.9b. The following simulations are set to run with the length of 10,000 years to estimate the maintenance cost and the unavailability.

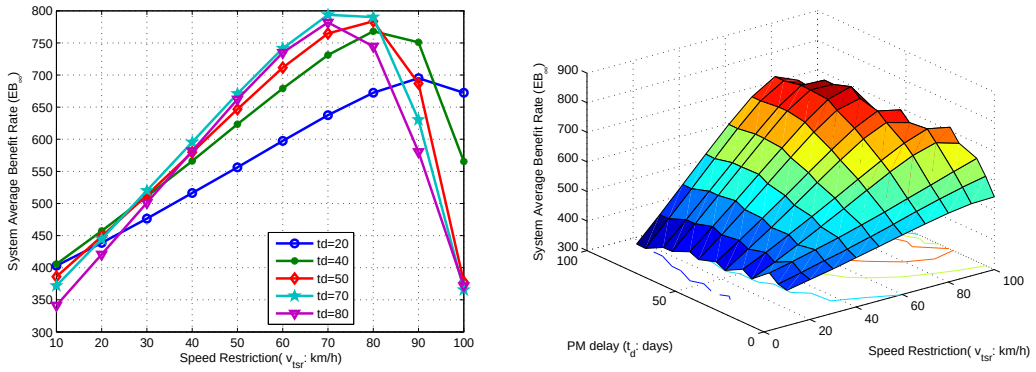
9.5.2 Results for the grouping policy

Figure 9.10a and Figure 9.10b show the results of the system benefit. Figure 9.10a illustrates some plots of system benefit against speed restriction for given repair delays, the maximum benefits are explicitly shown. Figure 9.10b is the system benefit against the



(a) Convergence of system benefit (b) Convergence of system unavailability

Figure 9.9: Convergences of the performance indices



(a) System Benefit B against v_{tsr} (b) System benefit B as a function of v_{tsr} and t_d

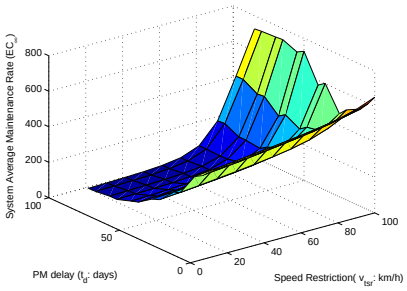
Figure 9.10: Plot of system benefit B with the grouping strategies

speed restriction and repair delays, where speed restriction is $v_{str} \in [10, 100]$ and repair delays is $t_d \in [0, 85]$. It shows the optimized system benefit explicitly when the speed restriction is $v_{tsr} = 80$ and the repair delay is $t_d = 55$.

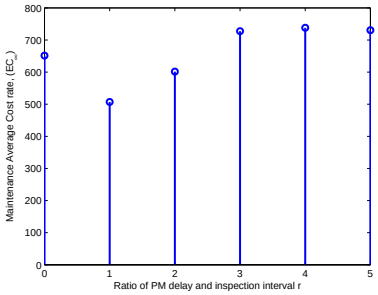
The maintenance cost for the system against speeds and repair delays is shown in Figure 9.11a. It shows that the lowest maintenance cost can obtained when the speed restriction is 10 and the repair delay is 85. For the given preventive maintenance delay, the maintenance cost increases along with the speed, since the higher speed may cause more failures and defects.

For a given speed restriction (for example $v_{tsr} = 100$), system maintenance cost against the floor of ratio of repair delay and inspection interval (i.e. $r = \lfloor \frac{t_d}{\theta_{insp}} \rfloor$[2]) can be seen in Figure 9.11b. An optimal maintenance cost for a given speed restriction $v_{tsr} = 100$ is obtained when the ratio is 1. It means we can schedule an optimized repair delay for a given speed restriction. Thus, we can also get the optimal repair delays for $v_{tsr} = 10$, but

[2]Notation $\lfloor a \rfloor$ represents the largest integer not greater than a, see Section 6.4.2.1



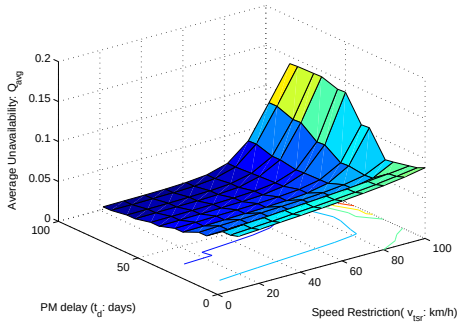
(a) Maintenance cost C against v_{tsr} and t_d



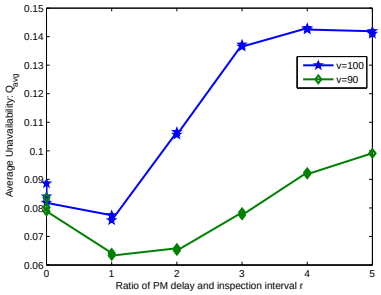
(b) Plot of C against $r = \lfloor \frac{t_d}{\theta_{insp}} \rfloor$ given that $v_{tsr} = 100$

Figure 9.11: Plot of long-term average system maintenance cost C given that $v_{tsr} = 100$ for grouping maintenance strategy

the track is assumed to be repaired within a period not longer than 3 months when the defect is identified, so we just show the results in Figure 9.11a when $t_d \in [0, 85]$ days.



(a) System unavailability Q as a function of t_d and v_tsr



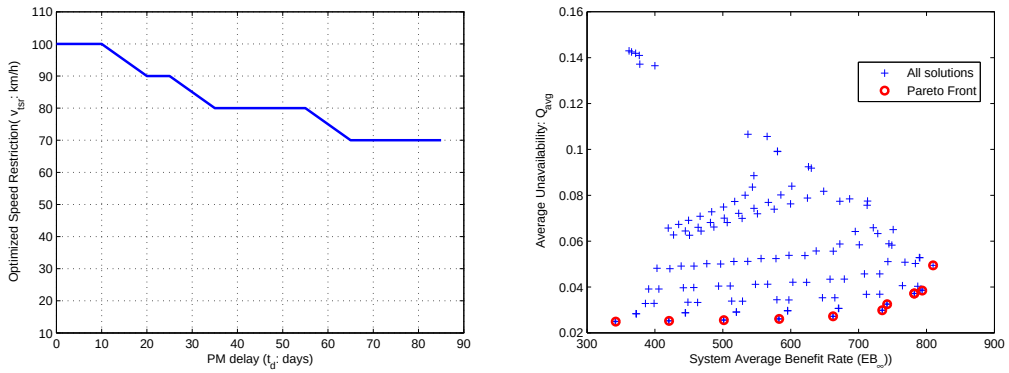
(b) Q given that $v_{tsr} = 100$ and $v_{tsr} = 90$

Figure 9.12: plot of system unavailability Q for grouping maintenance strategy

Another performance index is the system unavailability Q. The unavailability against speed restriction and repair delay is shown in Figure 9.12a.The lowest unavailability can obtained for the lower speed and longer repair delay. Similarly, we can get the optimized repair delays for the given speed restrictions, which means a longer repair delay could result in a lower unavailability.

According to the result of system benefit, Figure 9.13a shows the optimized speed restrictions for different repair delays to get the maximum system benefit for the given inspection interval and PM thresholds; it shows the slower speed restriction is needed for the longer repair delays.

In some cases, we need to evaluate the system performance considering the system benefit and unavailability at the same time, thus Pareto front is adopted. Figure 9.13b shows the solutions and the weak Pareto frontiers which are in red circles.



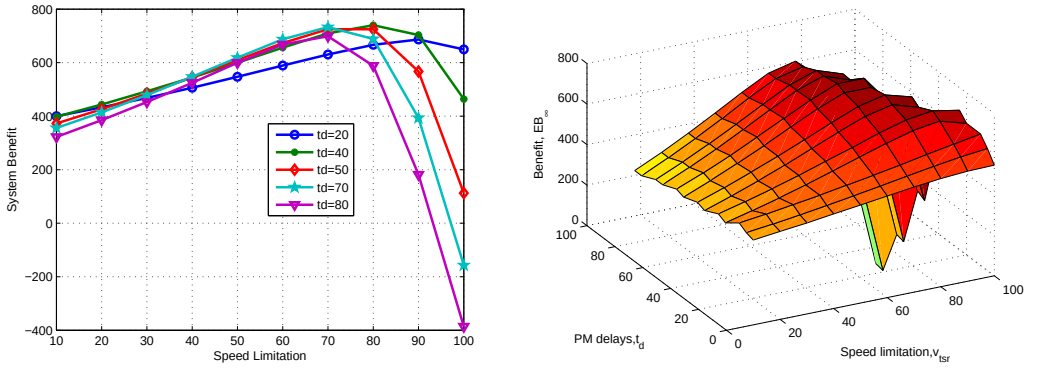
(a) optimized v_{tsr} for PM delay t_d

(b) Pareto Front of the grouping strategy solution with the parameter (v_{tsr}, t_d)

Figure 9.13: Grouping simulation results

9.5.3 Results for the non-grouping policy

We also run the simulations for the maintenance strategies without grouping for the chosen section. Figure 9.14a shows the system benefit against speed restriction v_{tsr}. Similar to the grouping maintenance strategy shown in Figure 9.10a, the maximum system benefits are explicitly shown . Figure 9.14b plots the system benefit as a function of preventive maintenance delay t_d and speed restriction v_{tsr}.



(a) System average benefit against v_{tsr}

(b) System average benefit as a function of v_{tsr} and t_d

Figure 9.14: Plot of system average benefit for non-grouping strategy

Figure 9.15 illustrates the plot of system unavailability as a function of speed restriction v_{tsr} and preventive maintenance delay t_d. It shows that the system unavailability increases against speed restriction, and for a given speed restriction v_{tsr}, an optimal system unavailability can be obtained.

Figure 9.16a shows the optimized speed for different PM delays if the non-grouping strategies is adopted.

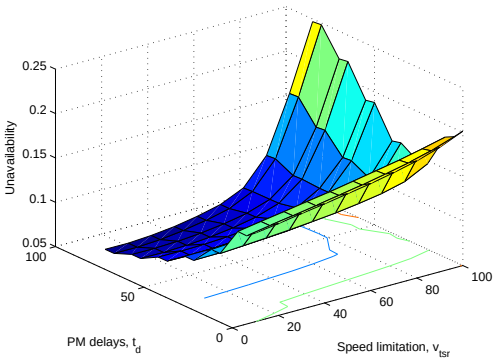
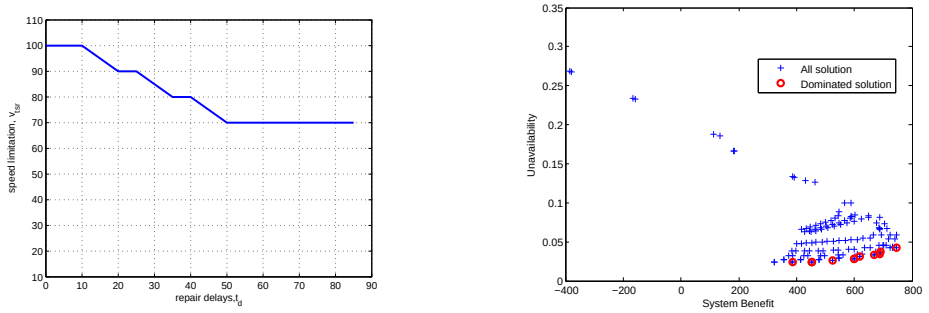


Figure 9.15: Plot of system unavailability as a function of speed restriction v_{tsr} and preventive maintenance delay t_d



(a) Optimized speed restriction for PM delays (b) multi-objective solutions and Pareto front

Figure 9.16: Simulation optimal results for non-grouping strategies

All solutions for the multi-objective evaluation and Pareto fronts for the non-grouping maintenance strategy are shown in Figure 9.16b.

9.5.4 Comparison of grouping and non-grouping policies

In this chapter, we want to assess the effect of speed restriction for the delayed maintenance strategy. Simulation results in Section 9.5.2 and 9.5.3 present that speed restrictions and preventive maintenance delays can be optimized to maximize system benefit. In this section, we compare the grouping maintenance and non-grouping maintenance based on the their simulation results.

Table 9.2 shows the result comparison for two configurations. The optimal performance are obtained at $v_{tsr} = 80$ for the maintenance strategy with the grouping option, and at $v_{tsr} = 70$ for the maintenance strategy without grouping. Obviously, introducing the possibility of maintenance grouping allows for a higher benefit, lower unavailability and the lower maintenance cost.

Figure 9.17 shows the comparison of the Pareto fronts of the grouping solution and the no grouping solution. The grouping strategy leads to both higher benefit and lower

Table 9.2: The results comparison. G:system gain; C: maintenance cost; B system benefit; Q: system unavailability

		v_{tsr}=80,t_d=55	v_{tsr}=70,t_d=55
' t_d' grouping	**G**	1028.26	955.00
	C	218.54	167.89
	B	**809.72**	**787.11**
	Q	0.049	0.037
no grouping	**G**	996.85	917.41
	C	251.43	172.3
	B	**744.87**	**745.11**
	Q	0.058	0.042

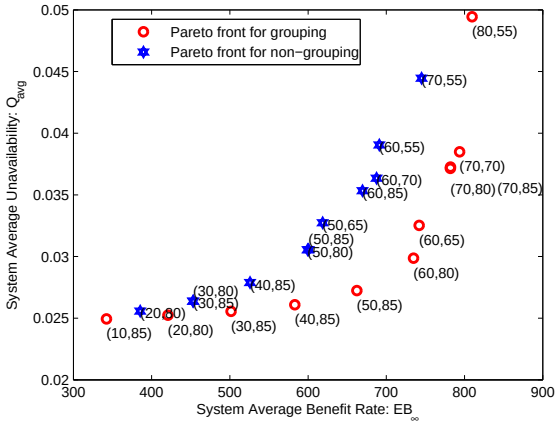


Figure 9.17: Comparison of the Pareto fronts of two strategies with the parameter (v_{tsr}, t_d)

unavailability for the multiple objective optimization.

Figure 9.18 and 9.19 shows the number of the PM actions in one maintenance group with or without the grouping strategy: the grouping strategy has more PMs for each group, i.e. there are 2.5 preventive repairs in one group while without the grouping strategy the number of PMs is 2.2. The grouping strategy saves the preventive set-up cost and the downtime thus the grouping strategy incurs a lower unavailability and maintenance cost, allowing hence for a higher system benefit.

9.6 Conclusion for the delayed maintenance with speed restriction

Speed is an important factor which impacts on both the railway maintenance cost and the traffic gains since the lower speed extends the component survival time but it reduces the number of passing trains. On the other hand, the longer survival time allows for longer repair delays, during which we can make better repair plans with a lower repair price by

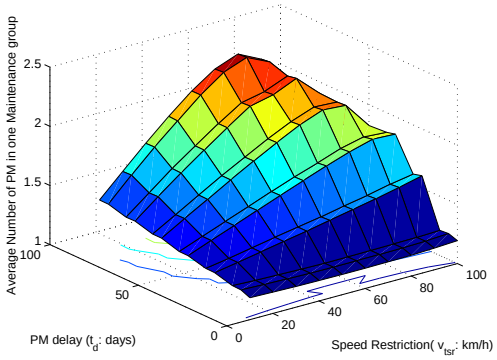


Figure 9.18: The average number of PMs in one maintenance group against speed and delay, with t_d grouping strategy

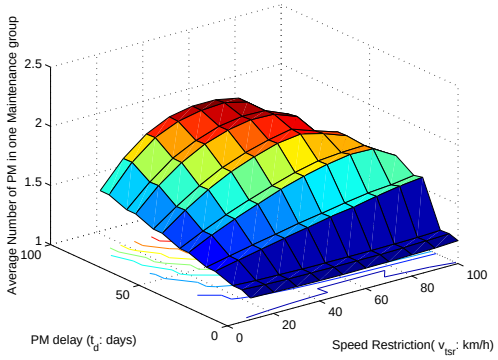


Figure 9.19: The average number of PMs in one maintenance group against speed and delay, no grouping strategy

reducing the maintenance setup cost.

In this chapter, we want to solve a maintenance optimization problem to determine the tuning of the speed restriction and the repair delay to maximize the system benefit (i.e. system profit minus maintenance costs) and minimize the system downtime. We propose a CPN model for a series track system to model a maintenance grouping strategy based on the preventive maintenance delays. We assume that the track deterioration depends on the speed of passing train. Two levels of maintenance and speed restrictions are scheduled according to the observed track states. In this model, speed restriction v_{tsr} and preventive maintenance delay t_d are the maintenance decision variables and system benefit B and system unavailability Q are used to evaluate the system performance.

Monte Carlo simulations are carried out to get the results of different v_{tsr} and t_d. When we evaluate the performance with only one performance evaluation, the results explicitly show the optimised system benefit and the trade off achieved between the speed restriction and repair delays. They show that the slower speed restriction is needed for the longer repair delays to maximize the system benefit. If we just consider maintenance cost or unavailability, the results show that the lower speed restriction is better since the higher speed may cause more failures and defects. The simulation results also show that the grouping strategy can lead to a higher system benefits, lower maintenance costs and lower unavailability than the strategy without grouping policies, since the grouping strategy reduces the setup cost.

If the strategies are evaluated considering the benefits and the system unavailability, we need to find the Pareto optimum from the solutions. We get parts of the Pareto Fronts for two maintenance strategies, and they indicate that grouping can lead to more efficient maintenance solution in most cases.

Part V

CONCLUSION & PERSPECTIVE

Conclusion and perspectives

General conclusions

Nowadays, more and more people choose to travel by train and hence railway assets need to be checked and maintained to prevent accidents and ensure safety. However, maintenance for railway assets lead to traffic stops and passengers disturbances, it also costs a lot of money. Railway networks consist of thousands of components and different operation modes; in addition, it is difficult to perform a maintenance which makes the traffic stop. All of the above factors lead not only to the necessity, but also to the complexity of the maintenance modelling. Most of the maintenance models in railway industry are assumed to be Markovian, along with the increase of input information, a more flexible modelling tool need to be used for the maintenance modelling. In this thesis, we are interesting in having a tool to help maintenance decision making for the failure process which may not satisfy Markov properties (for example, the delay repair model), and should be able to describe maintenance and operation for a multi-component system. Coloured Petri Net is one of the tools which can cover the above modelling requirements.

Works in the thesis

Part III works on the maintenance modelling for single component. Chapter 5 compares maintenance for lifetime distribution failure model and gradually deterioration failure model. Colour sets can model the observed component health data which represents the deterioration evolution. The CPN models for both failure descriptions are used to represent the same failure process, while different maintenance strategies are planned depending on the inspection data. Simulation results show that for the gradual deterioration model, inspection interval and preventive threshold are the maintenance decision variables which can be optimized to obtain the optimal maintenance cost; while for the lifetime model, preventive maintenance intervals are the maintenance variable. In addition, since the models can represents the inspection ability, thus the results can also indicates the more details we can collect from inspection, the lower cost the maintenance takes. Chapter 6 focuses on delay maintenance modelling based component condition. If the repair arrives in a delay time, the process is not Markov (Semi-Markov) anymore. Coloured Petri Net models are built to describe this deterioration process to investigate the effect of the delay on maintenance cost by the timed colour set representing the repair delays. Reset arcs are used to update the maintenance decision. Numerical results show that the floor of ratio of repair delay and the inspection interval has influence on the maintenance cost; a larger ratio may lead to higher maintenance cost since it may lead to more corrective maintenances.

In Part IV, we are interested in the maintenance modelling for a multi-component railway section where the inspection capacity may affect the maintenance decision or the delayed repair may lead to degraded operation on the running line. Chapter 8 assume that there are limitations of the inspection, which cannot detect the defective state under some

condition and hence a supplementary inspection is needed. Since accident scenarios are taken into account, the model can also evaluate the risk of the system. Chapter 9 considers the maintenance for a track section based on the collected health data. The deterioration of the component depends on the train speed and the number of passing trains, and the maintenance for defective trains arrive in a delay time. We built a CPN model to solve a maintenance optimization problem to determine the tuning of the speed restriction and the repair delay to maximize the system benefit (i.e. system profit minus maintenance costs) and minimize the system downtime. Since the preventive maintenance is carried out in a delay time, a grouping strategies for the delayed repairs are compared to the non-grouping strategy.

According to the models built in this thesis, CPN shows its modelling flexibility: with the transition and timed colour set, CPN can describe the behaviours of system by time, and it allows to model the details of health data using variables and colour sets. The priorities of the transition can model the events sequences. Furthermore, substitution transitions help us to build a hierarchical model which is more readable than Stochastic Petri Net.

Limitations of the models

In this thesis, we assume that the deterioration distribution and the maintenance gains are known, the parameters used in the simulation are not obtained from the real data. However, in practice, data analysis should be carried out before these maintenance modelling to estimate the modelling parameters.

The model will be large if we need to model a complex system. The CPN model for one component which is monitored by periodic inspections and maintained by two-level maintenance based on the observed condition in Chapter 6 consists of 14 places, 12 transitions and 44 arcs. The CPN for a series track section which consists of 5 track components in Chapter 9 consists of more than 180 places , more than 100 transitions and several hundreds of arcs. But in the real world, the number of the components in the railway network is far more than the quantity in this Petri Net model, the complex system structure and operation options undoubtedly will need more transition and places in the modelling.

The simulation process is long to get the probability of rare events. Using Petri Net or CPN, the probability estimation relies on Monte Carlo simulations. The simulation time depends on the length of the simulation cycles, the number of simulation cycles and the number of transition firing steps. The simulation time for one parameter configuration in this thesis varies from several minutes to dozens of minutes, so it may take several hours to several days for the simulations to optimize the maintenance decision variables.

The multi-component models in Chapters 7, 8 and 9 are more readable than the model based on Stochastic Petri Net, however, it is not an easy job to change the number of components, the number of machines involved in the section. For another section with a different number of component, the system level, section level and operation level CPN model need to be changed correspondingly.

Perspectives

The maintenance models proposed in this thesis are assumed for only one failure modes and a simple series system with a simple operation principle. However, some other aspects need to be taken into account in the maintenance modelling, such as multiple failure modes, the interaction between failures, a faster simulation or estimation method.

Combination of petri net and fault tree

Coloured Petri Net need a longer time for the performance evaluation but it can model the dynamic behaviours of the component. In contrast to Petri Net, fault tree is faster to calculate the top event probability using the logic gates but it is not powerful in modeling the dynamics behaviours. Therefore, it may be a good idea to combine these two methods for the risk assessments. Bobbio et al. propose a parametric fault tree with a high level petri net [22, 21] to model the partial repair and global repair. Moreover, repairable fault tree is a similar concept proposed for the repair grouping [161].

Multi-components with multiple states

Even though the substitution transitions help to divided system CPN model into different small modules, region modules and system modules could be different for two system consisting of different quantities of components. Wang et al. propose a kind of CPN model where the places represents the different states, tokens representing different components [202]. The CPN can be used to model the system consisting of different kinds of components involves in dynamic operation scheduling and different kinds of maintenance and inspection requirements.

Opportunistic maintenance modelling

For the multi-component system, besides preventive maintenance, opportunistic maintenance is another type of maintenance before failures. It is adopted in order to save the downtime due to the frequent maintenance. It will be interesting to optimize the threshold of opportunistic maintenance to minimize the downtime and the average maintenance cost.

Appendix A

Résumé en Français

Introduction

La SNCF (Société nationale des chemins de fer français) maintient et surveille 30000 km de voies en France tous les jours, et près de 15 500 trains circulent sur ce vaste réseau de transport, ce qui correspond à 126 900 000 passagers par an [50]. Selon les statistiques du site de la Banque Mondiale, Network Rail contrôle plus de 16000 km de longueur de la voie et réalise 2,75 millions de voyages de passagers chaque jour.

De l'importance de l'entretien de infrastructures ferroviaires

Les infrastructure ferroviaires jouent un rôle important dans la sécurité et le service ferroviaire. Les défaillances d'actifs ferroviaires peuvent provoquer une maintenance d'urgence, entraînant l'arrêt de la circulation : ces défaillances peuvent aussi dans le pire des cas conduire à des accidents.

Sur la période 1991-2001, environ 23,7 % des déraillements ont été causés par des défauts de la voie [143] et 10 % des déraillements se sont produits en raison à la fois de la voie défectueuse et l'état du véhicule et autour de 65 % des déraillements se produisant sur la ligne ont été dus à des défauts de la voie [105]. Par conséquent, il est important de mettre en place des procédures d'entretien et de maintenance pour de réduire les défaillances ferroviaires et pour garantir la sécurité et la disponibilité du réseau ferré.

La maintenance des actifs et infrastructures ferroviaires contribue par une forte proportion aux dépenses totales des compagnies ferroviaires. Le coût de l'entretien ferroviaire aux Pays-Bas a dépassé €250 millions d'euros en 2006 [54]. Dans le rapport financier de la SNCF, €746 millions sont dépensés pour les mises à niveau des gares et des bâtiments y compris le renouvellement de la voie, le remplacement du système de communication et ainsi de suite [175] . Network Rail a dépensé £391, 8 millions de pounds pour l'entretien de la voie au cours de 2013 à 2014 [121].

Afin d'assurer la sécurité et en même temps réaliser un entretien économique, des stratégies de maintenance sont étudiées pour améliorer la décision de l'entretien et pour planifier une stratégie de maintenance pour le système "réseau ferré" tout en respectant les contraintes de sécurité.

Dans l'avenir, le contexte de l'exploitation ferroviaire va devenir de plus en plus contraint: la vitesse augmente, le trafic est accru, donc la détérioration s'accélère et, de plus, le temps disponible pour les opérations de maintenance se réduit.

Motivation et objectifs

La maintenance préventive est importante pour prévenir les accidents de chemin de fer et par conséquent pour assurer la sécurité des passagers et des équipages de travail. Comme la maintenance peut perturber le fonctionnement normal des chemins de fer et coûter une grosse somme d'argent, les sociétés gestionnaires des infrastructure ferroviaires essaient de sauver le coût d'entretien et d'améliorer la disponibilité sans affecter la sécurité.

Comme la tâche de modélisation de la détérioration, de l'inspection et de l'entretien s'avère très complexe, en particulier pour un système multi-composant, il n'est souvent pas possible d'avoir une solution analytique pour la prise de décision. Nous nous sommes donc intéressé au développement d'un outil d'aide à la prise de décision de maintenance basé sur la simulation ; avec cet outil, nous pouvons ainsi prendre en compte la détérioration, la maintenance et l'exploitation pour un système complexe plus facilement.

Le principal objectif de cette thèse est de contribuer au développement d'outils de modélisation et de simulation pour l'évaluation des performances des stratégies de maintenance pour le système de chemin de fer et d'estimer la probabilité d'événement dangereux.

La thèse vise à étudier les problèmes suivants dans la modélisation de la maintenance des infrastructures ferroviaires :

1. comment comparer des politiques de maintenance pour différents niveau d'information surveillance ?

2. comment quantifier l'effet de délais de maintenance, sachant pendant le temps d'attente de maintenance, les composants sont toujours utilisés et donc continuent de se dégrader ?

3. comment établir conjointement une stratégie de maintenance et un plan d'utilisation opérationnelle d'une infrastructure lorsque le mode d'utilisation d'un composant affecte sa détérioration ?

Capacité d'inspection Plusieurs politiques d'entretien peuvent être planifiées pour un même composant en fonction des données d'inspection disponibles. Dans certains cas, l'inspection de routine peut présenter des limitations pour l'identification des défauts, et il s'avère nécessaire de programmer des inspections supplémentaires pour pouvoir prendre en connaissance de cause une décision de maintenance qui assurer un coût d'entretien et une sécurité optimales.

Délais de maintenance Il existe souvent une longue attente et de la procédure de négociation pour le maintien des actifs dans le système de chemin de fer. En outre, en raison du trajet jusqu'au point de maintenance et du nombre limité de machines de réparation, nous ne pouvons pas mettre en oeuvre l'entretien immédiatement une fois que nous détectons les défaillances ou les défauts.

Maintenance vs mode d'utilisation La configuration de fonctionnement et d'utilisation du réseau affectent les charges sur les voies. Si on met en oeuvre une limitation de vitesse

comme une sorte de fonctionnement dégradé pour une section, la vitesse inférieure et moins de passages de trains ralentissent la détérioration. Mais, d'autre part, la restriction peut réduire le bénéfice, il est donc intéressant de trouver compromis entre restriction de vitesse et délai de réparation.

Structure de la thèse

Les travaux sont organisés en cinq parties: introduction générale et motivation des travaux dans la première partie, l'état de l'art et les descriptions du système dans la deuxième partie, les modèles au niveau "composant" dans la troisième partie et les modèles au niveau "système" dans la quatrième partie.

La partie II est constituée de trois petits chapitres pour introduire le contexte de la recherche et les outils utilisés dans cette thèse:

- Le Chapitre 2 présente un exemple type d'une section de voie ferrée, un système de voies ballastées, les défaillances de la voie et les méthodes d'entretien correspondants.
- Le Chapitre 3 donne un bref aperçu de la littérature sur les modèles de défaillance, les politiques d'inspection et de maintenance sur les infrastructures ferroviaires.
- Le Chapitre 4 introduit les outils mathématiques utilisés dans cette thèse. En particulier, nous présentons le concept et les règles de modélisation de réseaux de Petri coloré (CPN). Un exemple de CPN est donnée pour montrer la capacité du réseau de Petri coloré.

La Partie III présente les modèles de coût/performances au niveau "composant":

- Le Chapitre 5 compare des politiques de maintenance mettant en jeu différents niveaux d'information de surveillance.
- Le Chapitre 6 étudie les effets des délais de maintenance pour les politiques d'inspection périodiques et différentes politiques d'inspection conditionnelle sont comparées.

Le réseau de chemin de fer est un système multi-composant, il ne suffit pas d'envisager la modélisation de la maintenance pour un seul composant. Donc, la Partie IV décrit le modèle de maintenance pour un réseau de chemin de fer:

- Le Chapitre 7 présente un modèle de maintenance pour un réseau ferroviaire compte tenu de la limitation de ressource de maintenance.
- Le Chapitre 8 propose un modèle de performance de maintenance mettant en jeu différents types d'inspections complémentaires.
- Le Chapitre 9 vise à définir un réglage optimal de vitesse limite et de délai d'intervention, l'évolution de détérioration de composant dépend du mode d'utilisation.

Partie V donne une conclusion générale pour cette thèse.

Le contexte et les outils de modélisation

Le Chapitre 1 vise à présenter l'importance de l'entretien de infrastructures ferroviaires et la motivation de cette thèse. Afin de modéliser le maintenance du système, la description du système et des outils de modélisation sont introduits.

La voie

L'état des infrastructures contribuent à la sécurité ferroviaire et d'entretien. Chaque année, l'industrie ferroviaire dépense des sommes importantes à l'entretien de la voie pour diminuer le nombre d'accidents.

La voie ferroviaire est l'infrastructure qui soutient les trains ; il faut maintenir l'écartement, dévers, niveau longitudinal et l'alignement des rails dans les limites pour assurer que les trains puissent passer en toute sécurité. L'écartement, les dévers, le niveau longitudinal et l'alignement sont les paramètres critiques de la voie. Les voie peuvent être classées en trois types: ballastées, slabbed et intégré[45]. On s'intéresse dans cette thèse uniquement aux voies ballastées. Une voie ballastée se compose du rail, des attaches de rails, des traverses et des ballasts, comme représenté dans la Figure A.1.

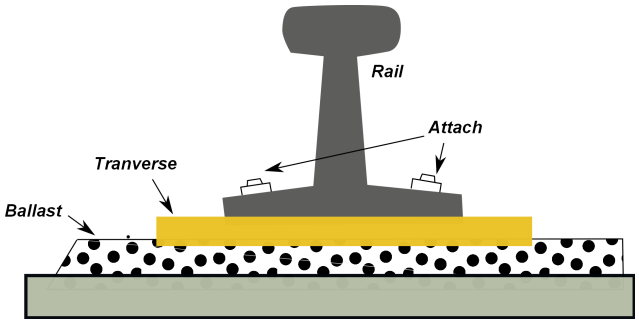


Figure A.1: Structure de la voie

Le ballast est utilisé pour résister aux forces appliquées aux traverses pour maintenir la position de la voie; il souffre de stress causé par les trains, cette force verticale provoquera l'écrasement et l'abrasion du ballast. Une traverse fournit un soutien vertical et latéral au rail et aux attaches de rail [64]. Dans cette thèse, les traverses sont en bois. Le rail est fixé sur les traverses par des attaches, qui sont utilisés pour empêcher la rotation et le mouvement du rail. Les rails supportent et guident les trains. Ils sont directement en contact avec les roues ; la forme de la tête de rail et la surface du rail sont donc importantes. Les rails sont assemblés par des joints de rail.

Défauts géométriques et maintenances de la voie

Suivant la présentation de la voie donnée dans la section précédente, la dégradation de trois dispositifs principaux (les traverses, le ballast et les rails) peut provoquer des défaillances du système de la voie. Les défaillances dangereuses de la voie comprennent les défauts

de géométrie de la voie et des défauts de rails, qui peuvent causer des déraillements. Les défauts de géométrie comprennent le sur-écartement, le nivellement longitudinal, le nivellement transversal et le dressage. Les méthodes d'entretien correspondantes et leurs effets devraient être pris en considération lorsque des décisions de maintenance sont effectués.

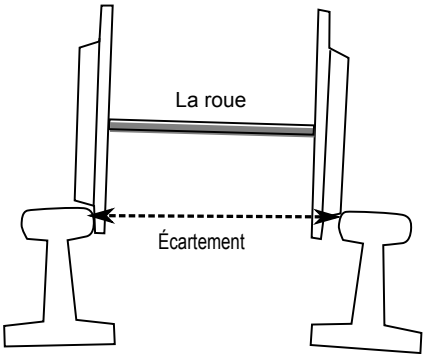


Figure A.2: Sur-écartement des rails

Sur-écartement des rails La Figure A.2 illustre l'écartement des rails qui est définie comme la distance entre les surfaces des rails. Deux types d'écartements sont définis en fonction de la charge de la voie. La voie mesurée avec la charge est définie comme étant un écartement dynamique de la voie, tandis que la voie mesurée sans la charge est un écartement statique de la voie.

Un sur-écartement des rails est défini comme la tendance de l'indicateur de la voie mal entretenus à devenir plus grand. Selon la définition de l'écartement des rails, les sur-écartements sont classés comme les sur-écartements statiques et les sur-écartements dynamiques.

Selon British Railway Engineering Encyclopédie de Ellis, un sur-écartement peut être causé par un système d'attache défectueux et par le mauvais état des traverses [53]. Si des attaches défectueuse sont détectées et réparées, le sur-écartement n'arrive pas; par ailleurs, les différentes façons de maintenir le sur-écartement doivent être effectués en fonction du niveau d'écartement. Dans la pratique, nous pouvons effectuer l'entretien suivant pour contrôler le sur-écartement: la pose d'un barre d'écartement (en Anglais: tie-bar), le remplacement de traverse (en Anglais: re-sleepering) et le renouvellement de la voie.

Le niveau 1 de sur-écartement est défini dans la gamme de 1435 à 1465 mm; pour ce sur-écartement, le défaut peut être contrôlé par une limitation de vitesse ou des mesures de contrôle, y compris la pose d'un barre d'écartement et le remplacement de traverse. Si l'écartement dynamique dépasse 1465 mm, une limitation de la vitesse et les contrôles doivent être effectués dans le même temps. Si l'écartement est chargée sur 1480 mm, la ligne devrait être fermée et la voie devrait être renouvelée.

Nivellement longitudinal et nivellement transversal Le nivellement longitudinal et Le nivellement transversal sont les problèmes du dévers de la voie qui sont causés par les problèmes de ballast. Le nivellement longitudinal est l'un des problèmes de géométrie illustré

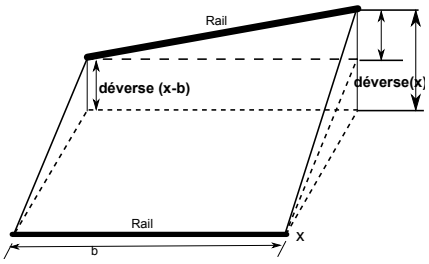


Figure A.3: Nivellement transversal

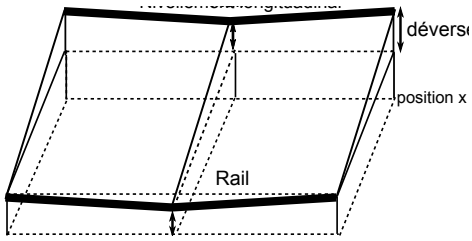


Figure A.4: Nivellement longitudinal

dans la Figure A.4 ; il apparaît comme un trou sur la voie. La définition du nivellement transversal est donnée comme une différence de nivellement transversal sur une courte distance (3 mètres) qui dépasse une quantité prédéterminée. Dans la Figure A.3, les lignes noires en gras représentent les rails, et le nivellement transversal peut être calculé comme dévers(x)-dévers(x-b) [54], où le “dévers" est la différence de niveau de rail.

Les défauts de nivellement transversal et de nivellement longitudinal peuvent être causés par le mauvais état du ballast incontrôlé. Le bourrage peut être effectuée pour contrôler ces défauts de nivellement de la voie. Par exemple, si le nivellement transversal est compris entre 1/126 et 1/199, la maintenance doit être effectuée sous 10 jours; et entre 1 / 91 et 1 / 125, la voie doit être maintenue sous 36 heures. Pour des situations pires, la fermeture de la ligne immédiate est nécessaire.

Les défauts verticaux de la voie peuvent être réparés par plusieurs méthodes d’entretien, tels que bourrage, relevage et le renouvellement. Le bourrage est une méthode d’entretien de ballast commune, la machine soulève tout d’abord la voie au niveau déterminé, puis il presse le ballast sous la traverse. Le bourrage peut niveler et aligner la voie à la position déterminée par la machine mesurée. Le relevage est une autre méthode d’entretien de ballast : le procédé de soufflage de pierre soulève tout d’abord le dormant (traverse) pour créer un vide, puis un injecte des pierres de taille adaptée dans le vide, puis le dormant est abaissé sur les pierres ajoutées.

Parce que la mécanique de l’outil de bourrage peut endommager le ballast, l’opération de bourrage fait de nouveaux points de contact entre les traverses et les pierres, qui peuvent briser à leur tour sous l’effet charges de trafic. Comparés aux dégât du bourrage, les dégâts sur le ballast dus au relevage sont négligeables. Ainsi, la nécessité pour le nettoyage et le remplacement de ballast est reporté. Cette incidence est amplifiée par le fait que le bourrage doit être réalisé plus fréquemment que le relevage. En outre, comme le relevage par injection de pierre utilise un matériau conforme pour le réglage de la géométrie, la correction de géométrie dure plus longtemps qu’avec le bourrage. Cependant, le relevage ne peut pas soulever la traverse en bois de façon adéquate et il ne peut pas être utilisé pour les branchements [44].

Inspections de la voie

Pour l’inspection de la géométrie de la voie on distingue l’inspection de la voie chargée et l’inspection de la voie non-chargée. Un véhicule lourd de contrôle de l’état géométrique

doit avoir une charge verticale et pouvoir mesurer des mesures dynamiques de la géométrie et l'inspection visuelle sont adoptées lorsque nous avons besoin des mesures statiques de la géométrie de la voie [124].

Une voiture de mesure peut détecter un défaut de géométrie de la voie ou une rupture de rail, mais il est difficile de détecter les petites fissures ferroviaires ; l'inspection par ultrasons peut être utilisé pour détecter les minuscules fissures des rails [144].

Dans la norme ferroviaire, les intervalles de contrôle sont donnés afin de maintenir la sécurité. Par exemple, l'inspection par ultrasons teste le rail sur la ligne simple à des intervalles de base; le rail sur un aiguillage doit être testé à des intervalles plus courts.

Réseaux de Petri colorés

Nous travaillons sur la modélisation de l'entretien des actifs ferroviaires. Selon les recherches existantes, les processus de Markov constituent l'une des méthodes qui prennent en compte différents états pour la modélisation. Toutefois, les problèmes que nous voulons étudier peuvent ne pas être adaptés à l'utilisation de chaînes de Markov ou semi-Markov processus: ainsi par exemple, l'un des problèmes que nous voulons étudier est l'effet de la maintenance préventive retardée, qui n'est pas modélisable par un processus de Markov. En outre, dans la modélisation du système de chemin de fer, des scénarios d'accidents ou le fonctionnement du système -pas nécessairement markoviens- doivent être pris en considération.

Nous choisissons donc de développer nos modèles avec des Réseaux de Petri colorés. D'une part, ils peuvent modéliser des comportements qui ne sont pas de Markov; d'autre part, les ensembles colorés et la représentation de temps font des CPN des outils de modélisation plus souples.

Un réseau de Petri coloré (CPN) est défini comme représenté dans l'Equation A.1 [87].

$$CPN_t = (P, T, A, \Sigma, V, C, G, E, I) \tag{A.1}$$

CPN_t est CPN avec temps, P est l'ensemble de "places", T est l'ensemble de transitions, A l'ensemble de arcs, Σ est l'ensemble de couleurs, V est l'ensemble de variables. G est l'ensemble de fonctions, I est le marquage initial , C est l'ensemble de fonctions d'ensembles colorés et E est l'ensemble de fonctions d'arcs.

Nous utilisons l'outil de CPN pour la modélisation. Cet outil dispose d'une interface graphique qui est développé en Java, le langage de modélisation est langage de programmation standard ML (SML). Il permet aux utilisateurs de définir différentes fonctions de modélisation pour les transitions et moniteurs concernant les exigences en matière de modélisation. L'outil de CPN a l'ensemble coloré, inscription à l'arc, inhiber l'arc et arc initial. En outre, il peut construire des modèles hiérarchiques avec les ports et les transitions de substitution.

Comparaison des modèles de défaillance pour l'optimisation de la maintenance

Les décisions d'entretien de la voie de chemin de fer sont prises en fonction de l'état de la voie. Comme les défauts de voie ne sont pas auto-décelables, des inspections sont effectuées régulièrement pour recueillir les mesures d'état de la voie afin de surveiller la qualité de la voie. En ce qui concerne les techniques d'inspection, il faut parfois différents types de données d'état. Un type de données indique simplement les états de santé binaires de la voie - fonctionnel ou en panne. Avec le développement des dispositifs d'inspection, nous pouvons recueillir des données précises sur l'état, contenant plus de détails sur la qualité de la voie, par exemple, nous pouvons utiliser la déviation standard pour un certain nombre de données sur l'état de la voie pour caractériser l'état de santé de la voie sur une certaine longueur. Sur la base de ces deux types différents de données d'inspection, deux modèles de défaillance sont adoptés pour décrire l'évolution de la détérioration des voies, puis plusieurs politiques d'entretien sont prévues pour maintenir la qualité de la voie. Nous voulons accéder aux impacts de ces deux modèles de défaillance.

Hypothèses concernant les modèles d'information à deux niveaux

Modélisation de la fiabilité basée sur la détérioration graduelle

Une défaillance se produit si $X_t \geq \delta_{DL}$; alors, une maintenance corrective est mise en oeuvre. Afin de réduire les défaillances, des inspections périodiques sont effectuées pour la maintenance préventive. Les détails sur les hypothèses sont répertoriés comme suit:

1. Les inspections sont menées périodiquement avec un intervalle θ_{Insp}. i est l'indice de l'inspection; I_i signifie l'i ème inspection, et X_i représente les états observés par l'i ème inspection.

2. Il y a deux seuils pour la maintenance:

   - Si $X_i \geq \delta_{DL}$, une maintenance corrective est effectuée immédiatement. Il peut restaurer la voie à une condition X_{cm}, ce qui signifie que l'état après la maintenance corrective est comme neuf.
   - Si $X_i \geq \delta_{II}$, une maintenance préventive est mise en oeuvre.
   - La maintenance préventive est imparfaite. La maintenance préventive peut ramener le composant à l'état de $X_h > 0.0$, ce qui signifie que l'état après l'entretien préventif n'est pas aussi bon que neuf.

3. Il n'existe pas de délais pour les deux niveaux de maintenance. La maintenance corrective (resp. préventive) nécessite d'immobilier le système pour un temps d'arrêt DT_{cm} (resp. DT_h).

Le seuil de la maintenance préventive δ_{II} et l'intervalle d'inspection θ_{Insp} sont les variables de décision de maintenance, à régler pour optimiser le coût de maintenance.

Modélisation de type "durée de vie"

Si on ne considère que les états binaires du composant maintenu -fonctionnel ou en panne, le modèle de distribution de la durée de vie est utilisée pour modéliser son état de santé. La durée de vie du composant est notée $T_{\delta_{DL}}$, qui représente l'instant où la condition du composant dépasse le seuil de défaillance δ_{DL}. La probabilité de défaillance du composant sur $(0, t]$ est défini comme $F_{T_{\delta_{DL}}}(t) = Pr(t \geq T_{\delta_{DL}})$.

Parce que le modèle de loi de durée de vie et le modèle de fiabilité basé sur la détérioration sont utilisés pour représenter le même processus de détérioration physique 'ie la même "réalité terrain"), pour la même condition de défaillance δ_{DL}, la répartition de la durée de vie est calculée par l'équation A.2 [182]:

$$F_{T_{\delta_{DL}}}(t) = Pr(t \geq T_{\delta_{DL}}) = \frac{\Upsilon(\alpha t, \beta\delta_{DL})}{\Gamma(\alpha t)} \tag{A.2}$$

La politique de maintenance périodique pour le modèle de loi de durée de vie propose une politique de maintenance à deux niveaux pour le composant de voie :

Comme la défaillance n'est pas auto-décelable, une inspection est nécessaire pour détecter la défaillance d'un composant. Les détails de la politique d'entretien périodique pour le modèle de durée de vie sont présentés comme suit:

1. L'inspection est effectuée périodiquement à l'intervalle θ_{insp}.
2. Deux niveaux de maintenance sont programmés pour le composant:
   - Un entretien préventif est prévue pour le composant, il est mis en oeuvre périodiquement, avec l'intervalle noté θ_T. L'intervalle θ_T est une constante indépendante de l'histoire de la défaillance d'un composant.
   - La maintenance préventive est imparfaite ; après la n ème maintenance préventive, l'âge virtuel du composant est fixé à V_n. Nous supposons que l'âge virtuel est égal à une valeur constante, $V_n = y, n = 1, 2, \ldots$.
   - La distribution de la durée de vie après la n e la maintenance préventive est obtenu selon l'âge réel X_n[95]:

$$F_n(t) = F_2(t) = Pr(X_n \leq x | V_{n-1} = y) = \frac{(F(t + y) - F(y))}{1 - F(y)} \tag{A.3}$$

   - Si la i ème inspection identifie la défaillance d'un composant, une maintenance corrective est effectuée.
   - La maintenance corrective est parfaite. Après la maintenance corrective, l'âge virtuel du composant est$V_m = 0.m$ est l'indice de la maintenance corrective.

Comparaison de résultats des modèles

Deux modèles de réseaux de Petri coloré sont construits pour la comparaison. Un premier modèle décrit le processus de défaillance comme une évolution de la détérioration graduelle, et un autre considère "seulement" le temps de défaillance. Parce que la maintenance

préventive est imparfaite par hypothèse, nous supposons un âge virtuel pour le modèle de durée de vie qui conduit à sous-estimer le risque de défaillance par rapport au modèle de dégradation stochastique.

En comparant les politiques de maintenance pour ces deux types des modèles, les résultats montrent que l'inspection précise peut avoir mener à de meilleurs résultats pour le coût d'entretien et de la disponibilité des composants, parce que l'inspection précise permet de mieux planifier la maintenance préventive non périodique.

Délais de maintenance pour un composant de la voie ferrée

La voie ferrée transporte des milliers de trains et de passagers tous les jours. Des machines d'entretien sont affectées à plusieurs dépôts : elles ne sont pas immédiatement disponibles sur le lieu où doit se faire la maintenance et elles ont besoin de se rendre à l'emplacement des actifs défectueux ; par ailleurs, les machines de maintenance et les équipages ne sont pas toujours disponibles pour l'entretien. Lorsqu'une dégradation d'actif est identifié, si elle est pas critique et ne dépasse pas le seuil extrême, la section de voie est maintenue ouverte pour permettre aux trains de circuler.

Par conséquent, l'entretien préventif pour un élément de voie ne peut pas être effectuée immédiatement après la détection d'un défauts.. Pendant le temps d'attente pour les réparations préventives, la section de chemin de fer permet encore le trafic et souffre du même processus de détérioration qui résulte peut-être dans la dégradation de l'actif à un état critique qui conduit à une maintenance corrective, même à un accident.

Nous voulons évaluer l'effet de délai de maintenance pour voir si il est nécessaire de prendre ce délai en considération dans la procédure de décision pour mettre en oeuvre une meilleure stratégie de maintenance pour l'infrastructure ferroviaire. Un modèle de maintenance est nécessaire pour résoudre le problème. Dans la mesure où l'état du système ne dépend pas seulement du dernier état observé mais aussi des états précédents selon la longueur des retards, le processus de détérioration n'est pas une chaîne de Markov. Au lieu de construire une chaîne de Markov comme introduit dans[114], nous proposons un modèle basé sur les réseaux de Petri colorés pour estimer le coût moyen d'entretien sur un horizon infini.

Hypothèses sur la maintenance avec retard pour un composant

Les politiques de maintenance avec retard proposées dans ce travail considèrent un composant unique. On suppose que la défaillance résulte d'un défaut de géométrie verticale. La bourrage est supposé être la méthode de la maintenance préventive et la relevage est la maintenance corrective. L'information sur l'état de la voie est mesurée par un train de surveillance automatique.

Les hypothèses de modélisation retenues dans ce travail sont les suivantes:

- Le composant est supposé être un élément de voie de de 1 km de long.
- Le composant se détériore suivant à un processus Gamma, X_τ est l'état du composant au moment τ et $X_{\Delta\tau}$ représente l'augmentation de la détérioration sur $\Delta\tau$, $X_{\Delta\tau} \sim$

$\Gamma(\alpha\Delta\tau, \beta)$.

- Les états de composant sont mesurés par l'inspection, qui est agencé pour être soit périodique, soit basé sur l'état. Nous comparons ces deux régimes de contrôle différents:
  - **Inspection périodique**: l'inspection est effectuée périodiquement, et l'intervalle est égal à θ_{insp}.
  - **Inspection conditionnelle**: Après la $i$ème inspection, l'intervalle θ_{i+1} jusqu'à $(i+1)$ème inspection est basé sur l'état observé du composant X_i qui est inspecté par la $i$ème inspection. θ_{i+1} est décidé par le seuil préventif δ_{II} comme indiqué dans l'équation A.4:

$$\theta_{i+1} = \begin{cases} \theta_{max} - \dfrac{X_i(\theta_{max} - \theta_{min})}{\delta_{\text{II}}}, & X_i \in (0, \delta_{\text{II}}) \\ \theta_{min}, & X_i \in [\delta_{\text{II}}, \infty) \end{cases} \tag{A.4}$$

    Si l'état dépasse le seuil préventive, qui est $X_i \leq \delta_{\text{II}}$, l'intervalle d'inspection est égale à l'intervalle d'inspection minimum,i.e. $\theta_{insp} = \theta_{min}$; sinon l'$(i+1)$ème inspection est $\theta_{i+1} \in (\theta_{min}, \theta_{max}]$.
  - Pour l'inspection périodique, il y a deux variables de décision à optimiser: θ_{insp} and δ_{II}.
  - Pour l'inspection conditionnelle, θ_{min} and δ_{II} sont les deux variables de décision à considérer.
- Deux types de maintenance sont envisageables, relativement à deux seuils de maintenance: un seuil d'intervention majeur δ_{DL} et un seuil de maintenance préventive δ_{II}.
  - Si $X_i \geq \delta_{\text{DL}}$, un entretien majeur est réalisé dans un délai t_D. δ_{DL} est donné par les règles de maintenance.
  - Si $\delta_{II} \geq X_i \geq \delta_{\text{II}}$, une intervention préventive est réalisée dans un délai t_d.
  - Les deux interventions sont imparfaites. Un modèle de régression linéaire est adopté pour les gains de réparation, qui est $G = c + mX + \varepsilon, \varepsilon \sim N(0, \sigma)$, X est l'état du composant lorsque la réparation est effectuée.
- Les délais de réparation t_d et t_D ne sont pas des variables de décision, ils sont fixés par les règles ou pratiques d'entretien sur le terrain, ou par les experts métiers. Lors d'une inspection, en fonction de la donnée t_d et t_D, il y a différents scénarios d'entretien possibles:
  - Si $t_d \leq \theta_{insp}$ **ou** $t_d \leq \theta_{min}$: si l'état observé dépasse δ_{II}, un entretien préventif est disposé dans un temps de retard t_d. Le type d'entretien ne sont pas mis à jour, même si l'état de la piste dépasseδ_{DL} pendent t_d.
  - Si $t_d \geq \theta_{\textbf{insp}}$ **or** $t_d \geq \theta_{min}$:

- ◇ Si les états observés ne dépassent jamais δ_{DL}, l'inspection ne change pas la décision de la maintenance préventive.
- ◇ Les inspections détectent des états $x \geq \delta_{\mathrm{DL}}$: le type d'entretien est alors mis à jour.

Comparaison de politiques d'inspection

Les politiques d'inspection périodique et les politiques d'inspection conditionnelle sont comparées sur la base de résultats de simulation pour $r = 0$, $r = 1$ et $r = 2$. Une inspection périodique et les politiques d'inspection conditionnelle (CBI) sont comparées en envisageant différents intervalles θ, ratios r et seuils préventifs δ_{II}.

Si $r = 1$, le coût minimum pour l'inspection périodique est 48,58 tandis que le coût pour la CBI est 38.15; le coût pour les deux régimes d'inspection quand $r = 2$ est plus élevé que pour $r = 0$ et $r = 1$, donc le maintien d'un petit r plus performant.

Pour voir la relation entre les intervalles d'inspection et le coût de la maintenance, les résultats montrent que le coût d'entretien contre intervalle d'inspection étant donné que $r = 0$, il montre les résultats de $\delta_{\mathrm{II}} = 0,95$ et $\delta_{\mathrm{II}} = 1,0$ pour les deux systèmes d'inspection.

Les configurations de maintenance optimisés dans les politiques d'inspection périodiques et d'inspection conditionnelle sont étudiés, soit pour l'inspection périodique, $\theta_{inspecteur} = 30$, $\delta_{II} = 0,95$ et pour CBI, $\theta_{min} = 30$, $\delta_{II} = 1.0$.

Le temps entre les deux PMs de la politique d'inspection périodique et politique d'inspection basée sur l'état sont comparées. Le pdf de la CMs et PMs pour les configurations de maintenance optimisés indiquent que la politique d'inspection périodique présente plus de CMs pendant le temps de simulation.

Modèle de maintenance avec deux niveaux d'inspection pour une Ligne

On considère dans cette section qu'il existe deux types de défaillances pour le composant réparable, l'un d'eux est auto-décelable, l'autre non. Les défauts de voie n'étant pas auto-décelable, nous devons effectuer les inspections pour nous assurer que le composant est assez bon pour le passage du train. L'entretien et le contrôle de la circulation correspondant sont prévus selon les résultats de l'inspection afin d'éviter tout incident ou accident.

La capacité d'inspection influe sur la planification de la maintenance et a donc naturellement un effet sur le coût de l'entretien, l'indisponibilité du système et ainsi de suite. Afin de décrire la capacité d'inspection dans le processus global de défaillance/maintenance, Christer et al proposent de concept de " delay time " [41]; Wang propose un modèle d'inspection pour un composant qui souffre de deux sortes de défauts et deux méthodes d'inspection sont mis à la deux défauts séparément [195] . Un autre modèle similaire " PF "processus est introduite par Podofillini et.al qui proposent un modèle de Markov pour les défauts de rail en supposant qu'il y a deux niveaux d'inspection pour le processus d'échec [144] .

Un sur-écartement (type de défaut de voie déjà évoqué plus haut) peut être classé en deux catégories : le sur-écartement statique et le sur-écartement dynamique. Deux types de mesures de contrôle différents sont établis pour ces deux catégories différentes. Nous supposons que l'inspection visuelle peut inspecter la voie et d'identifier l'écartement statique et la voiture de mesure peut identifier le sur-écartement dynamique. Nous voulons proposer un modèle CPN de l'inspection à deux niveaux pour étudier plus finement la planification des inspections de différentes nature et capacité.

Hypothèses de maintenance pour deux niveaux de inspection

Le modèle CPN peut être utilisé pour évaluer les politiques d'inspection différentes des deux programmes d'inspection. Quatre politiques d'inspection sont supposés:

- Politique 1: inspections périodiques à deux niveaux ; inspection visuelle avec intervalle $\theta_{vi} = 40$ unités et voiture de mesure passée à intervalle variable;
- Politique 2: l'inspection visuelle intervalle $\theta_{vi} = 40$ unités tandis que l'intervalle de la voiture de mesure dépend du nombre de défauts.
- Politique 3: inspections périodiques à deux niveaux ; inspection visuelle avec intervalle $\theta_{vi} = 50$ unités et voiture de mesure passée à intervalle variable;;
- Politique 4: l'intervalle pour l'inspection visuelle est $\theta_{vi} = 50$ unités tandis que l'intervalle de la voiture de mesure dépend du nombre de défauts.

Pour ces politiques d'inspection, l'intervalle de voiture de mesure prévue varie de 5 à 2000 unités. Les paramètres de la maintenance sont supposées être: $\tau_{f2} = 15$, $\mu_{f2} = 1$,$\tau_{f3} = 10$, $\mu_{f3} = 4$, $\tau_{f4} = 5$, $\mu_{f4} = 4$, $\tau_{f5} = 2$, $\mu_{f5} = 10$, $\tau_{f6} = 0$, $\mu_A = 70$.

Les résultats de modèles de deux niveaux inspection

Dans cette étude, nous considérons les performances du système à court terme. L'indice de performance du système 'disponibilité de la ligne programmée A_{sch}', 'disponibilité en ligne A_{uns}', ' le coût Prévu de Ligne C_{sch}', 'le coût total C_{uns}' et 'Le nombre de places disponibles $N_{derailment}$' sont utilisés pour comparer ces quatre politiques d'inspection.

$N_{derailment}$ est compté en surveillant la transition D dans le modèle d'accident. La disponibilité prévue A_{sch} et de la disponibilité de la ligne A_{uns} sont obtenues par la surveillance de la transition T_D and T_i_E selon l'équation A.5 et A.6. $T_{available}$ est la ligne du temps disponible, T_{total} est la durée totale, DT_{uns} est le temps d'arrêt non programmé.

$$A_{sch} = \frac{T_{available}}{T_{total} - DT_{uns}} \tag{A.5}$$

$$A_{uns} = \frac{T_{available}}{T_{total}} \tag{A.6}$$

C_{sch} and C_{uns} sont calculés par l'équation A.7 et A.8. C_M est le coût de la maintenance, C_{trv} est le coût de voiture de mesure (TRV), C_{vi} est le coût d'inspection visuelle et $C_{Accident}$

est le coût d' accident. Le nombre de voiture de mesure N_{trv}, le nombre des inspections visuelles N_{vi} sont comptées par la transition $INSP_TRV$ et $INSP_INT$. Le nombre de maintenances N_M est compté par la transition Tmms(refastening), TMms (la pose d'un barre d'écartement," tie-bar" en Anglais) and TMMs (le replacement de traverse) dans le modèle de CPN.

$$C_{sch} = C_M N_M + C_{trv} N_{trv} + C_{vi} N_{vi} \tag{A.7}$$

$$C_{uns} = C_{sch} + C_{Accident} N_{derailment} \tag{A.8}$$

Selon les résultats du nombre de déraillements normalisé par l'intervalle de TRV par an, la fréquence du déraillement augmente lorsque l'intervalle d'inspection visuelle ou de la voiture de mesure augmente. Si l'intervalle de voiture de mesure augmente, la disponibilité prévue augmente ; cependant, la disponibilité globale de la ligne diminue si l'intervalle TRV augmente.

En ce qui concerne le coût prévu et le coût imprévu, toutes les politiques d'inspection montrent l'existence coût total minimum. Pour la politique 1 et la politique 3, le coût de maintenance minimum peut être obtenu pour un intervalle de voiture de mesure de 65 unités. Pour les politiques 2 et 4, le coût total minimum peut être obtenu si l'intervalle de voiture de mesure est de 125 unités.

En ce qui concerne les déraillements, si l'intervalle de voiture de mesure varie de 0 à 300 heures , les politiques 2 et 4 présentent moins de déraillements et un intervalle d'inspection visuelle plus courte peut conduire à une diminution du nombre de déraillements. Si l'intervalle de voiture de mesure se situe entre 300 et 700 heures, les politiques 1 et 2 sont meilleures que les politiques 3 et 4, la politique 2 a un nombre de déraillements inférieur à celui de la politique 1. Si l'intervalle de voiture de mesure dépasse 700 heures, la politique 1 est meilleure que la politique 2.

Modèle de maintenance pour une section de voie avec limitation de vitesse

Les défauts de géométrie verticale de la voie dus à un mauvais état de ballast peuvent être réglés par des opérations de bourrage ou de relevage. Différents travaux de recherche ont étudié l'évolution de la dégradation de la voie et ils soulignent que la qualité de la voie dépend de certains facteurs tels que la vitesse, le tonnage (MGT),l'historique de l'entretien et des matériaux [11, 166, 203, 221].

La vitesse de train joue un rôle important dans la maintenance et l'exploitation ferroviaire. Zio et al [219] discutent de la flexibilité des limitations de vitesse afin de réduire les retards de train sur l'ensemble du réseau parce que la limitation de vitesse peut augmenter la sécurité des chemins de fer, mais peut aussi causer des retards.

Les limitations de vitesse ont des effets non seulement sur la sécurité et les temps de trajet, mais aussi sur les coûts de maintenance et sur les gains d'exploitation. En effet, une diminution de vitesse ralentit l'évolution de la détérioration qui permet l'entretien différé et réduit le nombre de maintenances. Cependant, les limitations de vitesse réduisent également les flux de voyageurs et de marchandises, et ainsi les gains. On se retrouve donc

face à un compromis que certains travaux on déjà abordé dans le cadre de recherche sur la politique de maintenance basée sur l'âge en fonction de la vitesse de production dans l'industrie de la production [204][180].

La limitation de la vitesse conduit à un processus de dégradation plus lente et à un temps résiduel avant défaillances plus long qui permet un temps plus long avant réparation. La possibilité d'un délai de réparation plus long permet de mieux organiser la maintenance à un coût de maintenance préventive réduite. Dans le même temps, le système avec la limitation de vitesse laisse passer moins trains, conduisant à la perte de débit de système d'où à un gain moindre du système. D'autre part, le retard de réparation plus longue donne plus de possibilités pour grouper les activités de maintenance et d'économiser ainsi le coût de mise en place et le temps d'arrêt en raison des réparations.

Ainsi, nous travaillons sur un problème d'optimisation de la maintenance, afin de parvenir à un compromis entre limitation de vitesse et le retard d'entretien préventif afin de maximiser les avantages du système et de réduire le temps d'indisponibilité du système pour une section de la ligne ferroviaire plaine, dans laquelle la détérioration de la voie dépend de la la vitesse et le nombre de trains qui passent.

Hypothèses de système

Nous considérons une section "série" composée de 5 composants de la voie sur une ligne simple. La détérioration de l'ensemble des composants est indépendante, et suit le même processus de dégradation. La vitesse des trains sur chaque composant sont également indépendantes, tandis que la densité des trains dépend de la valeur minimale de densité dans la section.

Détérioration des composants

La détérioration de la voie dépend du nombre de trains qui passent et la vitesse des trains. Deux niveaux de maintenance et trois options de vitesse sont prévues pour l'état de la voie observée périodiquement. Des trains plus nombreux et une vitesse plus élevée des trains peuvent entraîner la détérioration de la voie plus sérieuse.

Détérioration de la voie L'arrivée du train est supposé être un processus de Poisson avec le taux d'arrivée λ [163]. N_t est le nombre de trains jusqu'à t.

X_t représente l'état de la voie (soit la somme des détériorations) à l'instant t dans l'Equation A.9. Le k-ème incrément de détérioration est une valeur aléatoire y_k lorsque le k-ème train passe, qui suit une distribution Gamma. La taille de la détérioration y_k a deux paramètres $\alpha(v)$ et β, et le paramètre $\alpha(v)$ dépend de la vitesse v (comme indiqué dans l'équation A.10).

$$X_t = \sum_{k=1}^{N_t} Y_k, Y_k \sim \Gamma(\alpha(v), \beta) \tag{A.9}$$

$$\alpha(v) = \alpha_0 e^{a_0 v} \tag{A.10}$$

Le processus de dégradation est un processus de Poisson composé avec les tailles de saut Gamma distribués [182]. Selon les propriétés du processus de Poisson composé, l'incrément de détérioration pour une période de temps Δt est égal à l'équation A.11

$$X_{\Delta t} = X_{t+\Delta t} - X_t = \sum_{k=1}^{N_{\Delta t}} Y_k = \Gamma(\alpha(v) N_{\Delta t}, \beta) \tag{A.11}$$

Maintenance d'un composant

Une inspection périodique est prévue pour le composant de la voie sur le calendrier de l'opération, l'intervalle d'inspection est notée θ_{Insp}. Les stratégies de maintenance basée sur la condition sont largement discutés dans la littérature [71, 70], les maintenances ici sont programmées sur la base de l'état de la voie: La maintenance préventive et la maintenance corrective sont effectuées pour le composant j, en fonction de la dégradation observée.

- Seuil de maintenance préventive est défini comme δ_{II} et le seuil de la maintenance corrective est δ_{DL}.
- Si i-ème état observé X_{j_i} du composant j dépasse correctives seuil δ_{DL} ($X_{j_i} \geq \delta_{DL}$), un maintenance corrective est réalisée, qui peut fixer la bonne voie pour être aussi bon que nouveau. a maintenance est effectuée dans un temps de retard t_D. Pendant le temps de retard t_D, la circulation de trafic est arrêtée.
- Si $X_{j_i} \geq \delta_{II}$, un entretien préventif est effectué dans un délai t_d. La maintenance préventive est imparfaite, ce qui ramène l'état du composant à une valeur fixe.
- La vitesse après $i$ème inspection est notée comme v_i, qui est fixée en fonction de la $i$ème état détecté.

$$v_i = \begin{cases} v_0, & X_i \in (0, \delta_{\mathrm{II}}) \quad \text{Vitesse normale} \\ v_{tsr}, & X_i \in [\delta_{\mathrm{II}}, \delta_{\mathrm{DL}}) \quad \text{Vitesse limité} \\ 0, & X_i \in [\delta_{\mathrm{DL}}, \infty) \quad \text{Trafic arrêté} \end{cases} \tag{A.12}$$

La planification de la maintenance de ligne

La structure choisie pour la section de voie considérée est celle d'un système en série. Les trains peuvent avoir des vitesses différentes sur les différents éléments de la voie, mais la densité de train est la même pour tous les composants.

La ligne est régulièrement inspectée par le train de l'inspection, en ignorant le temps de déplacement du train d'inspection.

Si $X_{j_i} \geq \delta_{DL}$), une maintenance corrective est mise en place avec un délai t_D. L'action de maintenance corrective prend une durée t_R pour réparer le composant. Le coût de la maintenance corrective est composé de deux parties: le coût d'installation de maintenance corrective c_{csu} et le coût unitaire d'un travail de maintenance corrective c_{cm}.

- Si il y a n_m composants en pannes,n_m actions de maintenance correctives sont effectuées dans le même temps, la section des temps d'arrêt pour ce groupe de maintenance corrective pur est $t_d + t_R$. Ils partagent le coût d'installation de maintenance corrective, le coût d'entretien de ce groupe est de $c_{CSU} + n_m c_{cm}$.

- Si certains autres composants doivent subir des maintenances préventives, soit $\delta_{II} \leq X_{l_i} \leq \delta_{DL}, j \neq l$. La maintenance préventive est mise en place en même temps que la maintenance corrective. Ceci est un groupe de maintenance "mixte" (préventif et correctif). Le coût de maintenance comprend le coût de mise en oeuvre de la maintenance correctives c_{csu} , le coût de l'action de maintenance corrective c_{cm}, le coût de mise en oeuvre de la maintenance préventive c_{psu} et les coûts des actions de maintenance préventive $c_h(t_d)$.

- Pour le groupe de maintenance mixte, comme on a $t_d < t_d$ et $t_r < t_R$, l'indisponibilité de la voie est équivalente à $t_d + t_R$.

Au moment de t_i, si $X_{j_i} \geq \delta_{II}$, un entretien préventif est mis en place avec un délai t_d. Pendant t_d, si l'inspection suivante identifie uniquement des détériorations mais aucune défaillance, tous les composants détériorés sont réparés au moment $t_i + t_d$. Ceci est un groupe de maintenance préventive pur. La maintenance préventive a besoin d'un temps d'arrêtt_r.

Le coût de la maintenance préventive comprend le coût d'installation c_{psu} et le coût de chaque action de maintenance préventive $c_h(t_d)$. $c_h(t_d)$ dépend le plus de temps de retard de réparation dans le groupe, qui est t_d. Plus t_d est élevé, plus le coût d'entretien plus faible comme indiqué dans l'équation A.13. Si $t_d \in (0, T^*)$, le coût de l'action de maintenance préventive dépend sur le retard de temps de réparation t_d, si $t_d \geq T^*$, le coût de l'action de maintenance préventive équivaut à une valeur minimale de réparation $c_{p_{min}}$.

$$c_{pm}(t_d) = \begin{cases} At_d + B & t_d \in (0, T^*) \\ c_{p_{min}} & t_d \in [T^*, \infty) \end{cases} \tag{A.13}$$

Il existe trois configurations de densité de trafic en fonction de la vitesse minium d'un train dans la section: Si tous les états observés sont bons $X_{j_i} \leq \delta_{II}$, la densité de train est λ_0.Si le composant j est détérioré ($X_{j_i} \geq \delta_{II}$), pendant t_d, la vitesse sur ce composant j est $v_j = v_{tsr}$ et la vitesse pour l'autre composant normale est égale à $v_l = v_0, l \neq j$, la densité de train pour la ligne est $\lambda_{train} \frac{v_{tsr}}{v_0} \lambda_0$. Lorsque le travail de maintenance est exécuté, le système est fermé. Si composant j est en panne ($X_{j_i} \geq \delta_{II}$), la section est fermée et la densité de train est égale à 0.

Évaluation de la performance

Différents indices d'évaluation de performance sont introduits. Pour une évaluation mono-objectif, nous pouvons comparer le profit du système ou l'indisponibilité du système; pour une évaluation multi-objectif, nous adoptons une approche de type "front de Pareto".

Évaluation de le profit et le disponibilité

Le profit du système et l'indisponibilité du système sont utilisés pour évaluer la performance du système. L'indisponibilité du système est donnée par l'équation A.14:

$$Q_{avg} = \lim_{t\to\infty} \frac{[N_{csu}(t) + N_{mix}(t)](t_D + t_R) + N_{psu}(t)t_r}{t} \tag{A.14}$$

Le profit du système est le gain du système, moins le coût de la maintenance du système:

$$\mathbb{E}B_\infty = \mathbb{E}G_\infty - \mathbb{E}C_\infty \tag{A.15}$$

Le taux moyen des coûts de maintenance (EC_∞) et le taux de gain du système (EG_∞) sur une durée de temps infini sont:

$$\mathbb{E}C_\infty = \lim_{t\to\infty} \frac{C(t)}{t} \tag{A.16}$$

$$\mathbb{E}G_\infty = \lim_{t\to\infty} \frac{N_{train}(t)c_{train}}{t} \tag{A.17}$$

Le coût de maintenance se compose du coût de mise en oeuvre et des coûts d'opération de maintenance.

$$\begin{aligned} C(t) = & \underbrace{\sum_{m=1}^{N_{csu}(t)} (c_{csu} + n_m c_{cm})}_{\text{Pure corrective maintenance group}} + \underbrace{\sum_{n=1}^{N_{psu}(t)} (c_{psu} + n_n c_{pm})}_{\text{Pure preventive maintenance group}} \\ & + \underbrace{\sum_{h=1}^{N_{mix}(t)} (c_{csu} + n_{cm_h}c_{cm} + c_{psu} + n_{pm_h}c_{pm}) + N_{insp}(t)c_{insp}}_{\text{Mix maintenances group}} \\ = & [N_{csu}(t) + N_{mix}(t)]c_{csu} + (\sum_{n=1}^{N_{psu}(t)} n_n + \sum_{h=1}^{N_{mix}(t)} n_{pm_h})c_{pm} \\ & + [N_{psu}(t) + N_{mix}(t)]c_{psu} + (\sum_{m=1}^{N_{csu}(t)} n_m + \sum_{h=1}^{N_{mix}(t)} n_{cm_h})c_{cm} + N_{insp}(t)c_{insp} \end{aligned} \tag{A.18}$$

Afin d'évaluer ces quantités, nous avons besoin de construire un modèle de simulation pour collecter le nombre de trains N_{train}, le nombre d'inspections N_{insp}, le nombre de mise en oeuvre de maintenance (N_{mix}, N_{csu} and N_{psu}), le nombre d'inspections maintenance actions (N_{cm} and N_{pm}).

Évaluation multi-objectif

Le problème d'évaluation multi-objectif vise à évaluer la performance du système compte tenu du bénéfice rapporté par le système et son indisponibilité dans le même temps. Une approche basée sur le front de Pareto est adoptée [30] [122]; nous devons ainsi trouver la solution (v_{tsr}, t_d) pour satisfaire:

si et seulement si il n'y a pas $(v^*_{tsr}, t^*_d) \in (V, T_d)$

$$B(v_{tsr}, t_d) \geq B(v^*_{tsr}, t^*_d) \tag{A.19}$$

$$Q(v_{tsr}, t_d) \leq Q(v^*_{tsr}, t^*_d) \tag{A.20}$$

La solution (v_{tsr}, t_d) est une solution du front de Pareto "stricte". Si $B(v_{tsr}, t_d) > B(v^*_{tsr}, t^*_d)$ et $Q(v_{tsr}, t_d) < Q(v^*_{tsr}, t^*_d)$, la solution est "faible".

Comparaison des politiques de regroupement et non-regroupement

Le tableau A.1 montre la comparaison de résultat pour deux configurations. La performance optimale est obtenue à $v_{tsr} = 80$ pour la stratégie de maintenance avec l'option de regroupement, et à $v_{tsr} = 70$ pour la stratégie de maintenance sans regroupement. De toute évidence, l'introduction de la possibilité de regroupement des actions de maintenance permet d'obtenir des performances plus élevées, avec à la fois une indisponibilité inférieure et un coût d'entretien plus faible.

Table A.1: Comparaison des résultats . *B* Le profit du système; *Q*: L'indisponibilité du système

		v_{tsr}=80,t_d=55	v_{tsr}=70,t_d=55
' t_d' grouping	**B**	**809.72**	**787.11**
	Q	0.049	0.037
no grouping	**B**	**744.87**	**745.11**
	Q	0.058	0.042

Selon la comparaison des fronts de Pareto des solutions avec et sans regroupements, la stratégie de regroupement conduit à la fois à des performances plus élevées et à une indisponibilité inférieure pour l'optimisation à objectifs multiples.

Les résultats indiquent le nombre des actions de maintenance préventive dans un groupe de maintenance avec ou sans la stratégie de regroupement: la stratégie de regroupement a plus d'actions préventives pour chaque groupe. La stratégie de regroupement permet d'économiser le coût de set-up préventif et le temps d'arrêt ainsi la stratégie de regroupement encourt un coût d'indisponibilité et d'entretien plus faible, ce qui permet donc à une prestation du système supérieure.

Conclusion générale

Aujourd'hui, de plus en plus de gens choisissent de voyager en train et, en conséquence, les actifs et infrastructures ferroviaires doivent être vérifiés et entretenus pour éviter l'accident et assurer la sécurité. Toutefois, l'entretien des actifs ferroviaires peut conduire à l'arrêt de la circulation et entraîner des perturbations du trafic passager et fret. La maintenance coûte donc beaucoup d'argent. Le réseau de chemin de fer est constitué de milliers de composants et peut être opéré sous différents modes de fonctionnement, en plus, il est difficile d'effectuer un entretien qui réalise un arrêt de la circulation. Tous les facteurs ci-dessus conduisent à la complexité de la modélisation de la maintenance.

La plupart des modèles de maintenance développés avec des objectifs d'application dans l'industrie ferroviaire sont supposés être markoviens, mais cette hypothèse peut de

moins en moins être acceptée en pratique. Pour pouvoir prendre en compte l'augmentation des information de surveillance disponible, un outil de modélisation plus souple doit être développé pour la modélisation de la maintenance. Dans cette thèse, nous nous intéressons à contribuer au développement d'un outil de modélisation, d'évaluation des performances et d'aide à la décision en maintenance, en pensant aux processus de défaillance/maintenance qui ne peuvent pas satisfaire les propriétés de Markov (par exemple, le modèle de réparation avec délais), et en cherchant à décrire l'entretien et l'exploitation pour des systèmes multi-composants. Les réseaux de Petri colorés sont l'un des outils qui peut couvrir les besoins de modélisation ci-dessus et que nous avons retenu pour nos travaux.

Travaux dans la thèse

Partie III:Les modèles de maintenance au niveau composant

La Partie III travaille sur la modélisation de maintenance au niveau " composant".

Le Chapitre 5 compare la maintenance pour le processus de défaillance modélisé par une distribution de durée de vie d'une part, et par un modèle de fiabilité basé sur l'évolution de détérioration graduelle, d'autre part. Les ensembles de couleurs du RdP colorés peuvent modéliser les données sur l'état de santé des composants observés qui représente l'évolution de la détérioration. Les modèles CPN pour les deux descriptions de défaillance sont utilisés pour représenter le même processus de détérioration/défaillance, tandis que différentes stratégies d'entretien sont prévues en fonction des données d'inspection. Les résultats des simulations montrent une baisse du coût de maintenance lorsqu'on prend la décision de maintenance sur des données d'inspection plus riches en information.

Le Chapitre 6 met l'accent sur la modélisation de la maintenance conditionnelle avec délai. Si la réparation arrive avec un délai fixe, le processus ne peut pas être Markov(semi-Markov). Des modèles de réseaux de Petri colorés sont construits pour décrire ce processus de détérioration pour voir l'effet du retard sur le coût d'entretien par le jeu de couleurs chronométré représentant les délais de réparation. Les arcs réinitialisé sont utilisés pour mettre à jour la décision de maintenance dans le modèle. Les résultats numériques montrent que le rapport r entre le délai de réparation et l'intervalle d'inspection a une influence sur le coût de l'entretien: un grand r peut conduire à l'augmentation du coût de maintenance, car il peut conduire à plus de maintenances correctives.

Partie IV:les modèles de maintenance pour une voie

Dans la Partie IV, nous nous intéressons à la modélisation de la maintenance pour une voie de chemin de fer à plusieurs composants en considérant deux problème : la capacité d'inspection peut influer sur la décision de maintenance et la réparation retardés peut conduire à un fonctionnement dégradé sur la voie.

Le Chapitre 8 suppose qu'il existe des limites de l'inspection, qui ne peut pas détecter l'état défectueux sous certaines conditions et, partant, une inspection complémentaire est nécessaire. Parce que les scénarios d'accidents sont prises en compte, le modèle peut également évaluer le risque du système.

Le Chapitre 9 considère la maintenance pour une voie sur la base des données sur l'état de santé recueillies en ligne. La détérioration du composant dépend de la vitesse du train et le nombre de trains qui passent, et la maintenance pour les éléments de voie défectueux arrive avec un délai. Nous avons construit un modèle RdP colorés pour résoudre un problème d'optimisation de la maintenance pour déterminer conjointement le réglage de la limitation de vitesse et le délai de réparation afin de maximiser les gains d'exploitation du système et de minimiser les temps d'arrêt du système. Tenant compte du fait que la maintenance préventive est réalisée avec un délai, une stratégie de maintenance avec regroupement pour des réparations retardées est envisagée et comparée à la stratégie sans regroupement.

Selon les modèles construits dans cette thèse, les réseaux de Petri colorés montrent leur souplesse de modélisation: Avec la transition et les couleur sets chronométré, les RdP colorés peuvent décrire les comportements de système par le temps, et il permettent de modéliser les détails de données sur la santé en utilisant des variables et des jeux de couleurs. Les priorités de la transition peuvent modéliser les séquences d'événements. En outre, les transitions de substitution nous aident à construire un modèle hiérarchique qui est plus lisible que ceux obtenus par exemple avec des réseaux de Petri stochastiques.

Limitations des modèles

Dans cette thèse, nous supposons que la distribution de détérioration et les gains de maintenance sont connus, les paramètres utilisés dans la simulation ne sont pas obtenus à partir des données réelles. Cependant, dans la pratique, l'analyse des données doit être effectuée avant ces modélisation de maintenance.

Le modèle développé sera de grande taille si nous avons besoin de modéliser un système complexe. Le modèle de CPN pour un composant qui est contrôlé par des inspections périodiques et maintenu par l'entretien à deux niveaux basé sur la condition observée au chapitre 6 se compose de 14 places, 12 transitions et 44 arcs. Le CPN pour une ligne en série dans le chapitre 9 se compose de plus de 180 places, plus de 100 transitions et plusieurs centaines d'arcs. Mais dans le monde réel, le nombre de composants dans le réseau de chemin de fer est beaucoup plus que la quantité dans ce modèle de CPN, la structure et le fonctionnement du système vont sans aucun doute nécessiter de plus de transition et de lieux dans la modélisation : il sera donc nécessaire d'étudier la possibilité d'un passage à l'échelle pour les approches proposées.

Avec les réseaux de Petri ou SPN ou CPN, l'estimation des probabilités dépend des simulations des Monte Carlo . Le temps de simulation dépend de la durée des cycles de simulation, le nombre de cycles de simulation et le nombre de tirages de transitions. Il faut plusieurs minutes ou dizaines de minutes pour les simulations d'une configuration des paramètres, donc il peut prendre plusieurs heures à plusieurs jours pour optimiser les variables de décision de maintenance. Ici encore, la possibilité d'un passage à l'échelle devra être étudiée.

Les modèles de voie dans les Chapitres 7, 8 et 9 sont plus lisibles que les réseaux de Petris Stochastiques, cependant, ce n'est toujours pas une tâche facile de changer le nombre de composants, le nombre de machines dans les modèles. Pour une section comprenant un nombre différent de composants, il faut modifier les modèle de CPN au niveau composant,

au niveau ligne et au niveau fonctionnement.

Appendix B

Tables of track faults and maintenance in UK standard

Chapter 2 introduces the ballasted track system, as well as the track faults and rail breakages. In this part, the possible requirements for the track geometry faults and rail faults are shown in Table B.1 and B.2.

Table B.1: Track geometry faults

Failure modes	Possible Causes	Inspection	Repairs
Gauge spread	Poor fastening/poor sleepers	Visual inspection(weekly);	Tie-bar;
		Train recording vehicle(every 3 months)	Spot re-sleepering
Buckle	Hot temperature	Visual inspection(weekly); Train recording vehicle(every 3 months)	Slewing the track;
Twist	Poor formation	Visual inspection(weekly); Train recording vehicle(every 3 months)	Tamping

Table B.2: Rail breakage and rail joint breakage

Failure modes			Possible Causes	Inspection	Repairs
Broken Rail	Rail Contact Fatigue	Rail head checking/gauge corner cracking	Sidewear	Visual inspection(weekly);	Grinding
				Ultrasonic inspection(every 6 months);	
		Squats	Heel pressure	Visual inspection(weekly);	Grinding
				Ultrasonic inspection(every 6 months);	
	Single transverse rail crack		Rail crack at rail head, rail foot and at weld;	Visual inspection(weekly);	Clamp;
				Ultrasonic inspection(every 6 months);	Bridging
	Star crack		Crack pass through bolt hole	Visual inspection(weekly);	Clamp;
				Ultrasonic inspection(every 6 months);	Bridging
	Rail head missing		Rail head crack	Visual inspection(weekly);	Clamp;
				Ultrasonic inspection(every 6 months);	Bridging
Broken rail joint	Single fishplate break		Crack at fishplate bolt hole or fishplate section	Visual inspection(weekly);	Clamp;
				Ultrasonic inspection(every 6 months);	Bridging
	Pair fishplate break		Crack at fishplate bolt hole or fishplate section	Visual inspection(weekly);	Clamp;
				Ultrasonic inspection(every 6 months);	Bridging

Appendix C

CPN models for inspection and train density in Chapter9

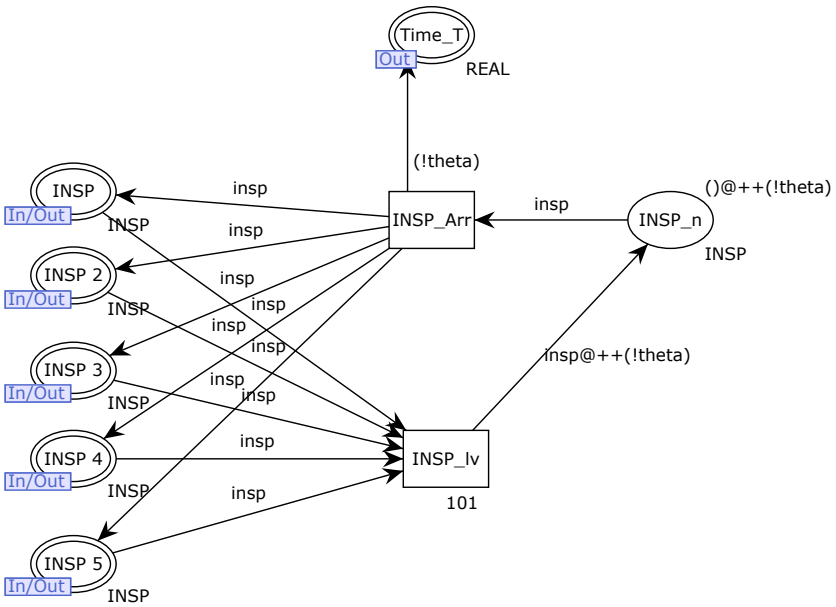


Figure C.1: Inspection CPN model

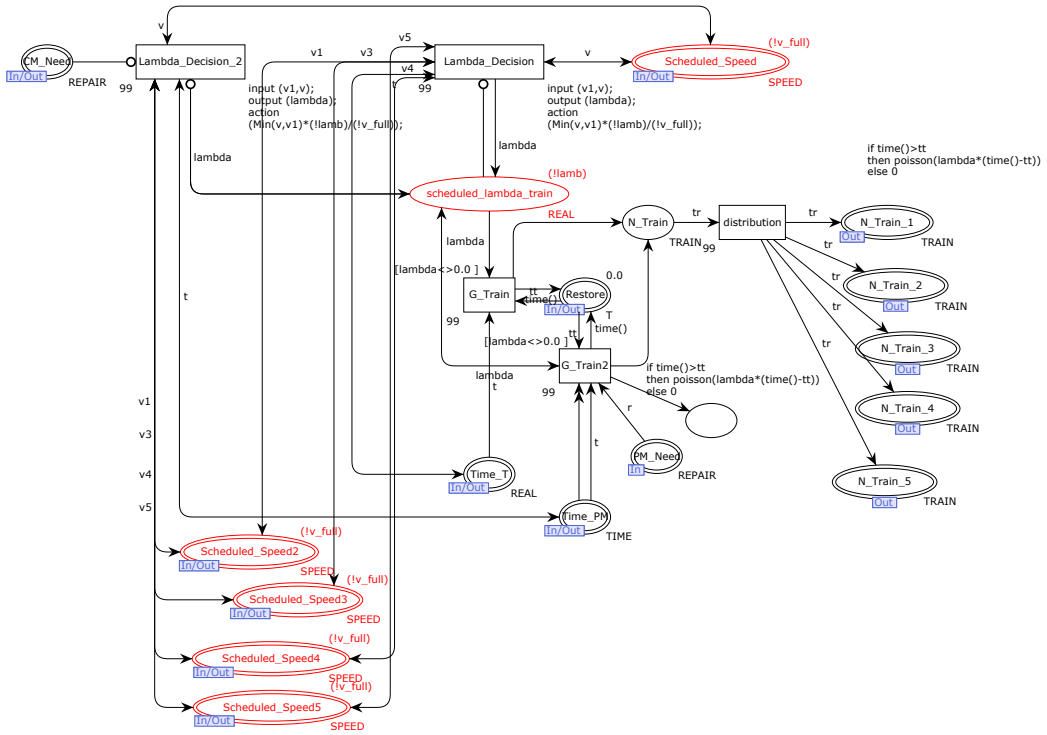


Figure C.2: Number of train CPN model

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Hui SHANG

Doctorat : Optimisation et Sûreté des Systèmes

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Modélisation, simulation et évaluation de performances de la maintenance des infrastructures ferroviaires

Les travaux présentés dans ce manuscrit visent à développer des modèles de coût/performances pour améliorer les décisions de maintenance sur les infrastructures ferroviaires exploitées dans un environnement de plus en plus contraint: trafic accru, détérioration accélérée, temps de maintenance réduits.

Les modèles de maintenance proposés sont construits à base de réseaux de Petri colorés ; ils sont animés par simulation de Monte Carlo pour estimer les performances (en termes de coût et de disponibilité) des politiques de maintenance considérées. Ils sont développés aux niveaux "composant" et "réseau", et plusieurs problèmes de maintenance différents sont étudiés.

Au niveau "composant" (rail), des politiques de maintenance mettant en jeu différents niveaux d'information de surveillance sont comparées pour montrer l'intérêt de surveiller la détérioration graduelle du composant. L'effet de l'existence d'un délai de maintenance est également étudié pour les politiques conditionnelle et périodique.

Au niveau système (ligne), une maintenance mettant en jeu différents types d'inspections complémentaires (automatique ou visuelle) est d'abord étudiée. On s'intéresse ensuite au cas de figure où l'évolution de la détérioration dépend du mode d'utilisation et de la charge de la voie : le problème de maintenance étudié vise alors à définir un réglage optimal des paramètres d'exploitation de la voie (vitesse limite) et de maintenance (délai d'intervention).

Mots clés : voies ferrées, entretien et réparations - voies ferrées, détérioration - maintenance conditionnelle - Petri, réseaux de - fiabilité - disponibilité (systèmes) - sécurité des systèmes - contrôle technique - simulation, méthodes de.

Maintenance Modelling, Simulation and Performance Assessment for Railway Asset Management

The aim of this thesis research work is to propose maintenance models for railways infrastructures that can help to make better maintenance decisions in the more constrained environment that the railway industry has to face, e.g. increased traffic loads, faster deterioration, longer maintenance planning procedures, shorter maintenance times.

The proposed maintenance models are built using Coloured Petri nets; they are animated through Monte Carlo simulations to estimate the performance of the considered maintenance policies in terms of cost and availability. The maintenance models are developed both at the component and network levels, and several different maintenance problems are considered.

At the rail component level, maintenance policies with different level of monitoring information (level of gradual deterioration vs binary working state) are compared to show the benefits of gathering monitoring information on the deterioration level. The effect of preventive maintenance delays is also investigated for both condition-based inspection policies and periodic inspection policies on a gradually deteriorating component.

At the line level, a maintenance policy based on a two-level inspection procedure is first investigated. Then, considering the case when the deterioration process depends on the operation modes (normal vs limited speed), a maintenance optimization problem is solved to determine an optimal tuning of the repair delay and speed restriction.

Keywords: railroads, track, maintenance and repair – railroads, track, deterioration - Petri nets - condition-based maintenance - reliability - system safety - engineering inspection - simulation methods – systems availability.

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