

Modelling Railway Overhead Line Equipment Asset Management

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Abstract

The Overhead Line Equipment (OLE) is a critical sub-system of the 25kV AC overhead railway electrification system, which is the main method of railway electrification on the British railway network. OLE failures can result in significant delays and pose risks to passenger safety, therefore, inspection and maintenance is undertaken to improve component reliability and uphold the availability of the system. OLE asset management strategies can be evaluated using a life cycle cost analysis that considers degradation processes and maintenance activities of the OLE components. The investment required to deliver the level of performance desired by railway customers and regulators can be based on evidence from the analysis' results. This thesis presents a methodology for modelling the asset management and calculating the whole life cost of the OLE to allow such analysis to take place.

This research has developed a High Level Petri net model to simulate the degradation, failure, inspection and maintenance of the main OLE components in a stochastic manner. The model simulates all the main OLE components concurrently in the same model and fixed time interval inspections and condition-based maintenance regimes are considered. The various dependencies between the different components and processes considered, such as opportunistic inspection and maintenance, are also taken into account. The use of High Level Petri nets allows the processes considered to be modelled in a more accurate and efficient manner in comparison to standard Petri nets. The model is used to calculate various statistics associated with the cost, maintenance requirements and reliability of the individual OLE components and the OLE system over its life cycle. This is demonstrated using an example analysis for a 2-mile section of electrified line, which also describes how the outputs obtained can be used by decision makers to study the performance of the components and the implications of the maintenance strategy evaluated by the model. Finally, a Genetic Algorithm is used in conjunction with the Petri net developed to find the optimum maintenance strategies that result in the lowest total cost of the system. The optimum strategy chosen results in a 15% lower expected total cost and 10% fewer expected failures in comparison to the maintenance strategy currently implemented for the OLE on the British railway network, whilst requiring a similar number of maintenance visits.

The methodology presented considers the OLE components and the processes described above in more detail than previous literature associated with asset management and life cycle cost analysis of the OLE. Additionally, the suitability and ways in which Petri nets can be used for modelling the asset management of other large engineering systems, comprised of numerous components with various dependencies, is confirmed. Furthermore, the practical use of the model, as an asset management tool, capable of calculating a comprehensive range of outputs calculated, is demonstrated.

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Publications

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Chapter 1 Introduction

1.1 Background and Research Motivation

The Overhead Line Equipment (OLE) is a sub-system of the 25kV alternating current overhead electrification system, the preferred railway electrification system in Britain, which currently represents 63% of the 5000 kilometres of electrified railway network (Network Rail, 2012). The OLE refers to the conducting wires, insulators and supporting components that provide electric trains with their traction power along the length of an electrified line. The OLE system is, therefore, comprised of numerous component types that repeat down the entirety of an electrified line.

Since the OLE system has no redundancy, individual OLE component failures often result in failure of the system, which can lead to delays of the timetabled train service. Therefore, it is imperative that inspection and maintenance of the OLE takes place in order to uphold system reliability. The degradation, failure, inspection and maintenance of the components are all associated with the asset management of the system. The term asset management refers to the processes implemented by an organisation to realise value, which can be related to performance or purely monetary, from their assets (International Standards Organisation, 2014). As part of its asset management strategy, Network Rail (the British railway infrastructure provider) aims to maintain its current portfolio of railway assets and correctly specify the assets to be installed in new systems, so that the required outputs, such as system reliability and the permissible railway line speed, can be achieved at the lowest whole life cost for the system (Skinner et al., 2011). The whole life cost of an asset is composed of its acquisition costs, associated with its design and installation, and its ownership costs, associated with its failure and maintenance over the asset's lifetime (British Standards, 1997).

With such a large electrified network and many electrification schemes planned in the near future, substantial economic savings can be realised through specifying the OLE installation types and maintenance regimes that achieve the required outputs at the lowest whole life cost. Through modelling OLE component degradation and failure over the whole life of the system, whilst also taking into account the inspection and maintenance regimes, the expected whole life cost for a given OLE installation type and maintenance regime can be estimated. The results for different project options and maintenance regimes can then be compared. This can allow future asset management and investment decisions to be better informed and strategies, or project options, can be selected for consideration based on modelling results.

The current life cycle cost models that Network Rail has developed for the OLE are based on the Markov method. These models use a simplistic approach whereby the overall rate of maintenance and failure of the components per year are considered, from which the future condition of the components is calculated. The future costs are obtained by considering the corresponding maintenance and failure costs. The models do not explicitly model all the asset management intervention actions undertaken therefore these processes cannot be analysed in detail.

There has been a limited amount of research focusing on modelling the life cycle cost and asset management of the OLE to date. Stochastic models have been developed to estimate the life cycle cost of OLE components and evaluate the reliability of the system using equations representing the lifetime or reliability of the different components. These models also consider fixed time interval preventative maintenance and rapid response maintenance after a component failure. However, the methods used are relatively simplistic and do not necessarily model all the processes that should be accounted for. Furthermore, instead of fixed time interval preventative maintenance, Network Rail implements a condition-based maintenance strategy, whereby an OLE component's maintenance is scheduled based on the condition it is found to be in during routine inspections. A more sophisticated modelling methodology is required to consider such asset management intervention actions accurately.

The research presented in this thesis uses the Petri net method to model the life cycle cost and asset management of the OLE. The Petri net method is a novel approach for modelling the OLE and previous studies have shown the method to be very applicable to modelling asset management processes due to its flexibility. Petri nets are particularly suitable for modelling such processes because both deterministic and stochastic processes can be considered and the dependencies between different components and processes can also be accounted for. This research aims to obtain more detailed statistics, associated with the performance and life cycle cost of the system, in comparison to other studies that have used Petri nets. Additionally, since other Petri net models described in literature have not been developed for studying the asset management of a system comprised of as many components as the OLE, the model developed in this thesis enables the suitability of Petri nets for modelling the asset management of large engineering systems to be studied.

1.2 Research Aims and Objectives

1.2.1 Research Aims

The primary aim of this research is to develop a model that considers the degradation and failure of the OLE components, as well as the asset management intervention actions that are undertaken to identify and rectify degraded and failed components, over the life cycle of the system. In addition to Individual models for the different OLE component types, a whole system model should be developed. The whole system model should consider the various dependencies between the different components (such as opportunistic maintenance). This will allow the main processes associated with the asset management and life cycle cost of the OLE to be studied.

The model developed should be capable of obtaining outputs associated with the life cycle cost of the system and other performance indicators than can be used to analyse the behaviour of the system and determine the suitability of the asset management strategy evaluated. For instance, the model can be used to calculate the expected future maintenance requirements, number of failures and the associated costs for each of the different component types studied and the system as a whole, over its life cycle.

The overall framework developed should allow the model to be used as an OLE life cycle cost and asset management analysis tool. Component information and the controllable asset management decisions are provided as inputs to the model, which is then evaluated to obtain outputs that describe the impact of the asset management decisions, in terms of the performance and cost of the components and the system for a section of OLE studied over its life cycle.

Finally, this research aims to include an optimisation feature within the model developed. This should allow calculation of the optimum asset management intervention strategies that minimise the life cycle cost of the system whilst ensuring that the required outputs, such as high system reliability, are achieved over the life cycle of the system.

1.2.2 Research Objectives

The following objectives are undertaken to achieve the aims of the research:

- To analyse available data and consult literature and industry experts to obtain information about the time to reach the states of component degradation and failure and understand the effect of component failure, in terms of the disruption to service, damage to the system and the costs incurred.

- To develop a Petri net model for the different OLE component types and for the OLE system as a whole. The main processes that influence the life cycle cost and asset management of the system will be encompassed. Therefore, component degradation, failure, inspection and maintenance must be modelled. Component degradation and failure will be modelled stochastically to allow the uncertainty associated with the occurrence of these processes to be accounted for. The methodology must be able to model the condition-based maintenance regime undertaken by Network Rail, which is more complex in comparison to a simple fixed time interval preventative maintenance regime. Models for the different component types should first be developed and then interlinked, by considering the dependencies that exist between different components (such as undertaking opportunistic maintenance), to form a whole system model, where all the main OLE components and processes studied are considered in the same model.
- To develop code to generate and evaluate the Petri net model developed, in order to obtain numerous statistics associated with the cost and performance of the system, such as the expected total cost and the expected number of failures and the number of maintenance actions for the different components. For example, information regarding the components that are present in the section of OLE that is studied, along with the asset management intervention actions undertaken, such as their degradation and failure behaviour, can be used as inputs to the model. The code should then be able to generate and evaluate the model based on these inputs. The results obtained need to be presented in a clear manner that shows the expected changes in the performance of the system and the components over their life cycles, along with the expected costs.
- To find the optimum asset management intervention strategies, i.e. find the optimum inspection, maintenance and renewal strategies, that result in the lowest whole life cost of the system using an optimisation technique, such as the Genetic Algorithm method, in conjunction with the Petri net model developed.

1.3 Thesis Outline

The organisation of this thesis is outlined below:

Chapter 2 provides an overview of electrification on the British railway network and describes the overhead line equipment system. A detailed description of the components' degradation and failure modes is also given and the different asset management intervention actions undertaken, to address component degradation and failure, are outlined. Finally, details about the analysis of historical failure data, in order to understand the effects of component failure in terms of the costs incurred, are explained.

Chapter 3 presents a detailed review of literature associated with the subject area. The main modelling methods that are applicable to analysing the asset management and the life cycle cost of the overhead line equipment are explained and their advantages and disadvantages highlighted. Models for analysing the asset management and calculating the life cycle cost of the overhead line equipment and other engineering systems are critically appraised.

Chapter 4 describes the Petri net model that has been developed in this thesis to model the asset management and calculate the life cycle cost of the overhead line equipment. The development of the model is explained along with examples showing how the Petri net models each of the main processes that are considered.

Chapter 5 presents the outputs calculated by the Petri net model developed. An example study is included, where the outputs obtained are presented along with a discussion of their relevance to asset management decision making and life cycle cost analysis.

Chapter 6 shows how an optimisation procedure has been implemented in conjunction with the Petri net model developed, in order to find the optimum strategies for the asset management intervention actions. The optimum solutions found are compared to the strategy currently implemented on the British railway network.

Chapter 7 gives a summary of the work completed and an assessment of how the research aims and objectives have been met. The main conclusions and contributions to research are outlined, followed by recommendations for future work.

Chapter 2 Overhead Line Equipment System Description

This chapter gives a detailed introduction to the subject area. It describes the main features of the Overhead Line Equipment (OLE) and the asset management processes that are studied in detail in this thesis. An overview of the different types of railway electrification and their history on the British railway network are outlined, followed by a description of the OLE system. Key terminology that is used throughout this thesis is then introduced. The degradation and failure processes for all the OLE components that are studied in detail are listed and the asset management intervention actions that are currently undertaken on the British railway network, to address component degradation and failure and ensure the availability of the system, are also explained. Finally, the different types of failure and maintenance data that are collected by Network Rail are described along with a description of the analysis of available data that was undertaken in this study.

2.1 Railway Electrification Overview

The purpose of a railway electrification system is to provide a reliable and safe supply of electrical traction power for electric trains. This can be achieved through numerous types of systems that work in a similar manner. To give a simplistic overview, a railway electrification system is composed of different assets or sub-systems that obtain the electrical power, convert it to the desired voltage, control its transmission and distribute it along the railway via live overhead lines or conductor rails that electric trains make a physical and electrical connection with to obtain their traction power.

The 25,000 volt alternating current (25kV AC) overhead electrification system is the standard railway electrification system in place on the British railway network and it is also used extensively throughout Europe and the rest of the world. The system works by obtaining a 3 phase high voltage (commonly 132kV) electrical power supply from the national electricity network or a local distribution network operator. At feeder stations, 1 phase of this power is taken and, using a transformer, the voltage is stepped down to 25kV. The power is then channelled into the desired feeding section through the use of high voltage circuit breakers and then high voltage cables feed it into the live overhead wires located directly above the track. Electric trains are equipped with a roof mounted pantograph that rubs against the lowest wire above the track (known as the contact wire) to collect the traction power. The return current flows through the train's wheels into the rails and back to the feeder station (sometimes via a separate return conductor wire) to complete the circuit.

The live conducting wires, insulators and supporting equipment installed along the line are collectively known as the overhead line equipment (OLE) and it is this group of components that this research

studies in detail. For completeness, this section provides a brief overview of the three types of railway electrification on the British railway network.

2.1.1 Railway Electrification on the British Railway Network

The following 3 railway electrification systems exist on the British railway network:

1. **25kV AC Overhead Electrification** (the preferred system described previously).
2. **660/750 Volt Direct Current (DC) Conductor Rail Electrification** (commonly referred to as 'Third Rail'). The electrical power is fed through a conductive rail placed to the side of the railway track. Electric trains are equipped with metal shoes that rub against this conductive rail to obtain the traction power.
3. **1500 Volt DC Overhead Electrification**. This system is similar to the 25kV AC overhead electrification system, but the overhead lines are supplied with a 1500V DC current instead.



Figure 2-1 25kV AC Overhead Electrification on the East Coast Main Line South of Darlington



Figure 2-2 Conductor Rail Electrification on the Brighton Main Line near London Bridge (FourFoot, 2016)

Figure 2-1 and Figure 2-2 show the 25kV AC overhead electrification system and the conductor rail electrification system respectively. The 25kV AC overhead electrification system is preferable to the other systems used because it can provide the electrical traction power for a railway line with lower energy loss and the assets and components required are generally cheaper (Alan Baxter, 2015). Electric trains can also gain more power from the 25kV AC overhead electrification system meaning they can accelerate faster and travel at higher speeds. Conductor rail systems can be advantageous compared to high voltage overhead electrification systems in situations where it is difficult to obtain the required electrical clearance (such as under bridges or in tunnels). As a result, conductor rail electrification systems are used extensively on underground metro systems. The prevalence of the different systems on the British railway network is addressed in the following section.

2.1.2 History of Railway Electrification in Britain

At the turn of the 20th century, there was a period when many suburban railway lines in Britain were electrified using either conductor rail or 1500V DC overhead electrification systems. DC traction power systems were first used because DC motors were more established than AC motors. Notably, during the period between the wars, the conductor rail system was extended to cover the railways in London and the area south towards the coast (British Transport Commission, 1956). During the 1950s, as part of a push to modernise the British railway network the 25kV AC overhead electrification system became the standard method of electrification and the West Coast Mainline was electrified shortly after. Much of the pre-existing 1500V DC overhead electrification systems were converted to the 25kV AC system and several of the intercity main lines were electrified. However, in the region south of London, because there was such a large area of the network that used the conductor rail system, further lines were electrified using conductor rail and the system has remained in place to this day.

According to the most recently available statistics, for the year 2014 to 2015, the British railway network contains 15,760km of route open for traffic- of which roughly a third (5,272km) is electrified (Office of Rail and Road, 2015). The prevalence of electrification across the network is shown in Figure 2-3. The 25kV AC overhead electrification system currently represents approximately 63% of the electrified network the conductor rail system represents 36% and is located exclusively in the region south of London and in Merseyside; the 1500V DC overhead electrification system represents less than 1% of the network and exists solely on the Tyne and Wear Metro. In the near future there are several schemes scheduled to electrify some of the existing non-electrified lines, as shown in Figure 2-3. This will be done using the 25kV AC overhead electrification system. The new electrification schemes will increase the number of passengers on electric trains further. Additionally, as part of the electric spine

concept, there are plans for electrified lines linking the port of Southampton to cities in the North to allow substantially more freight to be transported on electric trains.



Figure 2-3 Current and Future Railway Electrification on the British Rail Network (Alan Baxter, 2015)

2.1.3 Network Rail and the Advantage of Railway Electrification

Network Rail are currently the 'not-for-dividend' owner and operator of the railway infrastructure in Britain. They are responsible for the operation of all of the different electrification systems in place on the British rail network. They receive funding in the form of direct grants from the Government, charges for track access imposed on the passenger and freight train operating companies that use the network and raise other income from commercial property, for instance through the rent of retail units at stations. They are accountable to the Office of Rail and Road, which is an independent safety and economic regulator that determines the amount of funding Network Rail should receive from the government and what targets must be achieved during five-year control periods.

From Network Rail's perspective, the operation of electric trains is beneficial in comparison to diesel trains because they are more powerful and can, therefore, accelerate faster and travel at higher speeds. This can result in greater customer satisfaction with the rail network and an increase in the capacity of the network, which can result in more trains being run and therefore more revenue being obtained from the train operating companies. Additionally, since electric trains are also lighter in weight than diesels, they induce less damage on the railway track. Contrarily, electrified railways can also present difficulties for Network Rail. There is a large initial capital cost (said to be £550k-£650k per kilometre of track electrified) and difficult logistical decisions that need to be made when installing the electrification infrastructure (Rail Safety and Standards Board, 2007). Additional costs associated with the operation and maintenance of the new infrastructure that are not present on non-electrified lines are also incurred.

From other stakeholders' perspectives, in addition to the benefits described above, electric trains are said to be more than 35% cheaper to operate than diesel trains because they are more reliable and electricity is a far cheaper fuel than diesel (Department for Transport, 2009). The reduced cost of electric train operation is said to significantly outweigh the additional costs of maintaining the electrification infrastructure. However, on a railway network with privatised train operating companies, the cost savings associated with running electric trains may not be passed onto the infrastructure provider, Network Rail. As a result, it is commonly government led initiatives that call for new electrification schemes.

Electrifying lines can be beneficial to the local region and further afield for many reasons that are often interlinked. Such benefits include reducing journey times, stimulating economic growth and helping to provide more sustainable transport links (through reduced CO2 emissions and zero local emissions).

2.2 Overhead Line Equipment Description

The overhead line equipment (OLE) is a system that consists of the conducting wires, insulators and supporting components that provide trains with their traction power along the length of an electrified line. There are numerous different component types that repeat down the entirety of an electrified line. This research aims to study all the main OLE component types that have the greatest influence on the system's reliability and operational costs. This section describes the OLE system and its main components.

2.2.1 Main OLE Components and System Description

The main OLE components that are present throughout the system and have a large influence on the reliability, maintenance requirements and whole life cost of the system are listed below and shown in Figure 2-4. These are the main components studied in detail in this thesis.

- **Catenary Wire**- Tensioned wire that the contact wire hangs beneath.
- **Contact Wire**- Current carrying wire that the trains' pantographs connect with to obtain traction power.
- **Dropper**- Short wire that connects the contact wire to catenary wire.
- **Insulators** - Ceramic or polymeric insulators used to separate live parts of the OLE from earthed parts.
- **Registration Equipment**- The assembly of components that position the catenary and contact wires above the track.
- **Return Conductor**- Conductive wire that carries the return current.
- **Structures**- Main steelwork and associated foundations used to support the OLE.



Figure 2-4 The Main OLE Components

Structures, such as masts/poles (as shown in Figure 2-4), support the OLE components and raise them above the track. The registration equipment is attached to structures via insulators that separate the live OLE components from Earth. The contact and catenary wires are attached to the registration equipment with the contact wire suspended below the catenary wire, by attached dropper wires, such that it is the same height above the track along its entire length. Trains collect their traction power via a roof mounted pantograph that makes a physical and electrical connection with the contact wire (that carries the current). The registration equipment helps to hold the catenary and contact wires in the correct position and staggers the contact wire laterally, so that an even wear occurs across the pantograph's contact strip as it rubs against the contact wire (Kiessling et al., 2009).

The OLE is divided into tension lengths, known as wire runs, which express the length of the contact wire, which is typically a mile on plain line track. Just before the end of a wire run the contact wire of the next wire run overlaps, as shown in Figure 2-5, so that the pantograph remains in contact with the contact wire and the trains do not lose traction power.

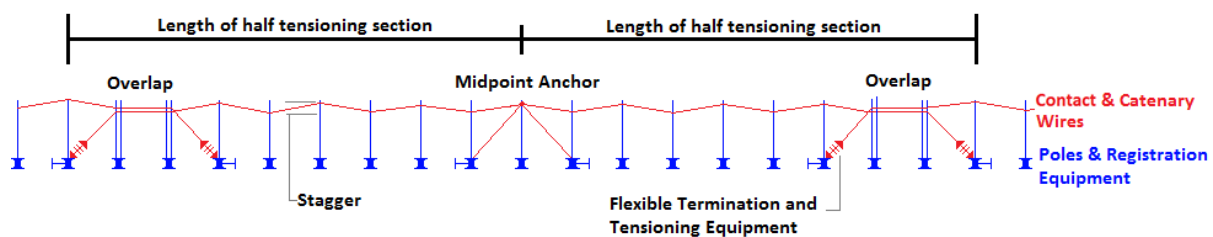


Figure 2-5 Aerial View Diagram of the OLE

An automatic tensioning system, where tensioning equipment is connected to each end of the contact and catenary wires, is commonly used. Each tensioning mechanism works through the use of wires, attached to the end of the contact and catenary wires, which pass through pulley wheels and have balance weights at the end that are free to adjust up and down. This mechanism maintains the tension in the contact and catenary wires automatically, when changes in temperature cause them to expand and contract. A midpoint anchor is required to prevent the contact and catenary wires shifting to one end of the wire run excessively.

For sections of railway containing two parallel tracks (up and down lines), the OLE system commonly contains structures, with cantilevers used to position the OLE above the track, located adjacent to each track, as shown previously in Figure 2-4. For sections of railway containing more than two parallel tracks (such as sections with up-fast, up-slow, down-fast and down-slow lines), there is often not enough room to install structures with cantilevers next to each track individually and the use of separate structures for each track can be expensive. In such cases, the OLE is not supported using structures with cantilevers, instead, headspans or portals are commonly used. Headspans consist of

cross-span wiring between structures located at either side of the parallel tracks, the OLE is then connected to these cross span wires. Portals are similar to headspans, but instead of wires spanning between structures at either side of the parallel tracks, steel or aluminium structures serve as portals/gantries to support the OLE components. The use of wires, as opposed to gantries, makes headspans a cheaper option than portals. However, with headspans, the individual catenary systems above the track can influence each other, because they are connected. Therefore, severe damage to one of these sections can result in widespread damage to the entire headspan meaning that other tracks beneath can also be affected. Portal structures alleviate these issues, due to the presence of lattice beams or solid girder structures instead of cross span wiring, making the OLE above the different tracks mechanically independent. In this thesis, the main type of OLE studied uses structures with cantilevers, as shown in Figure 2-4, because this type of system is prevalent across the entire electrified network.

2.2.2 Electrical Feeding Section

There are different methods of feeding the electrical power through the OLE and back to the feeder stations to complete the circuit in an electrical feeding section. As described previously the train obtains its power from the contact wire via its pantograph. The return current then flows through the train's wheels and into the rails. Commonly, on the British rail network, the return current is forced from the rails into a return conductor wire via a booster transformer, so that the adverse effects of inductance on signalling and telecommunications assets at track level are reduced. The return conductor then takes the power back to the connected feeding station, where the different feeding stations are approximately 60km apart. Further information about the different methods of feeding the return current can be found in Hill (1994). Earthing and bonding components also exist to provide the earth and return paths for the traction current and the safe removal of excess fault currents.

Different feeding sections, supplying the power to the OLE, are created through the use of circuit breakers at feeder station and track sectioning locations. This allows different sections of the OLE to be isolated and other sections to remain live during planned and unplanned interruptions to the system, such as during maintenance actions or after component failures have occurred. Additionally, different tracks on a line, such as the up fast and down fast tracks, can obtain their power from a different feeding section. Figure 2-6 shows a simple example of different feeding section configurations. Neutral sections are required at certain locations on the OLE to separate feeding sections with power that is transmitted at a different phase. When the train travels across a neutral section, a circuit breaker on board the train is closed so that the power from the different phases is not drawn across the neutral section. Similarly, insulated overlaps or section insulators are required

at certain locations, to allow separation of the OLE into the different feeding sections with power that is transmitted at the same phase. This research does not study neutral sections and sectioning devices in detail because these components only exist at certain locations on the OLE. Further information about these components and the other electrical power assets that control and distribute the traction power supply can be found in Kiessling et al. (2009).

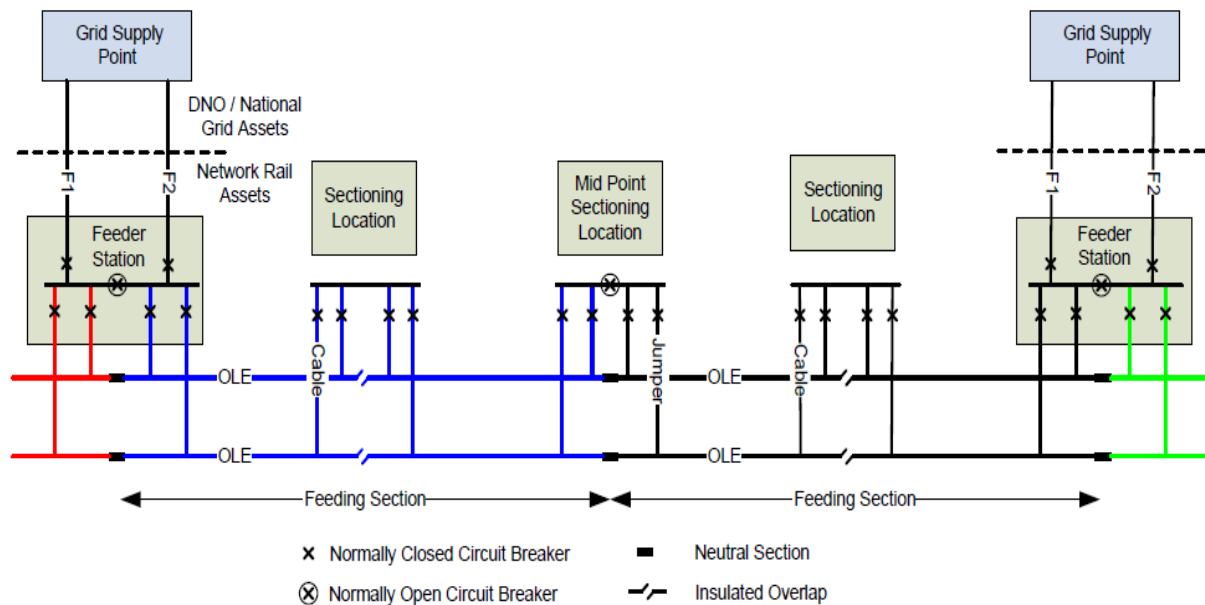


Figure 2-6 25kv AC Electrification High Level System Architecture (Network Rail, 2012)

2.3 Key Terminology

Key terminology that will be used throughout this thesis is defined as follows:

- **Span-** This is the length of OLE that extends between 2 adjacent structures. This is typically 50 to 70m in length on plain line track.
- **Wire run-** All the OLE components that are connected to, or support, a particular tensioning length of the contact and catenary wires on a section of the OLE. A wire run is typically one mile in length. Since the OLE system consists of different component types that repeat down the line in each span, a wire run is used as a useful measure for grouping all the different OLE components. A typical wire run will contain approximately 25 spans of OLE.
- **Access area-** This refers to the section of OLE that maintenance engineers can access for maintenance at the same time. From a maintenance perspective, an access area describes the region where different components can be maintained at the same time. An access area is assumed to be 2 to 3 wire runs in length.

- **Line category-** Network Rail classifies its lines into different categories according to the maximum line speed and the usage of the line (in terms of number of pantograph passages). This classification is used to determine different asset management strategies for different categories of lines, since the line speed and usage can influence the degradation and failure rates of the components. This research concentrates on the highest line category, Category 1, where the line speed is 115mph or greater and/or the number of pantograph passages per day is greater than 150. High category lines are studied because they make up the bulk of the electrified railway network and are of high importance to the overall railway network (in terms of capacity and connecting different cities).

Network Rail's asset hierarchy specifies a wire run of OLE as being an asset. Since this research considers individual OLE components, the components described previously will be referred to as different OLE component types of which there are multiple instances along a section of OLE. For instance, the droppers are considered as a component type and there are multiple droppers in place along a section of OLE. Some component types, such as registration equipment, may also contain sub-components, such as the registration arm.

2.4 OLE Component Degradation and Failure

This section provides further information about the OLE components that are studied in detail by describing how they degrade and fail. The information presented in this section has been gathered from various Network Rail sources and other literature, such as Kiessling et al. (2009).

2.4.1 Degradation Mechanisms and Drivers

According to Network Rail's Electrical Power Asset Policy (Network Rail, 2012), the principle degradation mechanisms for OLE components are as follows:

- Material ageing (influenced by environment and electrical load)
- Material fatigue (influenced by mechanical use)
- Wear (influenced by mechanical use)
- Corrosion (influenced by the environment and electrical load)
- Seizure (influenced by environment, mechanical use and electrical load)
- Loosening (influenced by mechanical use and impact)
- Loss of dimensional integrity (influenced by temperature, impact, mechanical and electrical load), track alignment and earthworks stability.
- Deterioration of electrical insulation (influenced by local environment, age, impact and electrical use)
- Obsolescence (due to loss of manufacturer support, lack of spares)
- Damage (such as vandalism, bird strikes, theft, fauna, lightning, and flood)

- Manufacturing, design or installation defect
- Load creep (system capacity exceeded by electrical load growth)

Often multiple degradation mechanisms will affect an individual component. However, there are commonly one or two mechanisms that dominate and determine the service life of a component. For example, in the case of the contact wire, the amount of wear is the main determining factor that indicates the need for maintenance or renewal of the affected component (Network Rail, 2012).

The rate of degradation is mainly influenced by:

- Environmental conditions (such as temperature, ice and water ingress and pollution)
- Equipment design (different component designs may degrade differently)
- Service demand (e.g. line speed, number of trains, power demand, number of pantograph passages)
- Local factors (such as the presence of vegetation, water ingress in tunnels).

2.4.2 OLE Component Degradation

This section describes the main features and degradation processes for each of the OLE component types that are studied in detail.

2.4.2.1 Structures

The structures that are used for OLE with cantilevers, as studied in this thesis, are commonly a universal column, with an 'H' cross-section, as shown in Figure 2-7, or a pole, with a circular cross-section. These components are made from steel and can have concrete foundations. If the foundations of a structure are built on low-bearing capacity soils, which had not been properly considered at the design stage, then they may move over time. This will result in movement or inclination of the structure and the OLE will no longer be held in the correct position. Such issues normally only occur in locations with particular types of underlying geology. Additionally, concrete foundations are subject to chemical and electrochemical erosion resulting in spalling where the timescale of such degradation is in the order of 60 years or more.

Metallic OLE components, like the structures, can degrade through numerous processes. While electrical corrosion can occur, the main form of corrosion is chemical corrosion, resulting in rust. The most prevalent section of rust for steel structures is at the base, where they connect to the foundation. Network Rail's maintenance engineers state that this process can manifest itself in just 15 years. Such positions can be protected with elastic coating systems. The rate of corrosion can be increased under coastal conditions due to the greater presence of chlorides. Similarly, the rate of corrosion can be up to six times higher in industrial regions, compared to rural countryside, due to air pollution (Kiessling,

et al., 2009). However, minor sectional loss of metal due to corrosion will not decrease the overall strength of the structure significantly. The service life of galvanised steel components, maintained through re-coating, is estimated to be longer than 80 years.



Figure 2-7 Universal Column Structure

In addition to corrosion, structures and other metallic components can degrade through deformation at extreme temperatures, mechanical overload during installation or maintenance, or due to design miscalculations, and deformation due to objects impacting with the components.

2.4.2.2 Registration Equipment

The type and design of registration equipment varies depending on the OLE type and the local conditions. Figure 2-8 shows a typical registration equipment design. The components are commonly made from steel or aluminium. The catenary wire (listed as CW in Figure 2-8) is fastened above to the cantilever tube and the contact wire is fastened below to the steady arm. The steady arm is free to move up and down at a hinge next to the drop bracket to allow the contact wire to uplift at these locations so there is not a large concentration of mass at this point along the contact wire's length. Various clamps allow for adjustment of the components. For example, the stagger and height of the catenary and contact wires can be altered by adjusting the clamps along the cantilever tube and the registration arm. Figure 2-9 shows examples of some of the clamps and fittings used in the registration equipment.

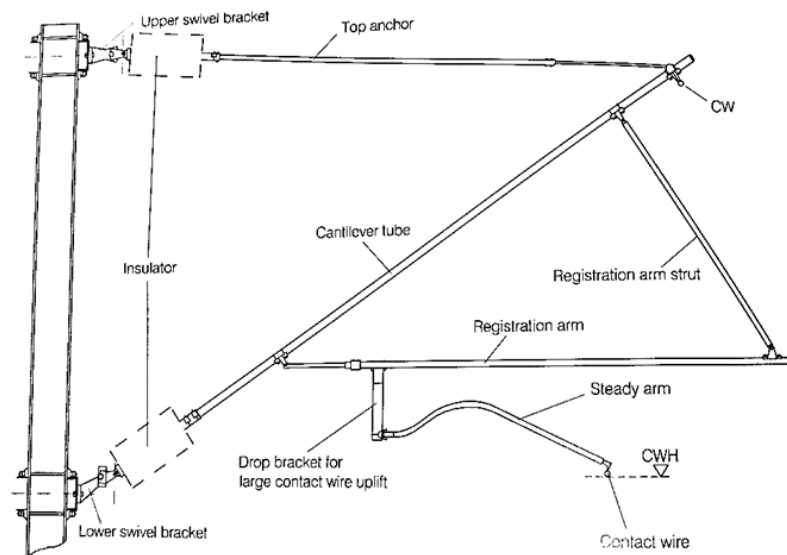


Figure 2-8 Typical Registration Equipment Design (Kiessling, et al., 2009)



Figure 2-9 Example of Clamps Used on the Cantilever Tube (left) and the Fitting to the Contact Wire (right) (Kiessling, et al., 2009)

The registration equipment will degrade in a similar manner to the structures, described previously, since it is comprised of metallic sub-components. Additionally, a loose attachment of the steady arm to the drop bracket (on the registration arm) can lead to degradation through mechanical wear and fatigue with pantograph passages, as the contact wire uplifts and the system vibrates. Over time, the registration equipment may move, or move relative to the track, causing the contact and catenary wires not to be aligned properly or to move outside of the specified height and stagger ranges. For example, changes to track geometry after maintenance (such as tamping) may result in the OLE being slightly misaligned.

2.4.2.3 Catenary Wire

The catenary wire is a stranded wire commonly made from a copper alloy, or a combination of aluminium and steel strands (as seen in Figure 2-10).



Figure 2-10 Catenary Wire

The catenary wire is subject to high electrical loads from the traction power supply and large mechanical stresses from tensile loads and vibrations of the system. The vibrations of the system, caused when a pantograph travels down the line or by strong winds, can lead to degradation through fatigue. This leads to reduced strength and cracks in the strands of the wire. The strands of wire can then burst or cage, which weakens the strength of the overall catenary wire. Vibrations in the system are highest near concentrations of mass, such as where the wires are clamped to the registration equipment. Damage to the strands of wires can also occur where the dropper wire rubs on the catenary wire at the saddle where it is connected. Electrical degradation can occur during power issues and locally under conducting clamps, which can cause sections of the wire to rapidly heat. Similarly, the formation of electrical arcs can also burn sections of the wire. Additionally, degradation through corrosion can occur, as explained previously for other metallic components.

2.4.2.4 Contact Wire

The contact wire is commonly made from hard drawn copper or a copper tin alloy. The cross-sectional area of the contact wire is specified as 107mm² or 120mm². The upper part of the contact wire is shaped to allow attachment of clamps (to connect to droppers and registration equipment), as shown in Figure 2-11.



Figure 2-11 Contact Wire (Network Rail, 2012)

The contact wire is subject to similar operational and environmental loads as the catenary wire. However, mechanical wear of the contact wire also occurs because the pantograph rubs against it.

This is the dominant degradation mode and the amount of wear is the main factor in planning for contact wire maintenance or renewal, because the wire's tensile strength decreases as its cross-sectional area is worn away. Due to the shape of the contact wire, the rate of wear experienced will be greater initially and then gradually reduce. According to Network Rail's asset policy (Network Rail, 2012), wear of 30% is used as a benchmark threshold to consider maintenance. Increased local wearing of the contact wire commonly occurs near concentrations of mass, such as near the registration equipment. At these points there are greater contact forces between the pantograph and contact wire, which can lead to increased wearing. There may also be temporary loss of contact between the contact wire and pantograph close to these locations (where the contact force will actually be zero) and this can result in arcing between the contact wire and the pantograph's collector strip. This arcing can anneal the contact wire's surface, changing its metallurgical properties, which can result in faster wearing at these locations. Contact wire wear at crossovers is also often greater due to poor set-up and greater contact forces. Track geometry changes, relative to the contact wire, can also result in larger variations in contact force. However, the train's suspension systems alleviate this to some degree.

Where sections of the contact wire have locally exceeded the wear limit then the worn section can be removed and replaced with a new splice of contact wire, rather than renewing the whole wire run/tension length of contact wire. These splices can change the system's behaviour due to different interactions with the train's pantograph as it runs beneath the splice. The installation of splices can lead to faster degradation of the contact wire and other components near to it and the splice itself can represent a weak point in the system.

2.4.2.5 Droppers

Droppers are short lengths of wire, commonly made from copper, that connect the contact wire to the catenary wire, as shown in Figure 2-12. These components are subject to electrical and tensile stresses. The vibrations of the system can lead to degradation through fatigue, which can reduce the strength of the wire and cause it to part. If the dropper has snapped but it is clear of the contact wire, then the system will remain operational and the dropper will be scheduled for maintenance. If a dropper is defective, i.e. it is missing or has snapped, then the remaining droppers in the same span will be under additional stress. If numerous droppers are defective in the same span then the contact wire's height relative to the track can drop and increase the risk of the pantograph snagging the wire and causing a system failure, therefore, rapid response maintenance must take place. Similarly, if a dropper has snapped and is not clear of the contact wire (for instance it is wrapped around the contact

wire) rapid response maintenance must take place to prevent the risk of the component becoming snagged around a train's pantograph and causing a system failure.

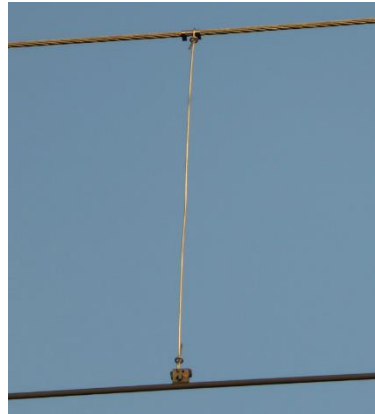


Figure 2-12 Dropper

2.4.2.6 Return Conductor

The return conductor is commonly made from strands of copper or a copper alloy wire, as shown in Figure 2-13. It will also degrade through fatigue, like the catenary wire, but it is not subject to the same mechanical loading, because it is not part of the catenary system so it will not vibrate due to the passage of the train's pantographs. Degradation through corrosion can also occur, as explained previously for other metallic components.



Figure 2-13 Return Conductor

2.4.2.7 Insulators

Insulators separate energised OLE components from earth. They attach the registration equipment, which is connected to the live components, such as the contact wire, to the structures, as shown previously in Figure 2-4. Therefore, in addition to electrical stresses, the insulators are subject to tensile and compressive forces, as well as bending moments. The insulators used on the British railway network are porcelain insulators (shown in Figure 2-14), made from ceramic materials, and polymeric insulators, where resins, plastic and silicone materials are used. Polymeric insulators are now

preferred by Network Rail, due to greater tolerance of pollution and weathering. Unlike porcelain insulators, a mechanical failure of a polymeric insulator is less likely to result in it breaking into pieces (which can cause the registration equipment to drop and lead to a dewirement).

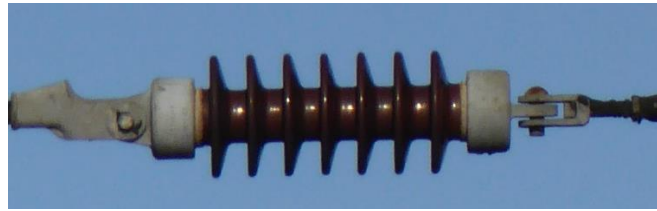


Figure 2-14 Insulator

The main degradation of insulators involves erosion and damage to the surface of the components. A common cause of this degradation is by flashovers, where the air around the surface of the insulator conducts current causing an electric arc along the outside of the insulator. Flashovers can be caused by bird strikes, severe pollution or overvoltage due to lightning. Whilst the insulators are designed to withstand flashovers, the arcing damages their surfaces and can partially destroy the sheds, which can increase the likelihood of further flashovers and potentially lead to fractures of the component. Erosion and early ageing can occur on moist and polluted insulators. Pollution can be particularly high on railway insulators due to diesel train usage on electrified lines. In addition, pollution is generally worse in tunnels where rainwater is not present to wash them. The above mechanisms can all degrade the insulators, reducing their strength and increasing the likelihood of a mechanical failure.

2.4.3 The Effect of Degradation

The effect that component degradation has on the operation of the system depends on the component type and the amount of degradation. For example, due to poor set up of a wire run, where components such as the registration equipment are misaligned, there can be a steep or changing gradient of the contact wire along the wire run. This can result in the contact force, produced by trains' pantographs as they traverse the contact wire, having greater variation. A greater variation in the contact force results in larger fluctuations of the catenary system, i.e. the catenary and contact wires, droppers and steady arm on the registration equipment will fluctuate to a greater extent with pantograph passages. This can lead to faster degradation of these components through fatigue. However, it is very difficult to quantify the amount of increased degradation that is encountered because the interactions between OLE components and the contact wire and the pantograph are so complex.

Component degradation usually has no adverse effect on the timetabled train service. Eventually, components will degrade to the extent that the probability of their failure increases significantly, at

which point Network Rail aims to maintain them to prevent service affecting failures. For example, if the catenary wire has a burst strand, electric trains will still be able to obtain their traction power from the OLE with no issues. However, the section of the affected catenary wire will have an increased chance of failure.

2.4.4 Quantifying Component Degradation

For some OLE components, their condition can be determined using a quantitative, measurable value, such as the thickness of the contact wire. However, due to the nature of certain OLE components and their degradation modes, there is often no quantitative, measurable, indicator that can be used to determine their condition. Instead, qualitative measures expressing the amount of corrosion or the extent of mechanical damage are often used. Determining the amount of degradation required for a component to be maintained can, therefore, be difficult and subjective. For some components, this level of degradation will result in the presence of a defect that can be recognised and recorded during an inspection, such as misaligned steady arm on the registration equipment, or a burst strand on the catenary wire.

Table 2-1 shows the estimated service life and the different defects that commonly occur due to degradation of each of the OLE components that are studied. These are the component defects that the Network Rail maintenance standards (Network Rail, 2011) list and specify the corresponding maximum scheduling times for their maintenance.

Table 2-1 Estimated Component Service Life and Summary of Defects Related to Component Degradation

Component	Service Life	Defect
Catenary Wire	60 – 80 years	Stranded, caged or damaged wire
Contact Wire	60 – 80 years	Damaged, kinked, abnormal wear on wire
Dropper	75 years	Snapped, misaligned, worn saddle, fallen off
Insulators	80 years	Coated in dirt/pollution, arcing damage, mechanical damage, broken shed.
Registration Equipment	70 years	Misaligned, damaged or seized components, wire stagger or height out of specified tolerance
Return Conductor	80 years	Stranded wire, incorrect tension, damaged insulation.
Structures	80 – 120 years	Corrosion/damage, movement of foundations

2.4.5 OLE Component Failure Modes and Causes

The large number of components that make up the OLE system (and the number of different OLE system designs) means that there are a variety of failure modes. Substantial degradation of a component will leave it in a condition similar to a failed state, even if the overall OLE system still works (albeit with an increased risk of failure and probably reduced functionality). In any case, if such degradation was revealed by maintenance engineers, the line would have to be closed or speed restrictions imposed for electrified trains, until the issue is rectified.

Detailed information about the failures of the different OLE components was obtained from a Failure Mode and Affects Analysis undertaken by Network Rail (Network Rail, 2012). The following modes of failure are considered for the OLE components:

- Detached component
- Fractured component
- Stranded conductor
- Parted conductor
- Melted component
- Loss of dimensional integrity
- Failure to maintain electrical clearance
- Failure to maintain acceptable pantograph forces
- Failure to allow free pantograph passage
- Obstruction of train gauge
- Failure to maintain electrical feeding

The degradation of OLE components, described earlier, can worsen to the extent that the component eventually fails. For example, the catenary wire may be degraded such that some of the strands of the wire are burst. Over time, more strands can become damaged and eventually the strength of the wire will deteriorate to the extent that it will completely break in two, unless maintenance is undertaken. Manufacturing defects and installation errors can also be a cause of failure. For instance, an incorrectly fitted steady arm on the registration equipment may become detached.

Many failures of the OLE are also due to third party influences, such as vandalism induced damage to the components. Other failure events that are often random and generally out of Network Rail's control can result in the failure of OLE components too, examples include bird strikes and extreme weather events causing damage to the components that results in their failure.

2.4.6 OLE Component Failure effects

The consequences of component failure are heavily dependent on the type of component and the severity of the failure. Some failures encountered on electrified lines result in the circuit breaker, which controls the electrical power supply to a section of OLE, being tripped if a live OLE component comes into contact with earth. This stops the trains obtaining power until the circuit is re-connected and prevents trains continuing to travel through areas where components have failed.

A large number of such situations are not directly due to failure of the system's infrastructure but, instead, due to external influences, such as vegetation or birds short-circuiting the system. Since many of the trips are attributable to events where the OLE has not failed so it is safe to re-energise the OLE, when the circuit breaker is tripped, the system operator will wait 2-3 minutes and then attempt to re-close the circuit. If successful, the train service will resume and an inspection of the affected area will then be scheduled to take place to inspect for damage. If the circuit fails to close after a trip, then a more serious failure involving the OLE is likely to have occurred. The system operator will contact nearby train drivers to see if they know the issue and a rapid response maintenance team will be sent out to address the problem. If the OLE is unusable, then electrified trains will have to be towed to a usable section of line by diesel locomotives.

Since a live part of the OLE has to come into contact with earth for the system to trip, many component failures will not result in the power supply being immediately tripped. Some component failures, such as droppers, will also have no effect on the system, unless several fail in the same span between structures causing the contact wire to drop considerably. Many component failures will be identified by rail users, commonly the train drivers, who will alert the route operators immediately.

Occasionally, some components may fail when a train passes through or the train's pantograph will make contact with a broken component whilst travelling at speed. This can result in what is known as a dewirement, where the conducting wires fail and collapse. The train's pantograph can snag and continue to drag further sections of wire down. Other nearby components, such as the registration equipment, can also be severely damaged during the process. The consequences of such a failure are often considerable, with a large amount of delay minutes often being incurred, as well as being a safety risk for rail users.

If the failure of the OLE results in delays, such that the timetabled train service cannot be met, then Network Rail pay fines to the train operating companies whose service is disrupted. These fines are referred to as Schedule 8 payments (Network Rail, 2012). Their cost is based on the number of delay minutes, but different routes can have slightly different rules for calculating the cost based on the

delay minutes. The costs that Network Rail pay in fines for a failure of the OLE are generally significantly greater than the cost of repairing the failed components.

2.4.7 Summary of OLE Component Failures

In this thesis, OLE component failures refer to failures that result in delays to the timetabled train service. Table 2-2 summarises the common failure modes of the different OLE components. The failures can occur with different severities and also lead to the failure of other nearby components. Failure rates, obtained from a Network Rail document that analysed component failures on the East Coast Main line (Network Rail, 2014) are also shown in the table. It shows the rate of service affecting failures expressed per km of standard track, per year. This research considers the effects of the failures in terms of the costs incurred to Network Rail. Historical data of delay costs, due to component failures, is used for analysis (this is described later in section 2.6.2).

Table 2-2 OLE Component Failure Modes and Failure Rates

Component	Failure Mode	Failure Rate per km per Year
Catenary Wire	Parted wire (leading to a dewirement), or severely stranded wire to the extent that the line must be closed to prevent it parting.	0.0029
Contact Wire	Parted wire (leading to a dewirement), or severely worn wire to the extent that the line must be closed to prevent it parting.	0.0090
Dropper	Detached dropper- If wrapped around or below the contact wire then the issue needs to be rectified immediately to prevent a train's pantograph snagging and potentially dragging down the OLE. If a dropper fails and is clear of the contact wire, it is not a service affecting failure and it will be replaced during a scheduled maintenance visit. Standards state that if 3 or more droppers are off in the same span then immediate repair must take place as the system cannot safely allow pantograph passages.	0.0097
Insulators	Electrical Failure- failure to provide insulation. Mechanical Failure- cracking, corrosion, or fracture can result in the insulator becoming detached which could also cause the registration equipment to collapse.	0.0020
Registration Equipment	Mechanical failure of sub-components – such as misaligned, damaged or detached component, severely seized components.	0.0016
Return Conductor	Parted wire.	0.0031
Structures	Movement and corrosion of structures is a slow process and issues are normally detected and rectified before a catastrophic failure occurs. Impact from a train or other object can cause the structures to fail. Service affecting failures of structures are extremely rare and are not considered in this thesis.	n/a

2.4.8 Failures due to External Influences

There are also service affecting failures that are related to the presence of the OLE but are not explicitly caused by the OLE components and they do not result in failure or damage to the OLE components. These failures are commonly characterised by tripping of the electrical supply, resulting in a disruption to the timetabled train service, although a failure of the OLE did not occur. In this thesis, such failures are referred to as failures due to external influences.

Such failures are commonly caused by bird strikes or encroaching vegetation causing the electrical supply to short circuit but do not result in damage of any components. The consequences of these failures are low, as their rectification commonly involves simply re-connecting the circuit to allow the trains to travel down the line. However, their occurrence is frequent in comparison to other failures associated with the OLE. Similarly, objects can become caught in the OLE, such as carrier bags or balloons, and disruption to the service may be required in order to remove the object so that it does not become caught around a train's pantograph and cause a serious failure. The misreporting of component failures can also result in service disruption as the line has to be closed while engineers assess the situation. The occurrence of these failures is random and in this thesis they are collectively referred to as external failures.

2.5 OLE Asset Management Intervention Actions

For all the different assets on the rail network, Network Rail undertakes various intervention actions to uphold the system's availability and meet the capacity and safety requirements. For OLE operation, inspection and maintenance regimes have been devised and standardised. Information about the asset management practices undertaken on the British rail network has been obtained from Network Rail maintenance standards (Network Rail, 2011) and interviews were conducted with Network Rail staff and maintenance engineers as part of this study. The main intervention actions undertaken involve the inspection or maintenance of the components. This section describes the intervention actions that Network Rail carries out on OLE.

2.5.1 Component Inspection

The most common inspection regimes are described as follows:

- **Cab patrol**- Maintenance engineers evaluate the system whilst riding on a train (at a slow speed). Issues such as disconnected wires, vegetation growing in close proximity and component breakages are detected.

- **Non-intrusive ground level inspection-** Maintenance engineers walk along the track to evaluate the system. The same issues as those detected through cab patrol are flagged and more detailed issues, such as mechanical wearing of components, cracked insulators and misalignment issues, can also be diagnosed.
- **High level intrusive inspection-** The section of line being inspected is isolated and maintenance engineers diagnose the system at a high level (at contact wire height). The closer proximity to the components allows a detailed inspection to take place, such that any issues should be detected. Various fittings and bolts are also checked tightened (to the correct torque settings) and grease reapplied to components where required. This inspection type requires track possession and the section to be electrically isolated. It is, therefore, undertaken out of service hours. During this period, where possible, any pre-existing work scheduled to maintain components in the area inspected is also undertaken (Network Rail, 2015).

Train-borne diagnostic systems can also be used to monitor the system. For example, Network Rail uses the New Measurement Train that is fitted with equipment that can measure contact wire height, stagger and wear, as the train travels down the line. Thermal image surveys can also be used to identify abnormalities in certain components, such as insulators and contact wire splices.

The inspection regimes take place at fixed intervals based on the category of the line. The category of a line is based on its maximum line speed and the number of pantograph passages across the line per hour. For the highest category lines, Network Rail specifies that a cab patrol should take place every 14 days, a ground level inspection every 28 days and a high level intrusive inspection every 4 years. These inspection intervals are based on past experience of the lifetime of the components. As a maintenance team is responsible for a large length of line, the inspection and maintenance of different sections of a line will take place at different times. A discussion with Network Rail maintenance engineers revealed that for ground level inspections, the experience of the person undertaking the inspection can influence the probability of all the component defects/issues being correctly identified.

Due to the nature of OLE components and their degradation, there is often no quantitatively measurable parameter that can be used to determine their condition. As discussed previously, most components will remain perfectly operational until they fail. Therefore, the maintenance engineers need to recognise component defects that signify that the component has degraded to the extent that maintenance is required. Recognising such defects can be difficult and subjective, but maintenance engineers who were interviewed stated that experienced staff are capable of recognising all the common component defects during a low level inspection. The common defects, associated with each OLE component type studied in detail, and the corresponding state of degradation that they represent

are listed in later Table 2-4, in section 2.5.5, which summarises the asset management actions undertaken for the OLE.

2.5.2 Component Maintenance

Currently Network Rail undertakes the following 3 maintenance regimes:

- Condition-based maintenance
- Fixed time interval preventative maintenance
- Reactive rapid response maintenance (corrective maintenance)

During condition-based maintenance, components will be maintained when their condition has degraded to the extent that maintenance is required to reduce the probability of component failure. The condition-based maintenance regimes rely on the regular inspections, described earlier, to identify defects. The inspection frequency is pre-determined, and based on experience of the components' behaviours. The results of an inspection determine what maintenance must be undertaken. This represents a risk-based maintenance regime, where maintenance is scheduled depending on the criticality of the defect found and the line category and the maintenance scheduling time is based on experience of the component's behaviour. The maximum durations that maintenance must be completed by are listed in the maintenance standards as being rapid response, 24 hours, 36 hours, 7 days, 28 days, 6 months, 1 year or 2 years. The maximum maintenance scheduling time for a certain component defect depends on the severity of the defect or degradation, such that more severe defects, where there is a greater likelihood of the component failing, are assigned a shorter maximum timeframe to be maintained within. The maintenance actions commonly involve like-for-like replacement, re-adjustment/re-aligning, tightening and cleaning. Certain issues that have been diagnosed may require additional technical advice to specify the maintenance procedure. The period that the maintenance engineers have access to an area of track, to perform maintenance, is referred to as a possession.

Preventative maintenance of some components is carried out at fixed time intervals to maintain their condition. This form of maintenance is only undertaken on a few component types, such as neutral sections, which have relatively high failure rates. These components are not studied in detail in this thesis.

Network Rail has made a concerted effort to move towards a risk-based maintenance strategy, where maintenance is scheduled based on the condition of different components, for all their different asset types. Condition-based maintenance is therefore the most common maintenance action currently

undertaken. However, until recently, fixed time interval preventative maintenance of all the component types was more common.

Reactive rapid response maintenance occurs when a component has failed (causing the system to trip) or a severe issue has been detected. A rapid response team is sent out to rectify the issue as soon as possible to reduce the number of delay minutes. For some large scale failures, the maintenance engineers may attempt to secure the OLE safely so that it does not interfere with non-electrified train travel or trains on the neighbouring tracks. If the area damaged is short enough then electrified trains can lower their pantographs and coast through the affected area. This way service interruptions and delay minutes can be reduced. The damage will then be fully repaired during a scheduled maintenance possession. The condition of other components may also be improved as a result of the repairs. For instance, if the contact wire requires re-wiring then the registration equipment may be adjusted to improve its functionality.

The maintenance of most OLE components, via any of the regimes described above, usually requires the section of line being maintained to be electrically isolated so that the work can be safely carried out. To ensure that an isolation is correctly applied, there are special procedures in place that only qualified members of staff are permitted to perform.

2.5.3 The Scheduling of Planned Maintenance

The rail system as a whole is comprised of numerous different asset types, each requiring regular maintenance. Since maintenance needs to be scheduled to occur, so that it does not interfere with timetabled train services, it is commonly undertaken during the night/early hours of the morning when trains are not running. Maintenance engineers can then gain access to track without interfering with the timetabled service. For some larger maintenance actions that may take longer to complete, a possession may have to be scheduled during the timetabled service hours meaning delays will occur and delay costs incurred. However, because the delay minutes, due to the possession, are planned, the costs incurred are not as large as during unplanned outages of the service arising from failures.

OLE maintenance commonly requires the use of a road rail vehicle, a vehicle that drives on the tracks and has an articulated deck for the maintenance engineers to work from, shown in Figure 2-15. The maintenance of OLE components is undertaken separately to the maintenance of other assets, such as signalling or the track, and cannot be scheduled to occur in the same place and time as when other work is scheduled. This is because the maintenance of other railway assets also requires full access to the track. Furthermore, the road rail vehicle can only access the track at certain access points.

If other asset groups are being maintained between the access point and the section of OLE needing maintenance, then the road rail vehicle cannot get there. The maintenance engineers will try to group together the maintenance of components in certain areas to efficiently use the access they have been granted. This results in certain areas of line where all the OLE components in the area can be accessible for maintenance during the same possession, the typical length of one of these access areas is 2 to 3 wire runs. However, the amount of time that the area is available for access and the number of available maintenance engineers will also limit the amount of work that can be completed during the possession. As a result of these constraints the scheduling process can be very complicated.



Figure 2-15 Road Rail Vehicle (Network Rail, 2015)

2.5.4 Other Intervention Actions

In addition to maintenance, renewals and refurbishments are undertaken to improve component condition. Refurbishment involves the maintenance or renewal of some or all of the components, of a certain type, in a wire run. Such work will not only improve component condition but can also improve the performance of the system as a whole. Network Rail can propose an extensive amount of such work to take place on a wire run to improve its overall quality to a desired level. This is referred to as a campaign change. The refurbishing and upgrading of various OLE components can result in a previously degraded, or low line speed, electrified line being able to safely support higher train speeds and trains with multiple pantographs. The work undertaken will primarily involve adjusting the registration equipment, so that the heights and staggers are within specified ranges and tensioning the system sufficiently. New component types may also be introduced or replace previous components. These changes can also improve the reliability of the system.

The renewal of the contact and catenary wires is a major undertaking, due to their length and interaction with all the other components. This thesis refers to such renewals as large scale renewals. The contact and catenary wire may be scheduled for renewal near the end of their service life, when they are likely to have degraded extensively across their entire length.

Due to the large quantities of work needed to be undertaken during the intervention actions mentioned above, it is likely that an extended possession of the line is required to complete the work. An extended possession will result in additional costs being incurred due to a disruption to the timetabled train service. It is therefore more cost effective to try to complete as much maintenance as possible during the possession of the line.

2.5.5 Summary of Asset Management Actions Considered

This study models all of the different inspection regimes that Network Rail undertakes. The fact that the different inspection types (such as cab patrol or high level intrusive inspection) have different capabilities with respect to revealing different component defects is also considered. The inspection intervals specified in Network Rail's standards are followed.

The condition-based maintenance of degraded components and the rapid response maintenance that takes place after a failure event are considered. Fixed time interval preventative maintenance is not considered as the components studied in detail are not subject to such a maintenance regime.

In order to model the scheduling of maintenance as accurately as possible, the fact that the maintenance of different components that require maintenance in the same access area is often undertaken opportunistically during the same maintenance visit is considered. Opportunistic inspection of nearby components during the maintenance of a component, should also be accounted for.

The different maintenance actions undertaken to rectify component degradation are listed in Table 2-3. Note that the same maintenance action is undertaken to rectify the failure and degradation of a component, but maintenance after a component failure will occur as soon as possible to reduce the disruption to the service. For maintenance dealing with component degradation, the component maintenance scheduling times can be found by looking at the Network Rail maintenance standards, which specify the maximum times within which maintenance must be completed for a given defect for each component type. These times are listed for each component defect, along with the inspection regimes that reveal the defect, for a high category line in Table 2-4, at the end of this section. The corresponding inspection intervals are listed in Table 2-5.

Large scale renewal works (such as the renewal of the contact wire) and other upgrade works are considered in this thesis. Information regarding the costs of the inspections, maintenance actions and replacement of components can be used to enable the asset management intervention actions to be considered as part of a life cycle cost analysis.

Table 2-3 Component Maintenance Actions

Component	Maintenance Actions
Catenary Wire	Wrap up degraded section or insert new splice of wire to replace degraded section
Contact Wire	Insert new splice of wire to replace degraded section
Droppers	Replace
Insulators	Replace
Registration Equipment	Replace degraded sub-component (e.g. steady arm) or repair through adjusting or tightening components.
Return Conductor	Repair damaged section (possibly insert new splice of wire)
Structures	Painting to protect from corrosion, adjustments to foundations
Adjustments to Wire Run	Adjusting components across the wire run (such as registration equipment) to ensure correct set up of the system.

Table 2-4 Component Degradation Conditions and Maximum Maintenance Scheduling Times for High Category Line

Component	Condition					
	Degraded			Severely Degraded		
	Description	Inspection Regimes Revealing Degradation	Maximum Maintenance Scheduling Time	Description	Inspection Regimes Revealing Degradation	Maximum Maintenance Scheduling Time
Catenary Wire	Singly stranded or caged, minor damage	Low Level Inspection, High Level Inspection.	6 months	Multi stranded or severe damage	Low Level Inspection, High Level Inspection.	7 days
Contact Wire	Excessive Wear or damage	High Level Inspection, NMT*.	1 year			
Dropper	1 dropper broken in a span (not below contact wire), misaligned droppers	Cab Patrol, Low Level Inspection, High Level Inspection, Train Driver Reports.	7 days			
Insulator	<3 sheds broken or minor damage	Low Level Inspection, High Level Inspection.	2 years	≥ 3 sheds broken, or damaged core, or major damage	Low Level Inspection, High Level Inspection.	7 days
Registration Equipment	Damaged, misaligned, or seized	Low Level Inspection, High Level Inspection	2 years			
Return Conductor	minor damage, incorrect tension	Low Level Inspection, High Level Inspection.	2 years	Major damage or sagging considerably	Low Level Inspection, High Level Inspection.	28 days
Structures	Excessively Corroded, or damaged, or leaning	Low Level Inspection, High Level Inspection.	2 years			
Adjustments to Wire Run	Incorrect stagger or height, poor set-up, along-track movement	Low Level Inspection, High Level Inspection, NMT*.	2 years			
*NMT = New Measurement Train						

Table 2-5 Inspection Intervals for High Category Line

Inspection Type	Inspection Interval
Cab Patrol	14 days
Low Level Inspection	28 days
High Level Inspection	4 years
New Measurement Train	1 year (assumed)

2.6 Data Collection and Analysis

It is important for infrastructure organisations, such as Network Rail, to have good quality, easily available information about their assets, in order to make informed decisions and understand the current condition and requirements of the system. The use of computers can help significantly with this process to allow large amounts of data to be stored and accessed easily. Collecting data about all the assets and processes that are undertaken as part of the asset management strategy can improve the overall knowledge of the system. As described later in this thesis, when describing the asset management strategy framework for railway infrastructure organisations in section 3.2.4 of the literature review, asset information is a key enabling mechanism for the overall asset management strategy. For example, Network Rail now record their maintenance work digitally, where the components found to require maintenance during routine inspections and maintenance actions are added to a database and a work order is opened. This information is then used to recall which components require maintenance. Upon completion of the maintenance, the database is updated and the work order is closed.

The collection of historical data describing component condition, component maintenance actions and component failure events over time can allow analysis of the degradation and failure rates of the components to be undertaken. This knowledge is imperative for creating accurate asset management models that aim to predict the future behaviour of the system and the associated costs. This section describes the maintenance data that is currently collected by Network Rail and discusses its suitability for analysis. As part of this study, Network Rail's failure data was analysed to separate the failures for each component type and investigate the effects and severity of the failures, in terms of the costs incurred due to the disruption to service. A description of the failure data and this analysis is provided, followed by recommendations for improving the current data collection processes, to allow more detailed analysis to be undertaken in the future.

2.6.1 Maintenance Data

A Network Rail database called ELLIPSE contains information about the maintenance actions undertaken on the railway network. For OLE components, every maintenance action undertaken should be recorded for every component maintained on every electrified line. Each record contains numerous details, such as the component type, defect type, component location, date at which the defect was discovered and the date that maintenance was undertaken. However, there is no information regarding the initial installation date of the component that was maintained so one cannot observe the components' lifetimes. There are also a few issues with the accuracy of the records;

occasionally component defects are entered under the wrong defect code, or an inspection is listed instead. For the OLE, ELLIPSE records start in 2002 but the entries are scarce with many areas of the network not containing records until around 2007.

The scope for detailed analysis using ELLIPSE data was limited because the records began after most electrified lines had already been operational for many years. There was no information about the number of each component type on each line and the components' installation dates were unavailable. Therefore, based on the current information available in ELLIPSE, there is no real opportunity to perform a detailed lifetime analysis to fit a distribution describing the time it takes a component to degrade to the extent that maintenance is required. Consequently, analysis of this data has not been undertaken in this research. Recommendations for how the data collection can be improved to allow detailed analysis to take place are provided in section 2.6.3.

2.6.2 Failure Data

When a failure occurs on the network, information about the failure is recorded in a database called the Failure Management System (FMS). Within this database, each failure record contains information regarding the date that the failure occurred, the location of the failure (including what line it was on and the start and end yardage), the type of system/asset (e.g. track or OLE) that failed, a text field that describes the failure details, a text field describing the causes of the failure and a text field containing the actions undertaken to rectify the failure.

Another database, called TRUST, contains more detailed information about the effects of failures that resulted in a disruption to the timetabled train service. Within this database, the main information contained for each record is the time and date that the issue was raised, the time and date that the issue was rectified, the number of full and part cancellations of trains (although most of this data appears to be missing), the number of delay minutes incurred (for all the affected trains), the costs incurred due to the delay minutes and the other costs incurred (due to rectifying the failure). If the failure record in FMS was service affecting, it will contain a reference to the corresponding record in the TRUST database, which provides information about the effects of the failure.

Data from the FMS and TRUST databases that contained all of the failures between March 2009 and March 2015 was obtained. The data was contained in a Microsoft Access database file so that queries could be run to extract the relevant information required for analysis. Firstly, the FMS data was filtered so that only OLE component failures were present, this left approximately 35000 failure records. The majority of the FMS records did not have a TRUST reference, meaning the failure was not service affecting. Many of the records involved failures due to external influences (such as objects on the OLE)

that were rectified without causing disruption to the service. Additionally, many of the records that described a non-service affecting component failure actually referred to component degradation, as the failure action text field often described the defect as being scheduled for repair as part of normal maintenance. These records were not considered to represent component failures in this study. Instead, only the FMS records with a TRUST reference (meaning the failure was service affecting) were considered. This left approximately 5500 failure records.

Each record of FMS data for OLE with a TRUST reference was combined with its corresponding TRUST record. Then, an attempt to separate the failure records for the different OLE component types was made. This was not an easy task because there was no data field containing the component types. Instead, text searches of the text fields describing the failure details, failure causes and failure actions had to be made. Some macros were developed using VBA in Microsoft Access and Excel in order to speed up this process using keywords to search for the different component types, but many of the failure records had to be reviewed manually to identify the component that had failed. The main findings from this analysis are presented in the following sections.

2.6.2.1 Number of Service Affecting Failures

Table 2-6 shows the number of failures for different failure types over the period analysed. There were 700 events associated with the failure of one of the main OLE components studied in this thesis. The number of failures for each of these components is shown later in Figure 2-16.

Table 2-6 Total Number of Service Affecting Failures of the OLE Between March 2009 and April 2015 for Different Failure Causes

Failure Cause		Number of Failures
Main OLE Components		700
Insufficient information		339
Other OLE Components		286
Failures due to External Influences	No Fault Found	223
	Object on OLE	1422
	Trip	2722

There were 339 records that did not contain enough information to ascertain which component was associated with the failure. If more information was available in written reports about the failures, the

large number of failures in this group could have been categorised with the corresponding components that caused the failure. There were 286 records showing the failure of other OLE components (such as neutral sections, sectioning devices and earthing and bonding), these failures are not studied in detail in this thesis.

The vast majority of the failures during the period analysed were failures due to external influences. As described previously in section 2.4.8, these failures are service affecting failures that are related to the presence of the OLE but are not caused by the failure of any OLE components and do not result in damage to any of the OLE components.

There were 223 failure records for events where no fault was found. These records commonly involved a report of a component failure resulting in the line being closed whilst maintenance engineers investigated the location where the failure was believed to have occurred. After finding no problems the line was then re-opened. There were 1422 failure records for events that refer to an object being on the OLE. These records commonly involved an object, such as balloon or plastic bag, being blown onto the OLE such that it was in danger of coming into contact with the contact wire. As a result, the maintenance engineers needed to close the line and remove the object. The main cause of external failures was due to a trip of the power supply, with 2722 occurrences of these events affecting the service. The failure records showed that this was commonly due to bird strikes and encroaching vegetation. During these events the power was commonly re-connected shortly after it first tripped. The number of external failures is far greater than the number of component failures. However, because the rectification of these external failures is often very fast, the service disruption encountered, in terms of the delay minutes and costs, is normally not excessive.

Figure 2-16 shows the number of service affecting failures for the main OLE component types over the period analysed. Note for the structures there were only 2 service affecting failures found so they are not included in the figure. Droppers failed the most out of all the components, however, in many of these failures the component was detached such that it could be dealt with during the normal maintenance regime but the train drivers contacted the route operator saying the component could be close to the contact wire, where it could be snagged by the train's pantograph, and the line had to be closed briefly to assess the situation. As a result, many of the dropper wire failures did not result in large disruptions to the service.

Number of Service Affecting Failures Between March 2009 and April 2015 for the Main OLE Components

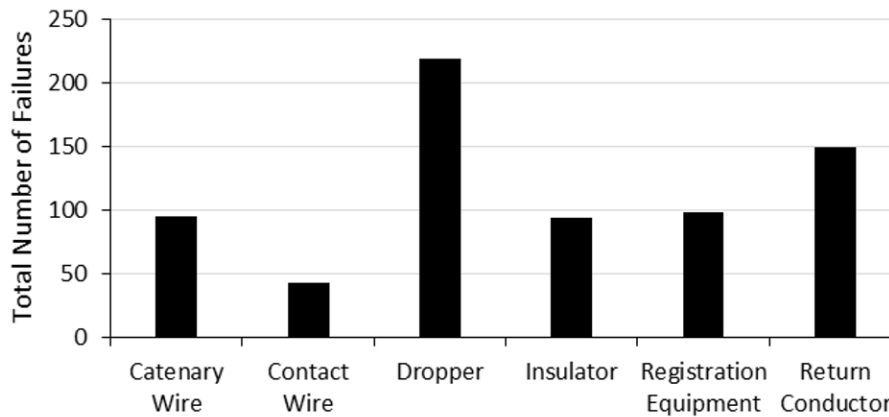


Figure 2-16 Number of Service Affecting Failures for the Main OLE Components Between March 2009 and April 2015

Many of the return conductor failures were due to theft which was associated with only a few geographical areas. Network Rail has taken measures to reduce return conductor theft and since 2012 the number of thefts has reduced considerably. The low number of contact wire failures is potentially attributable to the large volume of records that did not have enough information to determine which component failed. It is likely that many of those records were associated with the failure of the contact wire, as the failures were often referred to as a dewirement, but there was no record of the component that caused the failure.

Because many of the records did not contain sufficient information to correctly identify the component that failed, an accurate analysis of the overall failure rate for the different component types could not be undertaken. However, because the failures have been separated for the different component types, the effects of the failures for different component types can be studied. This is shown in the next section.

2.6.2.2 Effect and Severity of Component Failure

Each failure record that is considered contains information about the effect of the failure, in terms of the impact on the service. The main information relating to the effect of the failure is the time to rectify the failure (or the downtime of the system), the number of total delay minutes for the affected trains and the delay and non-delay costs associated with the service disruption and rectification of the failure.

The time to rectify the failure can be calculated by considering the time that the failure occurred and the time that the failure was rectified. However, for the majority of the records, the time that the failure was rectified is not provided meaning the downtime of the system cannot be calculated. The number of total delay minutes for the affected trains can be found and used as an indicator to express the severity of the failure. However, the values for the delay minutes are related to the number of affected trains at the time of failure, as a result the values can be confusing as they don't correspond to the amount of system downtime incurred.

The delay costs that are incurred as a result of the failure are similar to the delay minutes in that they are also dependent on the number of trains affected during the failure, but, these costs can be used directly in a life cycle cost model. Therefore, in this thesis, because data was not available to accurately consider the downtime of the system after a failure event, the delay and non-delay costs are considered instead. This allows the severity of a failure to be considered in terms of the cost that was incurred as a result of the failure. As mentioned previously, the delay costs are incurred in the form of a fine that Network Rail pays to the train operating companies due to the failure and is proportional to the number of delay minutes incurred. The delay costs normally far outweigh the non-delay costs (which represent the cost of the repair work).

The overall costs of a failure, the sum of the delay and non-delay costs, are therefore directly related to the severity of the failure. The failure costs have been analysed for the different component types. At the request of Network Rail, numerical information about the values of the costs are not provided in this thesis but a description of the analysis and a brief comparison between the failure costs of the different components is given.

Higher category lines generally have a higher usage, therefore, they are more likely to incur greater delays (hence greater costs) after a failure. The category of line was estimated by combining information from a track database that contains the line category for each yard of a line. Where a failure occurred on a section of line containing parallel tracks with different line categories, the text fields describing the failure were read to see if the engineer wrote what track it was on (e.g. up fast) in order to determine which track the failure occurred on. All the failure costs for each failure of a component type on a high category line were then found, which allowed a comparison between the failure costs of the different component types to be made. For example, the results show that a failure of the catenary wire or contact wire was more likely to result in a larger failure cost than for other components or failures due to external influences, due to the increased chance of a dewirement. In comparison, because many of the external failures result in a trip of the power supply to the system

and the route operator simply reconnects the power to rectify the issue, the disruption to service is minimal and the costs incurred are small.

Using the data, for each component type a distribution of the failure costs is found. This was done using the statistical software program Minitab, which can use maximum likelihood estimation or rank regression to fit parameters for a distribution, as described by Klein and Moeschberger (2003). A lognormal distribution, or a Weibull distribution with a shape factor less than 1, were found to be a satisfactory fit for all the different component types' failure costs. This describes how many of the OLE failures that occur often result in a low to moderate cost, where the probability decreases as the cost increases and there is a low probability of very high costs being incurred (due to large scale damage during extreme events, such as a dewirement). These distributions can be used to calculate the cost of component failure in a stochastic manner, as part of a life cycle cost model. This allows the large uncertainty in the cost of failures, due to different severities of failure, to be considered.

The suitability of the lognormal distribution that was fitted for the failure cost of droppers is shown in the following figures. Figure 2-17 shows a probability plot of the failure costs. All the data points, apart from one that represents a very low failure cost, are within the 95% confidence intervals of the lognormal distribution fitted. Note, at the request of Network Rail for confidentiality reasons, the cost values are not shown and the lognormal distribution's location and scale parameters are also hidden. Figure 2-18 shows the cdf of the lognormal distribution fitted to closely mimic the empirical cdf for dropper failure costs. The figures, therefore, suggest the chosen distribution fits the data well.

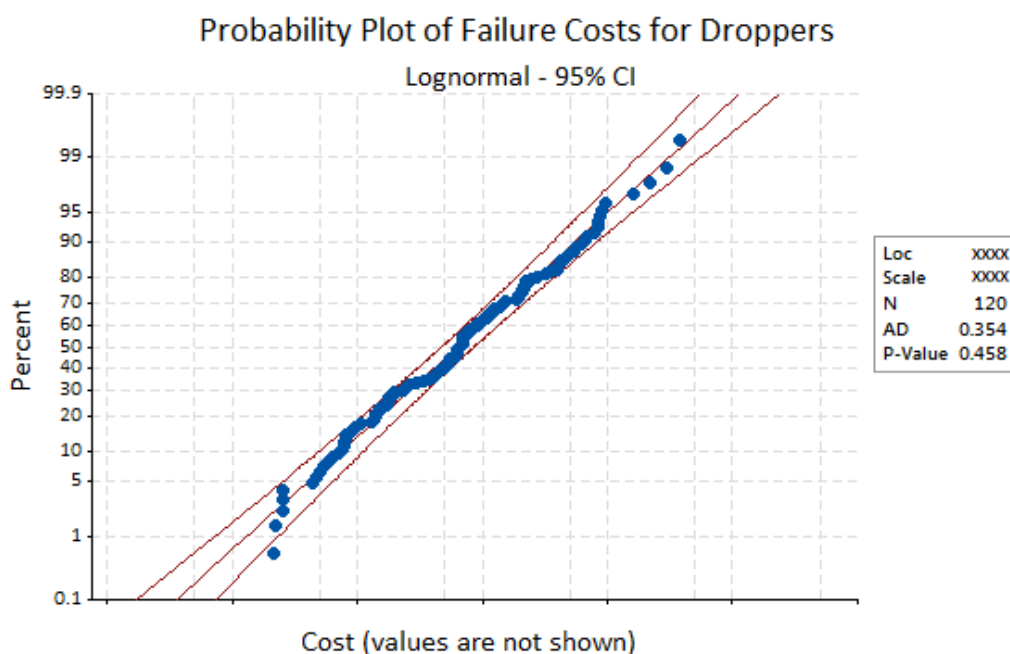


Figure 2-17 Probability Plot of Failure Costs for Droppers Fitted to a Lognormal Distribution

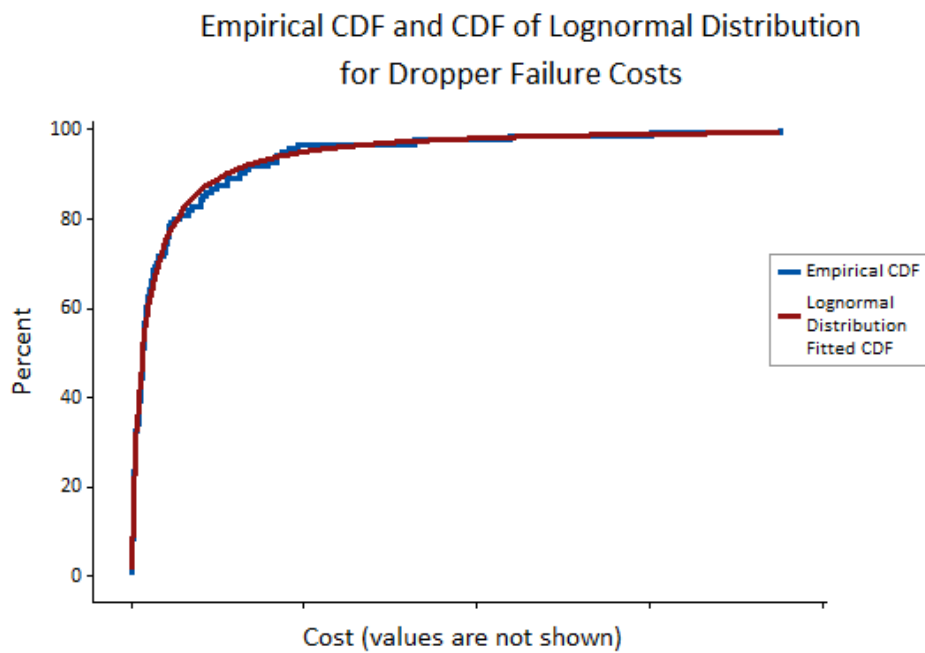


Figure 2-18 Empirical CDF and CDF of Lognormal Distribution for Dropper Failure Costs

2.6.3 Recommendations for Improved Data Collection and Future Work

In order to calculate failure and degradation rates from historical data more easily, the data needs to be collected with the purpose of data analysis in mind. Network Rail's current asset information systems work very well by recording information about the maintenance and failure of components in a digital format that is easily accessible. However, the information that is recorded is primarily used for scheduling component maintenance, ensuring it is completed and accounting for system failures. Some key information that is required for detailed analysis, to determine failure and degradation rates, is not collected or is not recorded in a clear, easily usable format. The main ways that the current data collection process can be improved are now outlined and a description of how this improved data could be used for detailed analysis follows. The use of computer systems and information technology make these recommendations possible to implement. However, due to the size of the network and the number of components, a concerted effort will be required to put such a data collection system in place.

Reference to the Degraded or Failed Component

In the maintenance and failure records, information about the component that is being maintained or the component that failed needs to be in a separate category to make it easily identifiable during analysis. Currently, the information is not explicitly collected and it is only available in text fields of the

failure data. The name of the component type and an explicit reference to the exact component that is being maintained or has failed should be added as distinct values for the data that is collected. Each instance of each component should have an identifiable reference so that maintenance and failure history can be collected for each component. This reference can be based on the location of the component, which can be based on the structure number assigned to each OLE structure along an electrified line and the track that it is on e.g. up fast or down slow. To do this a complete inventory of all the components that are present and their respective locations would be required.

A separate database that shows the location of the different components along the line and their respective maintenance and failure histories could then be made, which would be similar to the Linear Asset Decision Support tool (LADS) that Network Rail has developed for track assets. The maintenance and failure history of the different components can then be built up for all the components over time and saved in the database.

Network Rail has developed a mobile app that the maintenance engineers can use to record information during inspection and maintenance actions and after component failures, which is added to the various databases. Within the mobile app, GPS could be used to give the maintenance engineers a list of the nearby components which they can then select to enter the corresponding maintenance or failure record for. This would ensure that the component type and the reference to the components are recorded accurately and make the work easier for the maintenance engineers, through less reliance on text fields.

Component Installation Dates and Date of Last Maintenance

In order to obtain time to event data, which can be used to calculate the times to degradation and failure for different component types, information about the installation dates or date of last maintenance needs to be recorded for each component. This information can then be added to the database containing the maintenance and failure history of each component. Many of the installation dates for components currently installed may be unknown, but over time a thorough history of installation and last maintenance dates will be built up for all the components across the entire network, if the right database and collection processes are put into place.

The Type of Component Defect and Maintenance Action Required

Currently, there are standardised codes for the maintenance actions used to rectify certain component defects, e.g. replacement of insulators. However, for many of the maintenance records entered into ELLIPSE the text field containing information about the maintenance actions describes a completely different maintenance action relating to a different component to that specified by the

maintenance code used. When entering a record in the mobile app, if the associated component is added (as suggested previously) then it should be possible to restrict entries to only certain maintenance actions that are specific for each component type.

Information about the defect or component degradation that was rectified during the maintenance, e.g. catenary wire with a single strand burst, should also be entered so a detailed history of the component condition can be recorded.

The Cause and Effects of a Failure

When a component failure is recorded, the component type should be recorded, as described previously, and the cause of the failure should be chosen from a list of standardised options that represent all the plausible failure modes for the component. This will reduce the reliance on text fields and make the data easier to analyse.

After a failure, the amount of downtime that the system was closed for timetabled train services should be recorded, in addition to the number of delay minutes and the failure costs that are currently recorded. If the failure of the component resulted in damage or the failure of other components, then the condition, or maintenance actions undertaken, for these other components also needs to be updated in the respective databases that were described earlier. The actions undertaken to rectify the failure should also be recorded and, where possible, standardised actions should be selected, instead of relying on text fields.

Detailed Analysis of Maintenance and Failure Data

If time to degradation and failure event data is available, then a survival analysis can be undertaken, where a distribution of the times to an event, e.g. time from new state to a degraded state where maintenance is required, can be fitted for a component type. Meier-Hirmer et al. (2006) describe a survival analysis using OLE data on the French railway network to find the lifetime distributions for components. More information about this study is provided in section 3.3.3.1 of the literature review. These distributions can be used in life cycle cost models to stochastically model component degradation and failure. Additionally, the distribution parameters can give an insight into the behaviour of the components. For instance, a Weibull distribution with a shape factor greater than 1 suggests that there is an increasing hazard rate, i.e. the event represented by the distribution is increasingly likely to occur with time.

The time to event data collected will contain interval or right censored component lifetimes. Where maintenance has been undertaken for a component, its observed lifetime will be interval censored because it is known to occur within its installation date (or date of last repair) and some unknown

date, between the date it was inspected to require maintenance and the date of the previous inspection (where the component would have been inspected and found to not require maintenance). Since the inspection intervals are likely to be very frequent relative to the component lifetimes, for simplicity, interval censoring could be ignored and the components' observed lifetime (or time to degradation) could be assumed to be simply the time between the installation date (or the date of last maintenance) and the date at which it was inspected to require maintenance. If, at the time of analysis, a component has not required maintenance, the time to degradation has not been observed, therefore, the time to degradation is right censored with a value equal to the time between its installation date (or date of last repair) and the most recent inspection date in the study. A distribution for a component type's lifetime (or time to reach a degraded or failed state) can then be fitted, taking into account the censoring of the lifetimes, through various methodologies. For example, Meier-Hirmer et al. (2006) used maximum likelihood estimation to fit Weibull distributions to real data. This can be done using statistical packages within computer programs such as Minitab and Matlab or implemented using the programming language R.

By collecting data in the way suggested, where the complete condition, maintenance and failure history of the components is recorded, more complex OLE degradation and failure processes can also be investigated. For example, the effect that component condition has on the failure rate can be analysed by considering the failure rate of a component type when it is in a degraded condition where maintenance is required. Furthermore, the interaction between components, and other assets such as the track, can be investigated by considering how the degradation rate of different components influences the degradation and failure rate of nearby components.

2.7 Summary

This chapter has provided a description of railway electrification and its prevalence on the British railway network. The OLE is a critical part of the 25kV AC overhead railway electrification system, which is the preferred method of electrification on the British railway network. The OLE refers to the conducting wires, insulators and supporting components that provide trains with their traction power along the length of an electrified line. It is this group of components that are studied in this thesis. The main OLE components studied in detail are the catenary wire, contact wire, droppers, insulators, registration equipment, return conductor and structures. These components were chosen because they are present across the entire length of an electrified line and their reliability and maintenance requirements influence the life cycle cost and asset management of the system. A description of how

the OLE system works and a detailed overview of how the different component types degrade and fail was provided using information obtained from various literature and Network Rail sources.

The different asset management intervention actions currently implemented for the OLE on the British railway network were explained. Network Rail now undertakes a risk-based maintenance approach where maintenance is scheduled based on the results of routine inspections. Component degradation or defects are revealed during inspections and the maintenance, undertaken to rectify the degradation of a component, is scheduled depending on the severity of the degradation or defect. This is therefore condition-based maintenance that aims to repair components before their degradation leads to a failure. When a failure occurs, rapid response maintenance is undertaken to rectify the issue and minimise the disruption to the timetabled train service. OLE component failures can result in widespread damage and severe service disruption, therefore, it is imperative that the occurrence of failures is minimised.

An overview of the different maintenance and failure data that is collected was given and the results of analysis of the failure data were presented. This analysis focused on categorising the OLE failure events according to which component type failed. Because a large number of the available data records did not contain sufficient information to determine which component had failed, the component failure rates were not obtained in the analysis. However, the effects of the failures of different component types were analysed by considering the cost incurred due to the delay and rectification work associated with the failure. The different costs incurred can express different severities of failures. Distributions of the failure costs were fitted for each component type and these distributions can be used in a life cycle cost model to enable the uncertainty associated with the cost of failure, due to different severities of failures, to be considered. Lognormal and Weibull distributions were shown to be a good fit to the data. Recommendations specifying how the current data collection process can be improved, to allow detailed analysis of the times to degradation and failure of the components, were also provided.

The next chapter proceeds to review literature and various methods that are associated with modelling the asset management and life cycle cost of the OLE.

Chapter 3 Literature Review

3.1 Introduction

This chapter gives a detailed description of the subject area through explaining the key concepts and methods that are applicable to modelling the asset management of the OLE and discussing the merits and drawbacks of relevant studies presented in the literature.

Firstly, a description of the concepts of asset management and life cycle costing is provided, along with their relevance and implementation in the railway industry in general and for the OLE. The different methods that are used to model the asset management of the OLE are then explained, using examples from the literature. In particular, state-based models commonly used for asset management modelling, such as Markov models and Petri nets, are described in detail, highlighting their advantages and disadvantages.

3.2 Asset Management and Life Cycle Costing

3.2.1 Overview of Asset Management

As defined in Section 3.3.1 of ISO 55000:2014 (International Standards Organisation, 2014), which is the current international asset management standard, asset management refers to the *“coordinated activity of an organization to realize value from assets.”* In section 3.2.1 of the standards, an asset is described as being an *“item thing or entity that has potential or actual value to an organisation.”* Assets can be physical, which usually refers to the equipment, inventories or property that an organisation owns. However, they can also be non-physical and intangible entities, such as leases, brands and reputations, financial assets or other organisation-specific assets. This research focuses solely on physical assets. In order to avoid confusion with financial asset management, the asset management of physical assets is sometimes referred to as infrastructure asset management in the literature.

An organisation can achieve its strategic objectives more effectively by co-ordinating its activities and practices in a systematic manner, which allows optimal and sustainable management of its assets, along with their associated risks, performance and costs. Effective implementation of asset management involves identifying the appropriate assets to acquire and determining the best strategies for their operation and maintenance. Finally, suitable renewal or decommissioning processes must also be considered. Therefore, asset management is associated with the entire life

cycle of an asset, i.e. from its initial design phase right through to its renewal or decommissioning phase.

An organisation should implement a framework that facilitates the use of effective asset management principles with clear direction and leadership. Staff awareness, competency and cross-functional co-ordination are vital to the success of this process. The interrelationships between knowledge of asset condition, performance, risk and cost must be known. Obtaining the best value from a group of assets or a system can be a complex process and it often involves the need to compromise between the performance of the system, its cost and its reliability over its whole life cycle.

In addition to allowing an organisation to achieve its objectives and use its assets to deliver value, paying particular attention to asset management can result in improved knowledge of the asset base. Furthermore, due to the new approaches being undertaken to improve asset management, an organisation can potentially expand its capabilities and enhance its working culture, e.g. through expanding or creating new jobs associated with analysing and modelling the assets (Institute of Asset Management, 2015).

3.2.2 History of Asset Management

The Institute of Asset Management states that asset management is not a new discipline, since people have been managing assets for a long time. However, there has been an increasing recognition that effective asset management involves optimising the costs, risks and performance associated with an asset over its entire life cycle (Institute of Asset Management, 2015). During the 1980s, the term '*asset management*' began to be used in both the private and public sectors, in different environments globally, to refer to the management of physical assets. The Institute of Asset Management suggests that the modern concept of asset management, for physical assets, came from the following origins:

- **The North Sea Oil and Gas Industry.** Following the Piper Alpha disaster and crash of oil prices during the late 1980s, a substantial change in operations was needed and the term '*asset management*' was adopted by the industry. It was found that the introduction of dynamic, multi-disciplinary teams managing each rig and taking into account the whole life cycle of assets, resulted in increased performance, safety and productivity.
- **The Public Sector.** During the late 1980s, failing public services, high costs and poor planning in Australia and New Zealand led to the need for new innovative strategic thinking, taking into account the value for money of infrastructure projects. Similarly, in the US, following a report that evaluated the state of national infrastructure and its capacity to support future economic

growth (Pack & Altshuler, 1989), federal asset management policies that aimed to provide the desired service at the lowest cost over the whole life cycle of the asset were implemented.

As the importance of asset management became increasingly recognised, standards describing the best practices have been developed. In 2004 the Institute of Asset Management published the PAS 55 standard, through the British Standards Institute, which provides a specification for the optimised management of physical assets. This became the default global standard for asset management and one of the most popular standards of all time (according to the British standards website). Newer international standards, largely based on PAS 55, were introduced in 2014 by the International Standards Organisation. Using these standards, asset owners can implement the practices recommended in the standards to improve their asset management and optimise the value they can realise from their assets. Through becoming compliant with such standards, an organisation can demonstrate (to customers, stakeholders or regulatory bodies) that their system meets the requirements of an internationally recognised asset management standard.

3.2.3 Life Cycle Costing

As defined in BS 5760: part 23 (British Standards, 1997), life cycle costing refers to *“the process of economic analysis to assess the total cost of acquisition and ownership of a product.”* Life cycle costing is therefore directly related to asset management, since the costs associated with an asset or a system over its life cycle are related to the choice of assets to be installed in the first place, the operation and maintenance processes implemented (through the whole life of the assets) and the renewal or decommissioning of the assets, i.e. in all the key phases of asset management.

The life cycle cost of a system consists of its acquisition costs, which are associated with the design and installation of its components, and its ownership costs, which are associated with ensuring the operation of the system. Generally, the primary aim of an asset owner or organisation is to realise the best economic value from its asset base. Therefore, life cycle cost analysis can be used to evaluate the current asset management strategy of a system and identify asset management strategies that can be implemented in order to realise the greatest economic value from the asset base over its entire life cycle. Following the principle of life cycle costing ensures that both present and future costs are considered, so that an asset or a system can be operated in an economically responsible and sustainable manner (in terms of cash-flow and the performance of the system) over its entire life cycle. Note, that the term life cycle cost is also referred to as whole life cost by some organisations, such as Network Rail (Skinner et al., 2011).

3.2.4 Asset Management Framework for Railway Infrastructure Organisations

Railway infrastructure organisations, like Network Rail, can particularly benefit from implementing effective asset management practices due to the sheer number of assets that they own. The International Union of Railways (UIC) has published guidelines for applying asset management in railway infrastructure organisations (International Union of Railways, 2010) based on the PAS 55 asset management standard (British Standards, 2008). A framework was developed with high level guidelines that enable railway infrastructure organisations to determine what is required in order to implement the proposed asset management system, as shown below in Figure 3-1.

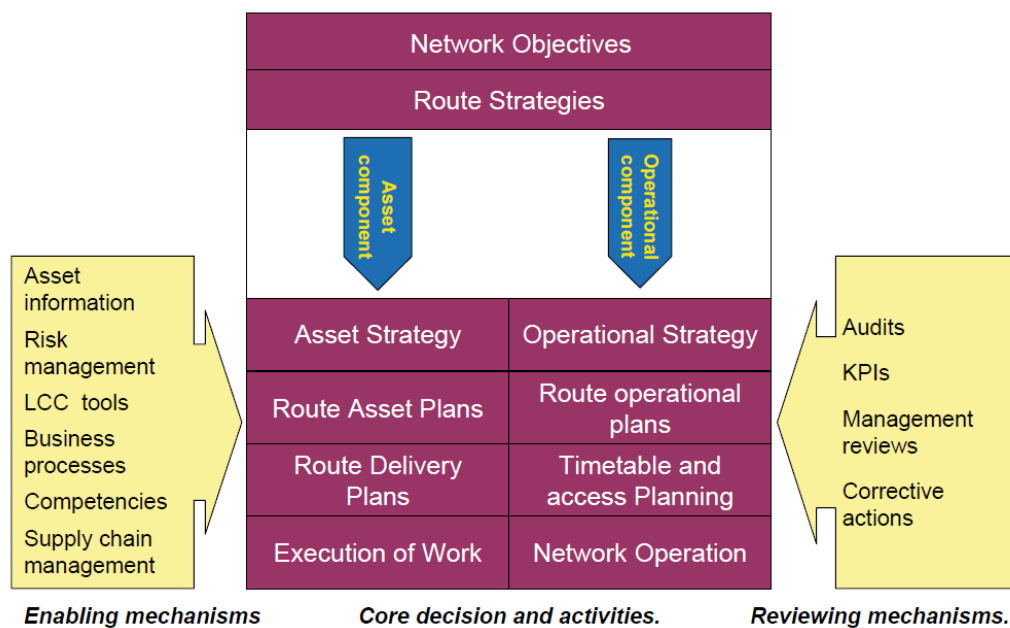


Figure 3-1 Asset Management Framework (International Union of Railways, 2010)

The framework is split into three main components:

- **Core Decisions and Activities.** These link the strategy to the delivery of the work, which can involve work on the assets and the operation of the network
- **Enabling Mechanisms.** These provide the information that the core decisions and activities can be based on.
- **Reviewing Mechanisms.** These provide feedback, so that the asset management system can be continually improved.

The network objectives, at the top of the core decisions and activities section, refer to the high level requirements of the railway in order to ensure that the demands from the passengers, train operating companies and funders (usually the government) are met. The required outputs of the system, such as the punctuality, safety and sustainability, are stated and the funding that is available to meet these

requirements is specified. The route strategies provide the targets at the route level over a period of years, so that the overall network objectives can be met. The route strategies, therefore, set the targets that the infrastructure on a route has to deliver.

In this diagram, the asset component branch of route strategies is linked to further core decisions and activities that are directly associated with the infrastructure. The asset strategy refers to how the assets are inspected, maintained and renewed. The asset management system aims to specify the optimal asset strategy, where the required outputs for a route can be delivered at a minimum whole life cost. The asset strategy is the main process that determines the cost and sustainable performance of the infrastructure. The route asset plans specify the enhancement and renewal activities and maintenance regimes for a specific location through selecting an appropriate asset strategy. The route delivery plan refers to how the work specified in the route asset plan will be undertaken. Finally, the execution of work refers to the delivery of the work planned.

The operational component branch in this diagram is linked to further core decisions and activities that are directly associated with the operation of the infrastructure (in terms of train operation and access). The operational strategy specifies the future configuration of the infrastructure, used to meet the required outputs, the required capacity of the routes and the optimal access regimes. The route operational plans and the timetabling and access planning activities determine the capacity of the route and, through collaborating with the train operating companies, produce a timetable for train services and access arrangements (for maintenance/renewal or enhancement works). Finally, the network operation activity refers to the delivery of safe and reliable paths for the timetabled train service.

When core activities are planned and implemented, the enabling and reviewing mechanisms support and monitor the asset management system. For instance, life cycle cost tools can be used to determine the asset strategies that result in the lowest whole life cost. There is a clear relationship between many of the different processes in the asset management system. For example, asset information and specific competencies within a company are required to develop accurate life cycle cost models. Therefore, asset management is something that needs to be addressed at all levels of an organisation and good communication between different work groups is imperative.

The asset management system described by this framework defines all the processes that a railway infrastructure owner should consider for asset management. The process can be continually improved as more information about the system and the different assets is obtained and the competencies and expertise within the organisation are developed.

3.2.5 Network Rail's Life Cycle Cost Modelling Capabilities

Network Rail aims to correctly specify the assets to be installed in new systems and then manage the condition of its asset base by implementing appropriate maintenance regimes, such that the required outputs for an asset (e.g. the required reliability and line speed) can be achieved at the lowest whole life cost for the system, (Skinner et al., 2011). The life cycle cost modelling is implemented to determine appropriate asset strategies and to estimate the future costs of the system. Network Rail undertakes life cycle cost modelling at 3 different levels of granularity. Tier 1 models are used to forecast the volume of work, outputs and expenditure required for a portfolio of assets at the network level, such as for the overall OLE system, for all the OLE installed on the network. Tier 2 models are used to calculate the whole life cost for a particular asset type, such as the whole life cost for a wire run consisting of a specific type of OLE. Finally, Tier 3 models are more tactical models that are used to calculate the whole life cost of a particular asset type on a particular route. The asset strategy to be implemented can be chosen based on the results from the various models. The Tier 3 model is commonly used for estimating the costs of a new installation or upgrades in a small area of line, whereas the Tier 1 and 2 models are used for estimating the overall cost of the network or strategic routes for a given maintenance strategy.

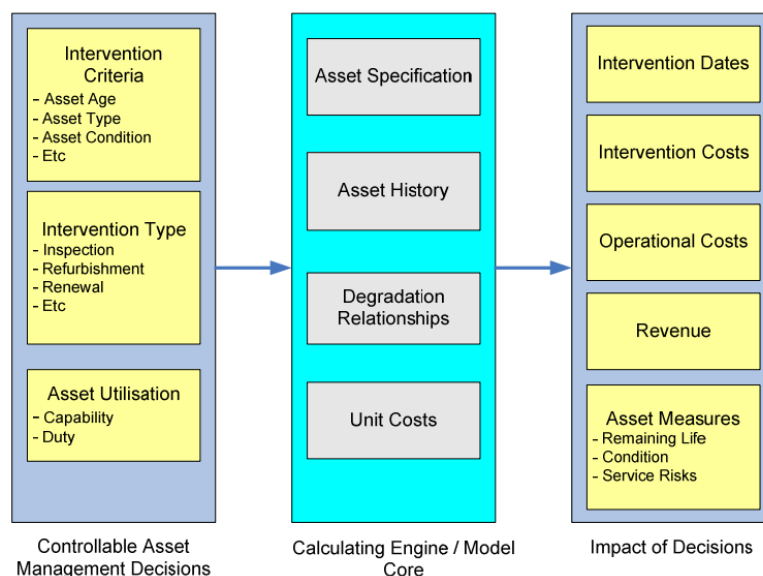


Figure 3-2 Overview of Network Rail's Life Cycle Cost Model (Skinner et al., 2011)

Network Rail's life cycle models are split into 3 elements, as shown in Figure 3-2. The controllable asset management decisions refer to the different processes that Network Rail has control over and can change, in order to influence the behaviour or state of its assets.

The main element of the model is the calculating engine, which works out the required statistics based on the controllable asset management decisions that were chosen. The model requires various information, such as the asset specification, current condition and maintenance history, degradation relationships and the unit costs associated with the various capital and operational costs incurred. This information is needed to accurately analyse the behaviour of the asset over its whole life. The model is used to predict the costs over the life cycle of the asset studied by calculating the occurrence of future events or states of the system, which result in costs being incurred, e.g. the future failure costs and future maintenance costs.

Numerous outputs describing the impact of the asset management decisions are obtained. These outputs contain the whole life cost of the asset and other performance indicators, such as the condition of the asset over its whole life. The modelling results for different asset management decisions can then be compared, so that the best asset management strategy is obtained. This is done by comparing the results obtained by the model using different asset management strategies as inputs.

Network Rail generally models different asset types (such as the track or the OLE) separately, since different modelling methodologies may be better suited for different asset types and separate teams are responsible for the asset management of the different asset types on the railway. The results for different asset types can be collated to obtain the expected whole life cost for a group of assets, such as the track, OLE and signalling along a section of line.

Since the British railway network is intended to remain in place for the foreseeable future, it is important that the future costs, associated with the system's long term operation, which may become significant as the system ages, are considered. Network Rail commonly undertakes a life cycle cost analysis for a group of assets located on a section of line for a 100-year period of operation. A 100-year period is chosen because within this timeframe most of the assets or components in a railway system will have exhibited their entire life cycle. This allows all the different costs associated with the different phases of their life cycle to be analysed. At the same time, the expected costs in the short to medium term (5 to 30 years) can also be used for comparison. Network Rail applies discounting to the future expected costs, which results in the costs incurred after 100 years being negligible. The principle of discounting is used to allow a comparison between the costs and benefits/ incomes that occur in different time periods by taking into account the fact that people prefer to receive income and services sooner and defer costs for the future. For example, the costs of a renewal of an asset in 70 years' time is less important to Network Rail than the cost of a renewal that is scheduled to occur in the next 5 years, due to a more immediate need to ensure that it has the means to pay the costs that occur in the short term. The future costs are discounted by certain rates that vary over time to express the

changes in the preference to defer future costs. Network Rail uses the discounting rates published by the British Treasury (2003) in *The Green Book- Appraisal and Evaluation in Central Government*.

The accuracy of the life cycle cost model is highly dependent on the available asset information, in particular the failure and degradation relationships (that describe how a component fails or degrades with respect to time or usage) that the models are based upon. It is important that data is collected to derive the failure and degradation rates for the different components. Network Rail's life cycle cost models use either deterministic or stochastic methods to model component degradation and failure. The different modelling techniques that can be used to analyse a system and calculate its life cycle costs are described in section 3.3 of this chapter. Both deterministic and stochastic approaches are described and the methodology behind Network Rail's Tier 2 life cycle cost model for the OLE, which is based on the Markov method, is also explained (in section 3.3.3.3).

3.2.6 Asset Management in this Thesis

As discussed before, asset management is a very broad subject area that encompasses numerous processes within an organisation. The research in this thesis focuses on the asset management processes associated with modelling the life cycle cost of the OLE. As described earlier, in the UIC framework, the asset strategy, which describes how the assets are selected, inspected, maintained, enhanced and renewed, is the main process that influences the system's performance and cost. Life cycle cost models, that calculate the whole life cost of the OLE, can be used to compare different strategies and options. The most appropriate asset strategy, which results in the required outputs being met at the lowest expected whole life cost, can then be chosen based on the modelling results. To do this, focus is primarily applied to modelling the behaviour of the components installed over their life cycles and the intervention actions that are undertaken, such as inspection and maintenance actions. Note that these processes were explained in detail previously in Chapter 2.

3.3 Methods Applicable for Modelling OLE Asset Management

Relatively little academic research into asset management and life cycle cost modelling of the OLE has been completed to date. This is perhaps due to the long lifespans of most OLE components and poor availability of historical data. More focus has been placed on other critical railway assets such as the track, since this is the main railway asset (whereas OLE is not present on every railway network) and there has also been more, high quality, historical data collected over the years.

This section explains notable research concerned with modelling the behaviour of the OLE components and describes the main methods that are applicable to modelling the asset management

and life cycle cost of the OLE. The methods that are reviewed have been categorised into three groups; deterministic studies, risk analysis studies and lifetime and state-based models. In general, the deterministic studies used dynamic models (where deterministic values were obtained) to analyse the physical behaviour of components, risk analysis studies can use deterministic and stochastic methods to analyse and understand the risk associated with a system and the state-based and lifetime models studied used stochastic methods to model component behaviour and the life cycle cost of the OLE and other systems. In this section, firstly, the difference between deterministic and stochastic methods is explained and a detailed description of each of the different methods is then provided, using examples from literature. Deterministic modelling of the OLE is described in section 3.3.1. Qualitative or quantitative risk analysis studies that have been undertaken on the OLE using deterministic and stochastic methods are described in detail in section 3.3.2. Finally, lifetime and state-based models, that use stochastic methods, are described in section 3.3.3. The advantages of the Petri net method, which is the state-based modelling method used to model the asset management of the OLE in this thesis, are also presented before a summary.

Analysing the asset management of a system over its life cycle requires analysis of its behaviour so that the future conditions and events of the system can be predicted (Skinner et al., 2011). Numerous qualitative and quantitative methods can be used to analyse the behaviour of a system. The suitability of a method is dependent on the type of system being analysed and the objectives of the analysis. For the purpose of predicting system behaviour, a system can be described as being deterministic or probabilistic (Kirchsteiger, 1999). The behaviour of a deterministic system is perfectly predictable, such that the exact future condition or state of its components can be determined based on a known law, equation or fixed process. The behaviour of a probabilistic system, however, cannot be predicted with such certainty, so the future condition of a system, or the time when a certain event will occur, cannot be determined exactly.

Deterministic methods model the behaviour of the system using an equation or a fixed process and are best suited for modelling deterministic systems. However, many large-scale engineering systems, like the OLE system, are not purely deterministic. There is often an element of uncertainty related to the future condition and the occurrence of events in such systems. For example, for a group of identical components in a system, maintained in the same way, and operated under the same usage, the occurrence of degradation and time to failure can vary for each component (Andrews & Moss, 2002). It is therefore important that this statistical variation is accounted for. Due to the complexity of some systems, like the OLE, it can be very difficult to model the future condition of the components deterministically. Important factors or physical processes, that influence the degradation, may not be found or realised which can invalidate the modelling results. Instead, probability theory can be used

for system analysis, for example, to express the likelihood of the future condition of the system or the probability of an event occurring in a certain time interval.

Various studies have analysed the behaviour of a system by considering component degradation, failure and maintenance in a stochastic manner, which takes into account the uncertainties associated with the components' degradation and failure rates. Stochastic models use statistical methods to determine the degradation and failure processes in a probabilistic manner. The probabilistic distribution of times to degradation and failure events can be found through analysis of historical component degradation and failure records (if available), or through expert judgement. Stochastic models can therefore be based on what has actually happened and will therefore take into account all the physical processes of degradation and failure that take place for a component (Andrews, 2012).

3.3.1 Deterministic Modelling of the OLE

For the OLE, the vast majority of literature currently available used dynamic models to investigate OLE component behaviour and the interaction between a train's pantograph and the catenary system. Such methods are not directly suitable for modelling asset management and calculating the whole life cost of the OLE. However, they can be used for determining how a component degrades and fails and used to specify the design of new OLE installations. Note that dynamic models can consider the probability of the physical processes modelled, however these models consist of equations that represent the time dependence of a point in geometric space to describe the components' physical behaviour, therefore, they differ from the stochastic models reviewed later. Since the dynamic models reviewed did not consider probability and the results obtained were deterministic, they are described in this section along with other deterministic studies undertaken, such as laboratory analysis.

The main dynamic models that have been used to analyse the behaviour of OLE components in industry, i.e. by railway organisations like Network Rail, are the finite element method, dynamic lumped mass modelling of the OLE and rigid body spring-damper modelling of the pantograph-catenary interaction (Railway Safety and Standards Board, 2007). These methods work by dividing the system, or the component studied, into smaller elements, which are modelled by equations that express the physical properties of the components (such as their thickness, stress or strain). These equations are combined and numerical analysis is used to find the approximate behaviour of the system or component when it is subject to physical effects, such as external forces and loading. Railway organisations have developed software that uses these methods to analyse the behaviour of different catenary system designs. For example, Bobillot et al. (2010) describe the features and uses of the software developed for the French rail network. Such software can be used to obtain a better understanding of the influences that trains containing multiple pantographs have on the system, in

particular, the effect on the pantograph–catenary interface. In addition, it can be used to investigate how perturbed situations influence the system’s behaviour, such as how misaligned or damaged droppers can affect the variation in the contact force exerted on the contact wire by the pantograph. The analysis of the contact force is commonly undertaken because high contact forces can lead to excessive wear of the contact wire, whilst low and varying contact forces can result in the pantograph intermittently losing contact, which can result in arcing. Furthermore, issues associated with the pantograph-catenary interface can increase the likelihood of component failures and a dewirement (Kiessling et al., 2009). Therefore, these models are particularly useful to railway infrastructure owners when considering the design specifications, such as the required tension in the catenary and contact wires, and the span length, for a new electrified line.

Examples of such methods in academic research are described by Bai et al. (2013), who investigated how the design parameters of the OLE can influence the pantograph-catenary interaction, and Har  l et al. (2005), who investigated the effects that trains with multiple pantographs have on the more vulnerable sections of the OLE, such as near sectioning devices, using the finite element method. Gonzalez et al. (2008) also described a study that used the finite element method to analyse the tensile stress in the contact wire in areas of localised wear, which can allow the potential risk of the wire breaking to be evaluated. Using experimental methods and numerical analysis, Collina et al. (2007) investigated the influence that contact wire irregularity (in terms of vertical displacement from its correct position) has on the pantograph-catenary interface. This research considered the impact that various defects of the OLE system, such as variations in the contact wire’s tension, or incorrect dropper lengths, have on the contact force exerted by the pantograph on the contact wire.

Research using laboratory experimentation and metallurgic analysis of the OLE components on actual railways has also been undertaken. These studies primarily focused on the wear of the contact wire. For example, Bucca and Collina (2009) described a method to predict the wear rate of a contact wire and pantograph collector strip, whilst considering the effects of friction and electrical phenomena, such as arcing between the pantograph and the contact wire. The authors stated that the wear is mainly influenced by the pantograph’s sliding speed, contact pressure, the metallurgic qualities of the contact wire and the pantograph’s collector strip, the temperature, electrolytic corrosion and current intensity.

An artificial neural network (ANN) has been used to predict the contact wire wear based on the design and operating parameters that are obtained during inspections (Wai Chung, 2011). ANNs work by emulating how a brain can infer an output from a range of inputs. An ANN is a system of interconnected nodes, known as neurons, which can compute values based on input parameters. Each

input parameter is connected to each neuron that exists in a hidden layer. Each of these neurons is then connected to each neuron in the next hidden layer, or, if there are no subsequent hidden layers, each neuron is connected to the output. These connections are assigned weights to relate the input parameters to the outputs. Using various back propagation algorithms, which compare the output produced by the ANN with the actual value from data, the weights are found. This is known as training the network (Hagan, et al., 2002). Once trained, the ANN should be able to accurately estimate the output from the input parameters. Wai Chung (2011) used real OLE data from a railway in Hong Kong that has a direct current traction power system. The inputs to the ANN were parameters that influence the wear, but only those that were easily quantifiable and where data was available were included. As a result, the following 15 input parameters were chosen: the average span length, the number of trains per hour, the number of times a train is in motoring mode, coasting mode and braking mode and both the average and variation of the system's height, stagger, train speed, contact force and voltage. The ANN was trained using 70% of the data and the remaining 30% was used for testing and validation. Upon completion, certain parameters were varied slightly to understand their effect on the contact wire wear. The contact wire height, contact force and the span length (between adjacent structures) were found to have the largest influence on the wear rate of the contact wire. One limitation to the ANN method is that high quality data must be available to train the network. Also, only the change in the output parameters based on the inputs is known, i.e. the underlying physical processes that are acting on the components are not identified or directly quantified.

Overall, the deterministic methods described above can be useful for railway asset management by helping to improve the knowledge of the OLE components' behaviour. The numerical methods can also be used as part of a cost benefit analysis in order to determine the appropriate specifications or requirements of the system. For instance, in order to safely run electrified trains at higher speeds, the specific permissible range of the contact wire's height in the system (which can be obtained from modelling results) needs to be considered. This should be done whilst also taking into account the possibility of higher installation and maintenance costs associated with ensuring the wire's height remains within the specified range (Collina, et al., 2007). However, such methods are not directly applicable to life cycle cost analysis, since the main processes that influence the life cycle cost (i.e. component degradation, failure and maintenance over the system's whole life) are not considered in these approaches.

3.3.2 Risk Analysis Studies of OLE

Formal methods used to analyse the reliability and the risk associated with a system have been developed to allow decision makers to gain a better understanding of the cause and effects of

undesired events in a system (Smith, 2011). Understanding the reliability of components can help railway infrastructure owners implement their asset management strategy by enabling better informed decisions to be made and manage the risks associated with the system's operation. For example, the critical components of the system can be identified and the associated risks reduced, through specifying suitable maintenance regimes to decrease the probability of component failure.

Failure Mode and Effects Analysis (FMEA) and Fault Tree Analysis are two methods commonly used for risk analysis of engineering systems (Andrews & Moss, 2002). A description of these methods and a discussion of their use in studies that have analysed the OLE are given below.

3.3.2.1 Failure Mode and Effects Analysis

FMEA is a technique used to systematically identify the potential issues and failure modes of a process or component/system and then assess the risk of the failure, the effect of the failure and what corrective actions must be taken to rectify the failure. The method was initially developed for military purposes and was first formally used during the 1960s in the aerospace industry to improve safety and reliability. Since then it has been used in a wide range of industries, such as the automotive industry, and standards have been published that explain how to undertake the analysis, see for instance *BS EN 60812:2006* (British Standards, 2006).

For the OLE, relevant research has been undertaken in conjunction with the Spanish railway infrastructure owner, ADIF (Administrador de Infraestructuras Ferroviarias), which devised a methodology based on the FMEA method to determine the criticality of OLE components based on actual failure records (Duque et al., 2009). Zorita et al. (2010) then incorporated this methodology into a following study that described how the maintenance frequencies of the OLE components can be determined and optimised.

Duque et al. (2009) stated that OLE components represent a large-scale distributed system of many components that are spread over a large area. The system consists of large populations of relatively uniform and unsophisticated components, in comparison to an aircraft system, where all the components' functions and failure modes must be examined in detail. Since performing a detailed FMEA on such a large system would be time consuming, it was suggested that, for the OLE components, a less thorough FMEA can be undertaken, whilst still achieving acceptable results. The FMEA undertaken focuses on a simplified definition of the components' functions and only considers the failures that are most likely to occur. As in a traditional FMEA, the aim was to obtain an index based on the severity, occurrence and detectability of the likely failure of an OLE component. For each OLE component type studied, failure records were used to obtain the mean time to repair (MTTR), the

failure rate and the mean time of delay (MTOD) due to the failure. The values obtained were then used to express values for the severity, occurrence and detectability of the failure of each OLE component type. A traditional FMEA calculates a risk priority number (RPN) by multiplying the values of severity, occurrence and detectability, where all these values are expressed by numbers between 1 and 10). The RPN value is often difficult to interpret, so the authors developed an alternative index defined as the component criticality index (CCI), which is calculated by adding the values of severity, occurrence and detectability. The severity, occurrence and detectability values were obtained during analysis of the failure records. These values were then standardised so each has a value between 1 and 10, and equal mean and standard deviation, to ensure that each value has equal importance when calculating the CCI. The CCI obtained for each component describes its criticality relative to the other OLE components studied. In an asset management strategy, more attention can be applied to the components that are found to be most critical. In their study, which investigated 6 electrical power component types on a section of a 3000V D.C. railway in Spain, droppers and structures were found to have a low criticality. In contrast, the current carrying connection was found to have a medium criticality and the overvoltage protection device was found to have a high criticality- note that these components are not considered to be part of the OLE in this thesis.

Further research on the Spanish railway network, that concentrated on specifying OLE components' inspection frequencies, was then undertaken by Zorita et al. (2010). The OLE system was split into different zones which separate maintenance teams were responsible for. In a similar way to the maintenance of OLE on the British railway network, there were areas where a maintenance team could inspect or maintain all the components present in the area during the same maintenance visit (this was referred to as the access area in this thesis as defined in the key terminology listed previously in section 2.3). Using the criticality index from the previous study (Duque et al., 2009) and the minimum frequencies of inspection for each component, the target inspection frequencies for a group of a specific component type in an area were determined by Zorita et al. This was done by calculating indices for the criticality of the area and the local reliability of the component in the area. These indices were then used to modify the initial minimum inspection frequency of the component. The target frequency represents a more appropriate inspection regime for the component type in the area studied and using this frequency should improve the system's reliability by identifying component defects more effectively. The area criticality index was calculated by taking into account the following characteristics of the area: the economic benefits, the strategic importance, the type of OLE installed, the usage and the current condition of the components. The local reliability index was calculated by considering the component's failure rate in the area, relative to its failure rate across the whole system. The feasible frequencies of inspection were then calculated by considering the target frequencies of

inspections for each component type for each area of a zone and the available maintenance resources (in terms of available hours to undertake inspection) in that zone. The optimum inspection frequencies under the available resources were then calculated for each component type in each area by solving a quadratic programming problem.

The overall approach described by these two studies is successful in specifying inspection regimes based on the criticality of the components at the current time of evaluation, rather than the route planner's judgement and previous experience. The failure rates used are constant, but can be continually updated if the rate changes with time as the system ages. The criticalities would then need to be re-calculated and the inspection frequencies re-evaluated. The local variation in component criticality and reliability is also addressed, as is the fact that maintenance is often grouped into specific areas that are dealt with by maintenance teams subject to resource constraints. The methodology can, therefore, be useful when planning an asset management strategy by improving the knowledge of the system through determining the current component failure rates and revealing the most critical components. Determining the most effective inspection regimes to implement should also result in improved system reliability.

3.3.2.2 Fault Tree Analysis

Fault Tree Analysis is a method commonly used in reliability engineering to understand what can cause system failure. It involves the construction of fault trees that represent the combinations of possible events that can lead to a failure or undesired event (Andrews & Moss, 2002). The interdependency of the various events is taken into account using Boolean logic gates (generally "AND" and "OR" gates) to show how a combination of events can lead to a failure. All the input events entering an AND gate must occur to produce the output event, whereas just one input event entering an OR gate needs to occur to produce the output event. This results in a series of branches leading from the initial input events to the final top event, which could be defined as the failure of the system. For example, Figure 3-3 shows a simple fault tree, with a top event of System Failure and three lower level events considered, which refer to the failures of components A and B, which work in parallel, and component C, which is in series to the rest of the system. The fault tree shows that for the top event to occur, components A and B must fail at the same time (due to the AND gate), or component C must fail (due to OR gate).

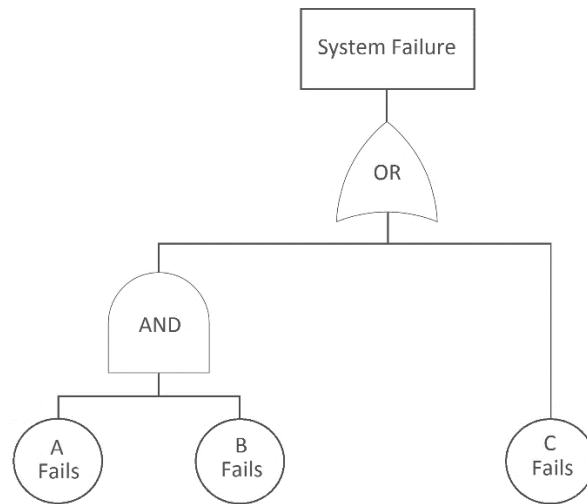


Figure 3-3 Example Fault Tree

Various techniques can be used to analyse the fault tree in a qualitative and quantitative manner to reveal the necessary combinations of events, known as the minimal cut sets, which result in the occurrence of the top event and are used to quantify its likelihood. Particular focus can then be placed on improving the reliability of certain events, or areas of the system, that were identified as having the greatest importance with respect to the occurrence of the top event.

Chen et al. (2007) used Fault Tree Analysis to evaluate the overall reliability of a section of electrified railway. The critical components of the system, that have the greatest influence on the overall system's mean time to failure, were identified by means of a sensitivity analysis. The failure events of OLE components, as well as other electrical power assets, such as the transformers and circuit breakers, were considered. The top event analysed was entitled "Unavailable supply system on down-track in a railway power supply section." The fault tree produced contained events that were categorised into two groups, associated with either transformer substations or catenary systems (the OLE system). The components considered in the catenary system were the contact wire, catenary wire, insulators, mid-point anchors and tensioning equipment. Other OLE components were omitted as they were deemed not to influence the reliability of the system. Within the fault tree the catenary system's components represent a series system, such that if any component fails then the overall system also fails. Therefore, this section of the fault tree simply contains low-level events, representing the failure of each component, that are linked by an OR gate to the top event (system failure). The section of the fault tree associated with the other electrical assets was more complicated due to various redundancies in that part of the system. A binary decision diagram method was used to evaluate the fault tree, due to its speed and efficiency, and the minimal cut sets were obtained.

A case study, considering a 127km section of double-track on the Jing-Guang mainline railway in China, was provided as a part of the study. The time to failure for each of the components studied was described by a Weibull distribution. The reliability, over time, of the overall catenary system, the substations and the overall supply section was calculated using the minimal cut sets. From the analysis of the minimal cut sets, component failures in the catenary system were found to be more likely to cause failure of the overall system. Individual failures of the components in the transformer substations have less impact on the power supply due to the redundancies built into this part of system. The importance measures calculated showed that the catenary system has higher importance than the other sub-systems. Within the catenary system, the contact wire was found to have the highest importance. A sensitivity analysis was also undertaken, whereby the mean time to failure of components was varied and the corresponding impact that this had on the mean time to failure of the subsystem that the components belonged to was analysed. For the catenary system, it was found that the contact wire had the greatest influence (this is expected, as it was found to have the highest importance). Insulators were the only other component where a variation in their mean time to failure was found to have a significant impact on the mean time to failure of the catenary system. It was suggested that in order to improve the overall reliability of the railway electrification system, particular attention should be taken to prolonging the lifetime of the components with higher importance (such as the contact wire) so far as possible during the manufacturing process and to perform maintenance on them more frequently.

Finally, the last part of this study evaluated the reliability of the system over time. Fixed interval preventative maintenance was considered and the improvements in reliability after each maintenance action were accounted for. The reliability function of the overall system in a given maintenance interval is calculated using Equation 3-1.

$$R_j(t) = \begin{cases} R(t) & 0 \leq t \leq t_1, j = 1 \\ \left(\prod_{i=1}^{j-1} R(t_i) + m_2 \left[R_0 - \prod_{i=1}^{j-1} R(t_i) \right] \right) R \left(\frac{1}{m_1} \left[t - \sum_{i=1}^{j-1} t_i \right] \right) & \sum_{i=1}^{j-1} t_i \leq t \leq \sum_{i=1}^j t_i, j \geq 2 \end{cases} \quad \text{Equation 3-1}$$

Where $R_j(t)$ is the reliability function of the overall system in the j th maintenance interval, $R(t)$ is the reliability function of the overall system without maintenance, which can be evaluated by the fault tree analysis. R_0 is the initial reliability of the system, t_i is the period of time at the i^{th} maintenance interval, m_1 is an improvement factor of extinct conditions of failures (described as failures due to degradation of components that will worsen with time) where $0 < m_1 \leq 1$, and m_2 is the improvement factor of instinct conditions of failures (e.g. failures due to short-circuiting that occur randomly) such that $0 \leq m_2 \leq 1$. In the case of a maintenance regime where repairs are undertaken, $m_1=1$ and $m_2=0$,

whereas in the case of replacement, $m_1=1$ and $m_2=1$. Tsai et al. (2004) described the method of calculating these improvement factors.

The maintenance interval was varied to see how it influences the system's reliability. The expected cost for each maintenance regime was also calculated. This approach allows decision makers to choose the desired maintenance regime by considering the expected reliability of the system and the expected maintenance cost.

This study reiterates the importance of the OLE system to the overall railway electrification system. The sensitivity analysis was effective in revealing the critical components and quantifying the impact that extending their mean time to failure has on the overall system's reliability. The research shows that fault tree analysis can be a useful method for analysing the reliability of large systems, like the railway electrification system.

3.3.3 Lifetime and State-Based Models

Lifetime models consider the reliability, or future lifetime, of a component by stochastically modelling how its condition can change from a working state to a failed state. These models commonly use an equation that represents a component's lifetime, or its reliability over time, in a probabilistic manner to calculate the expected number of failures and maintenance actions for the component over a period of time. Numerical methods, such as Monte Carlo simulation, are often used to evaluate these models to calculate the mean number of future failures and maintenance actions. A cost model can also be formed by multiplying the number of failures and maintenance actions by the corresponding failure and maintenance costs respectively, in order to predict the future costs.

Similarly, state-based models consider the change in condition of a component or system in a stochastic manner. These models contain states that represent the condition of a component or system, e.g. a working or degraded condition. The different states are linked by stochastic processes, which represent the change in the state of the component or system. These processes are represented by equations that express the probability of changing state in a certain time interval or by the probabilistic distribution of times to move to another state (e.g. the time for degradation to occur).

This section firstly describes the use of survival analysis for finding the distributions of the times to failure or degradation for components, which can be used in the other modelling methods that are discussed. The main features of stochastic lifetime and cost models described in literature, which evaluated the behaviour and cost of OLE components, are then explained. A description of Markov models, which are a state-based model widely used in literature and industry for modelling component failure, degradation and maintenance, then follows. Finally, a thorough description of

Petri nets, which are a particularly suitable method for modelling the asset management of engineering infrastructure systems, is also given, with reference to literature describing their use in modelling asset management processes for various systems.

3.3.3.1 Survival Analysis

Survival analysis involves the use of statistical methods to find the time to occurrence of an event based on available data (Klein & Moeschberger, 2003). In the field of asset management, the events considered can refer to component degradation or failure. In this subject area, survival analysis involves the analysis of failure and maintenance records to fit probabilistic distributions that describe the times to certain levels of degradation, or the times to failure, for the different OLE components. Parametric distributions can be used to express the times to reach certain levels of degradation or failure. These distributions are obtained using statistical methods to find acceptable values for the distribution's parameters, so that they fit the available data. Methods such as regression analysis or maximum likelihood estimation are commonly used. For components in engineering systems, like the OLE, the Weibull distribution is commonly found to fit data sets well, due to its versatility. The parametric distributions found, can be used in the various models described later (in sections 3.3.3.2 to 3.3.3.4) to stochastically model the times to the occurrence of the processes considered, such as the time to degradation or failure events for a component.

For example, Meier-Hirmer et al. (2006) described the methodology behind a study that estimated the lifetime of OLE components through the analysis of historical data on the French rail network. The OLE reliability is discussed in a practical manner based on the issues that the French rail provider (SNCF) encounters. The lack of quality historical data in an easily usable and digitised format, from which OLE component's lifetimes can be observed, makes survival analysis difficult, this problem is also encountered by Network Rail.

The authors described how the OLE components' conditions were classified and the maintenance and inspection regimes that were undertaken on the French rail network. It was stated that for each component there is a parameter that describes the wear or amount of degradation that is likely to lead to its failure. This parameter can be characterised by exact dimensions, for instance percentage wear in the case of contact wire, or by classes indicating the component's condition. The classes indicating component condition are specified below:

- VO- the objective value. This corresponds to the component's condition being similar to when it was first installed.

- VA- the alarm value. This corresponds to the wear parameter for the component suggesting that maintenance should be scheduled.
- VI- the intervention value. This corresponds to the wear parameter for the component suggesting that corrective maintenance must be undertaken imminently.

Maintenance and inspection of the components takes place during the following intervention actions:

- Periodic revisions. This intervention aims to maintain the OLE; both preventative and corrective replacement of components will take place.
- Detailed visits. This intervention is used primarily as an inspection to determine what components will need to be replaced during the next periodic revision and, if necessary, corrective replacement will be performed on components in a poor condition.

These interventions are undertaken periodically. The detailed visits inspect the component condition and specify what issues need to be addressed. If a component is found to be in the condition VA, it is scheduled to be maintained during the next periodic revision. At the periodic revisions, the components in condition VA at the previous detailed visit are maintained, along with any other components found to require maintenance, i.e. those that are found to be in the VI condition.

The survival analysis undertaken used specific data containing details about each component's condition at each periodic revision or detailed visit, the corresponding date that the inspection took place and the date of replacement. However, only paper records contained this detailed information, so a significant effort was undertaken to digitalise this data into a more useable format for the more critical, high speed electrified lines. A non-parametric maximum likelihood estimator (NPMLE) was used for estimating the time that a component spends in the VO state. The estimator is similar to the Kaplan-Meier estimator, but it also allows for interval-censored data. The method used was described by Fay (1999). The aim of this study was to find a simple parametric model that gives a reasonable approximation for the lifetime distribution compared to the NPMLE. Exponential and Weibull distributions were used for this parametric analysis. A likelihood function was constructed and maximised to calculate estimates for the distribution parameters. The likelihood function was adapted to deal with interval and right censored data, following methods described by Klein and Moeschberger (2003).

Using the maximum likelihood estimator method referred to above, the parameters for both the Weibull distribution and the exponential distribution, which describe the time residing in both the VO and VA conditions, were found. A convolution of the distributions' densities was used to find the

density of the overall distribution function, which represents the time it takes for a component to degrade from new to the VI state.

In summary, this study was able to perform a survival analysis using detailed data for OLE components. In comparison to the non-parametric estimator of a component's lifetime, the Weibull distribution was shown to represent an appropriate fit for an OLE component's lifetime distribution. A similar method could be employed for the analysis of OLE components on the British railway network, if quality data is available. Note that the different data currently collected on the British railway network for the OLE was described earlier in section 2.6, followed by recommendations for future data collection schemes.

3.3.3.2 Stochastic Lifetime and Cost Models

Ho et al. (2006) described a stochastic lifetime model for evaluating the maintenance schedules and cost of components on a railway electrification system. Fixed time interval preventative maintenance was considered and the change in the overall operational cost and reliability of a component with respect to different maintenance intervals was investigated. The methodology presented for the first part of the study was not applied to any specific components in particular. However, since stochastic methods were used to model the component's lifetimes, the methodology was described as being applicable to all components in the electrification system, including the OLE. The second part of the study focused on accelerated ageing of components due to electrical stress, which is more applicable to other components in the electrification system, such as transformers and switchgear.

The authors state that the evaluation of risk and costs should involve the use of lifetime models. Since samples of identical components do not necessarily have the same lifetime, there is a need to derive lifetime distributions to perform an effective lifetime analysis. The lifetime distributions should be derived using empirical data to find their parameters. For all components in the traction power system, it was assumed that the component is initially operated within its useful life period t_u (assumed to be provided by manufacturers). A constant failure rate, λ , is exhibited during t_u , after t_u the component enters its wear-out period, where its condition deteriorates and the failure rate increases with time. The probability density function (pdf) of a component's lifetime was said to be a combination of the exponential distribution (during the component's useful life) and Weibull distribution (during the wear-out period). The cumulative distribution functions (cdf) for the two distributions were then rearranged, so that the component's time to failure can be found, to give Equation 3-2.

$$t_F = \begin{cases} -\frac{1}{\lambda} \ln(1 - u_F) & (0 \leq u_F \leq u_U) \\ (1 - \beta)t_u + \beta \left[-\frac{t_u^{\beta-1}}{\lambda} \ln(1 - u_F) \right]^{\frac{1}{\beta}} & (u_U < u_F \leq 1) \end{cases} \quad \text{Equation 3-2}$$

Where t_F is the time to failure of the component, t_u is the component's useful life period, λ is the failure rate of the component during its useful life (the exponential distribution's rate parameter), β is the shape parameter of the Weibull distribution, u_F is a uniformly distributed random number between 0 and 1 used for sampling the time to failure, and u_U corresponds to the upper bound that the random number chosen can be used to sample a failure time from the exponential distribution, which represents the component failing within the period deemed to be its working life (the interval from time 0 to t_u), where $u_U = 1 - \exp(-\lambda t_u)$.

When u_F is greater than u_U , the time to failure is sampled from the equation representing the component failing during the wear-out period after its characteristic life. This equation is obtained by adjusting the cdf of the Weibull distribution, to account for the fact the component's lifetime is first described by the exponential distribution. Note that the Weibull distribution's scale parameter is dependent on the shape parameter and the mean time to failure of the initial exponential distribution, therefore it is not present in Equation 3-2. Billinton and Pan (2000) provided a detailed description of formulating the combined lifetime distribution that was used in this study.

Next, a Monte Carlo simulation was undertaken, whereby random numbers were generated and then the corresponding time to failure was chosen using Equation 3-2. Fixed time interval preventative maintenance and corrective maintenance (after a failure has occurred) were considered and it was assumed that all maintenance actions leave the component in a new state, such that its age returns to the start of its useful life period. If the failure time sampled is such that the failure will occur before the next scheduled preventative maintenance, then corrective maintenance is performed. Conversely, if preventative maintenance is scheduled to occur before the component's failure, then the maintenance is carried out and the failure is prevented. This process repeats until the total simulation study time is reached. The total amount of corrective and preventative maintenance actions undertaken were recorded. Also, from the statistics recorded, the failure frequency and the overall cost were calculated by assigning costs to the different maintenance actions, where the cost of corrective maintenance was far greater than the cost of preventative maintenance. The pdf of the failure frequency and overall cost for all the simulations undertaken were then found. The Monte Carlo simulation was repeated for different fixed time intervals of preventative maintenance and the pdfs for the number of failures and cost for each different maintenance interval studied were obtained.

This allowed the influence that the maintenance interval has on the failure frequency and overall maintenance cost to be evaluated. The example given was for a single component that was not identified, the purpose of the study was to describe the features of the methodology rather than present the findings from the analysis of a specific OLE component.

This model is effective in investigating how the fixed time interval preventative maintenance influences the expected failure frequency and overall cost in a quantitative manner. Decision makers can therefore use the results to specify the maintenance interval through the consideration of the time intervals that produce the lowest expected overall cost, whilst ensuring that the component's expected reliability is also satisfactory. The simulated results clearly show that short maintenance intervals lower the failure frequency, but result in excessive costs due to over-maintenance. On the contrary, longer maintenance intervals result in comparatively more failures occurring and also higher costs. An optimum maintenance interval can, therefore, be found. However, this methodology would not accurately represent how maintenance is undertaken on the British railway network, as Network Rail now performs condition-based maintenance, where maintenance is scheduled based on component condition (which is revealed during routine inspections), rather than fixed interval preventative maintenance. The assumption that maintenance returns the component to a condition where it is as good as new is also invalid for some of the maintenance actions undertaken on OLE components, for example, in the case of the contact wire a splice is inserted to replace a damaged section, meaning the wire does not return to the new condition.

A similar method was also used by Min et al. (2009) to develop a reliability and cost model. A stochastic model, involving equations for the reliability of OLE components, was used in conjunction with a genetic algorithm, to find the optimum maintenance strategy for seven of the most critical OLE component types with respect to cost and system reliability. The equations expressing the reliability of the components were represented by Weibull distributions that were fitted using 10 years of OLE component failure data on a 100km section of the Beijing-Guangzhou high speed rail line in China. The seven components studied in detail were the contact wire, catenary wire, tensioning equipment, registration arms, droppers, overlaps and isolators. The reliability of the remaining components was combined and modelled by the exponential distribution. The preventative maintenance actions considered were a simple mechanical service, a replacement/repair of parts of the component and a complete renewal of the entire component. Each maintenance action had a different cost and improved the components' reliability by different amounts. These maintenance actions occurred at fixed, constant intervals. At the start of each interval one of the three maintenance actions or no maintenance were chosen to occur. The reliability was evaluated during each maintenance interval and the equations expressing the component reliability were altered by a reliability improvement

coefficient that took into account the previous maintenance actions. If a component failed, then rapid response maintenance took place with a larger cost incurred. A fixed total period of 168 months of OLE operation was modelled and the total cost of maintenance and the average system reliability, over the entire period studied, were calculated.

A genetic algorithm was used to find the optimum maintenance strategies by choosing the different maintenance actions at the start of each interval and attempting to minimise the cost, whilst maximising the system's reliability. A multi-objective problem was defined, where a set of optimal strategies, with respect to minimising the cost and maximising the reliability of the system, were found. Each optimum solution referred to the maintenance strategy with the lowest expected cost for the corresponding expected reliability of the system. The optimum strategies were also found for different time lengths of the fixed maintenance intervals.

This model is effective in estimating the reliability and the maintenance and failure costs of the OLE. The results of the optimisation give a set of optimal maintenance strategies that specify the different maintenance actions to be undertaken at each fixed preventative maintenance interval. The results allow decision makers to choose an appropriate strategy based on the expected values of the system's cost and reliability. The most critical OLE components are considered and historical data has been used to derive the distributions that describe the component failure times. The different restoration effects that the different maintenance actions have on component conditions are also considered. However, as in the work previously described by Chen et al. (2007) and Ho et al. (2006), fixed interval preventative maintenance is the only maintenance regime considered in the model. Therefore, further modifications would be required in order to accurately model the OLE on the British rail network, where condition-based maintenance is undertaken.

Overall, the lifetime models described are capable of modelling both the failure and maintenance of the different components to calculate the component failure and maintenance costs over the life cycle of the system. However, because the equations simply model how the components are working and then fail, they may over simplify the behaviour of the components, in terms of their degradation, failure and maintenance. For instance, there are no degraded component conditions modelled, where condition-based maintenance would be undertaken (based on the results of inspections) to address the degradation before the failure. The principle of lifetime models could be used to describe the time to reach the degraded states (not just a failed state) which can be used in a state-based model, which are described in the following section.

3.3.3.3 Markov Models

A Markov model is a state-based, stochastic model that can be used to calculate the probability of a component/ system residing in a certain state, which is defined in the model, at a certain time. The model relies upon the Markov property, where the probability of moving from one state to another is dependent on the current state only and the history of the system (in terms of the previous states visited beforehand) does not matter (Billinton & Allan, 1983). The Markov property therefore implies that the rate of moving between two states is governed by the exponential distribution. The states within a model are commonly used to represent different conditions of a system, such as working, degraded or failed, and the transitions represent the rate of moving between the two connected states. For system reliability purposes, Markov models are commonly discrete in space, meaning there are a set of discrete states in which the system can be identified to reside. However, they may be discrete or continuous in time. Where the Markov model is discrete in space and time it is commonly referred to as a Markov chain, whereas when it is discrete in space and continuous in time, it is referred to as Markov process or a continuous time Markov chain.

Markov Chains

In a discrete time Markov chain, the probability of moving from one state to another, or remaining in the same state, is set for a fixed (discrete) time step and a set of non-overlapping states are identified, in which the system must reside at any time. The sum of the probabilities of all the transitions leaving a state must be equal to 1. From these transition probabilities, one can calculate the probability of being in a state after a certain number of time steps, depending on the state that the system was initially in. Figure 3-4 shows a simple Markov chain describing how a component can move between 2 states, working and failed. The probabilities of moving between the states and residing in the same state are listed.

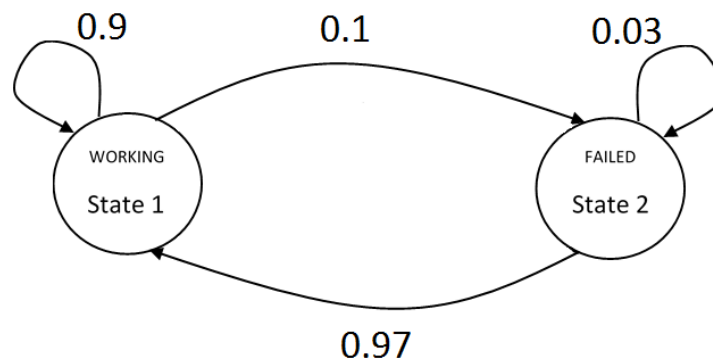


Figure 3-4 State Transition Diagram for a Simple Markov Chain Example

To find the probability that the component resides in a certain state after a given number of time steps, a transition probability matrix, containing the probability of moving between each of the states or remaining in the same state, can be formed and then multiplied by itself for the number of time steps, before multiplying the result obtained by a row vector describing the initial state of the component. This is described by Equation 3-3, where $\pi(n)$ is a vector describing the probability of being in each of the states after n time intervals, $\pi(0)$ is a vector describing the initial state of the component and P is the transition probability matrix. The transition probability matrix is a square matrix with dimensions equal to the number of states in the model and the matrix is formed such that element P_{ij} represents the rate of moving from state i to state j . Since each row of the matrix refers to the probability of remaining or leaving a certain state, the probabilities in each row must sum to 1. A generic transition probability matrix, for a Markov chain containing k states is shown in Equation 3-4. The corresponding transition probability matrix for Figure 3-4 is shown in Equation 3-5 and the probability of remaining in the different states after four time intervals is shown in Equation 3-6, where the probabilities calculated for the component residing in the working and failed states, given that the component was initially in the working state, are 0.907 and 0.093 respectively. The probability of the component being in a certain state during future time intervals can then be analysed to study the expected behaviour of a component over time.

$$\pi(n) = \pi(0)P^n \quad \text{Equation 3-3}$$

$$P = \begin{bmatrix} p_{0,0} & p_{0,1} & \cdots & p_{0,k} \\ p_{1,0} & p_{1,1} & \cdots & p_{1,k} \\ \cdots & \cdots & \cdots & \cdots \\ p_{k,0} & p_{k,1} & \cdots & p_{k,k} \end{bmatrix} \quad \text{Equation 3-4}$$

$$P = \begin{bmatrix} 0.9 & 0.1 \\ 0.97 & 0.03 \end{bmatrix} \quad \text{Equation 3-5}$$

$$\pi(4) = [1 \quad 0] \begin{bmatrix} 0.9 & 0.1 \\ 0.97 & 0.03 \end{bmatrix}^4 = [0.907 \quad 0.093] \quad \text{Equation 3-6}$$

Markov Processes

In a Markov process (or continuous time Markov chain), since time is continuous, a transition modelling a change in state can occur at any time. The probability of residing in a certain state at any time can then be calculated, where the transition times are governed by the exponential distribution. Figure 3-5, shows an example of a simple Markov process consisting of a working state and a failed

state, where the transitions between them model how a component can fail (where λ represents the failure rate) and be repaired (where ν represents the repair rate).

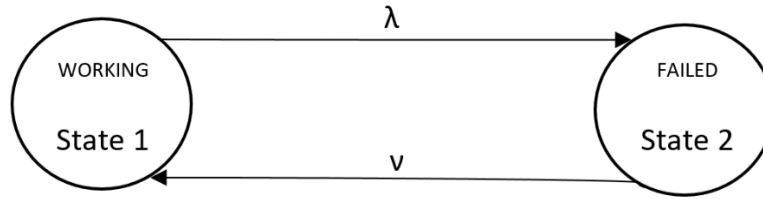


Figure 3-5 State Transition Diagram for a Simple Markov Process Example

The probability of a component being in a working state after a small time interval is equal to the probability that the component was in the working state initially and did not leave the state, or the probability that the component was in the failed state initially and was repaired during the small time interval to be in the working state. This is shown in Equation 3-7, where $P_w(t)$ and $P_f(t)$ are the probability of the system being in a working or failed state at time t respectively, λ and ν are the failure and repair rates respectively (as shown in Figure 3-5) and dt is a small time interval.

$$P_w(t + dt) = P_w(t) \cdot (1 - \lambda dt) + P_f(t) \cdot \nu dt \quad \text{Equation 3-7}$$

Rearranging and considering when dt approaches 0 gives Equation 3-8, which shows the rate of change of probability of residing in the working state.

$$\frac{dP_w(t)}{dt} = -\lambda P_w(t) + \nu P_f(t) \quad \text{Equation 3-8}$$

Similarly, Equation 3-9 shows the rate of change of probability of residing in the failed state.

$$\frac{dP_f(t)}{dt} = \lambda P_w(t) - \nu P_f(t) \quad \text{Equation 3-9}$$

These equations can also be obtained using the transition rate matrix, commonly referred to as Q , which is a matrix describing the rate of moving from one state to another. The dimensions of Q are equal to the number of states in the model and the matrix is formed such that element q_{ij} represents the rate of moving from state i to state j . The diagonal elements in the matrix, i.e. q_{ii} , are calculated to ensure that the sum of each row equals 0. Equation 3-10 shows Q for the Markov process shown in Figure 3-5. Multiplying the transition rate matrix by a vector of the probabilities of being in the states at time t , gives the rate of change of probability of residing in the different states (shown in Equation 3-8 and Equation 3-9). This is shown by Equation 3-11, where $\dot{P}$ is a vector where each element refers to the rate of change of probability of residing in the different states, P is a vector where each element refers to the probability of being in each of the states at a given time and Q is the transition rate matrix.

$$Q = \begin{bmatrix} -\lambda & \lambda \\ \nu & -\nu \end{bmatrix} \quad \text{Equation 3-10}$$

$$\dot{P} = P \cdot Q \quad \text{Equation 3-11}$$

A Markov process containing n states will yield n differential equations. Solving this system of equations analytically can be complicated for all but the simplest/smallest of models. For smaller models, the probability of residing in a state at a given time can be found analytically. For example, for the Markov model shown in Figure 3-5, Equation 3-8 and Equation 3-9 are solved to find the probability of the component residing in each state at time t . Since $P_w(t) + P_f(t) = 1$, the equations can be solved using the initial conditions $P_w(0) = 1$ and $P_f(0) = 0$ (i.e. the component starts in the working condition). This gives Equation 3-12 and Equation 3-13, which express the probability of the component being in a working and failed condition, at any time, respectively. Note that for larger, more complex models, the differential equations are normally solved numerically.

$$P_w(t) = \frac{\nu}{\lambda + \nu} + \frac{\lambda e^{-(\lambda + \nu)t}}{\lambda + \nu} \quad \text{Equation 3-12}$$

$$P_f(t) = \frac{\lambda}{\lambda + \nu} (1 - e^{-(\lambda + \nu)t}) \quad \text{Equation 3-13}$$

By calculating the probability of a component or system being in a certain condition over time, the reliability and maintenance requirements can be analysed. Note that the examples given in this section are simple and only contain 2 states. The Markov models described in the literature reviewed in the following section contain more states as they considered more component conditions and processes, such as inspections and renewals.

The use of Markov Models for Asset Management Modelling

Markov models are used widely in the field of reliability engineering and they are the main probabilistic method used in modelling for asset management purposes (Remenyte-Prescott & Andrews, 2013). Markov models have been used in a variety of fields across different infrastructure types. For example, Golabi et al. (1982) described the use of a Markov model in a pavement management system that was used to determine the maintenance regimes to implement on the road network in Arizona. After implementing the maintenance regime specified from modelling results, the cost savings over the next 4 years were estimated to be over \$100million with no adverse decline in the road condition. This example shows the power and benefits of correctly applying a Markov model for determining the asset management strategies for a large infrastructure system.

To date, the application of Markov models to railway infrastructure has been concentrated primarily on track and bridge assets. For example, Le and Andrews (2013) used a Markov model to analyse the degradation and maintenance of bridges on the British railway network. A continuous time Markov model (Markov process) was created to model the degradation, inspection and maintenance of bridge elements. The degradation rates were found through the analysis of maintenance records. To allow for inspections to take place at discrete time intervals, the calculation of the model has 2 phases; a continuous phase between inspections, where the transition rate matrix is based on the degradation rates and repair rates (moving between the various states), and a discrete phase, which takes place when the inspections are scheduled. During this discrete phase, the probabilities of being in the unrevealed condition states are transferred to the revealed condition states. A numerical method was used to solve the model and the results showed the expected costs each year (over a 60-year period analysed) and the probability of the bridge being in a certain condition each year.

In addition, Prescott and Andrews (2013) used a similar method to determine railway track performance under a given maintenance regime. The Markov model consisted of 8 sets of 10 states, where each set of 10 states models the degradation of the track, for a specific maintenance history, taking into account inspection. In order to account for different degradation rates after maintenance (specifically modelling how the rate of track degradation may increase after tamping) whilst satisfying the Markov property, every time maintenance is undertaken a different set of 10 condition states is used in the model to represent a system that has experienced a given number of maintenance actions. After 8 maintenance actions, it is assumed that further maintenance will no longer affect degradation rates and the system will degrade at the same rate as after 8 maintenance operations. Renewals result in the system returning to its initial state, where the track is in a new condition with no maintenance operations having been undertaken. The model was solved numerically using a Runge-Kutta algorithm. Statistics were obtained describing the proportion of time that the track is predicted to spend in certain conditions and the probability of maintenance being performed over the track's life cycle.

The current model that Network Rail uses for life cycle cost modelling of the OLE is based on a discrete time, Markov chain approach (Network Rail, 2012). A 100-year future period is analysed using a fixed time step of one year. For a component being studied, at the start of each time step, the model considers its current age and then calculates whether it fails (in which case it is repaired or replaced), it is maintained (in which case it is repaired or replaced) or it continues to operate normally (in which case it will be a year older at the beginning of the next time step). In the case of repair, the component's current age is reduced by a certain number of years to model how the component's condition has been improved. In the case of replacement, the component's current age is reset to zero. Age is effectively used as a proxy for the component's condition. The underlying Markov chain

representing this process, therefore, contains states describing the age of the current component at the start of each time step and the transitions represent the component failing, being maintained, or operating normally during the current time step. The transition rates are based on the maintenance and failure rates for different ages of the component studied. These rates have been found using expert judgement and analysis of historical data. A Monte Carlo simulation is used to evaluate the model and, for the components studied, the probability that maintenance is required and the probability of failure during each year of the 100 years considered is calculated. The expected yearly failure and maintenance costs are calculated by multiplying the typical maintenance cost and failure costs by the probability of the component requiring maintenance or failure in the corresponding year respectively. Whilst large scale renewal actions can be modelled (by scheduling the replacement of the component to occur at a certain time), the model does not consider other asset management actions in detail. Since the model works by considering the overall rate of maintenance or failure in a given year, component inspections and the scheduling times for corrective or preventative maintenance of the different component types are not modelled. As a result, the model cannot be used to evaluate different inspection and maintenance scheduling times that are used in the condition-based maintenance regime undertaken.

Appraisal of Markov Models

Since Markov models are commonly represented by a state-transition diagram, they can be intuitive and can clearly communicate the processes of a system that are modelled. The transition rates can be based on real data (such as the failure and degradation rates of a system), which can allow the model to accurately represent the occurrence of various processes in a system. Markov models are well suited for modelling degradation, failure and repair processes and the results express the future probabilities of the system being in the various states considered, which can be very useful for understanding how the system will behave over time. Therefore, Markov models are directly applicable for use as an asset management or life cycle cost model (as the literature described above has shown). The solutions for the probability of staying in the various states can be solved analytically for smaller models, meaning the results can be obtained instantly. However, due to their reliance on the Markov property, Markov models are memoryless, i.e. any processes that are dependent on the history of the system require additional states that represent a state of the system with the relevant history, as Prescott and Andrews (2013) demonstrated in their work (described earlier). This can lead to extremely large models that will be difficult and computationally expensive to solve. Complex systems with many processes and components to consider can also result in unfeasibly large models. Another issue is that the timing of transitions must be governed by the exponential distribution, which

may be too restrictive an assumption to make and it may not accurately fit the available asset data for a given system.

3.3.3.4 Petri Nets

A Petri net is another state-based modelling method that can be used to study the behaviour of a system by modelling the relationship between the different conditions of the system and the concurrent and dependent events that occur. Petri nets were first developed in 1962 by Carl Petri as part of his thesis (Petri, 1962). Since then, due to their power and flexibility, they have been used in a variety of different fields, such as modelling system processes in engineering and business (Girault & Valk, 2003). Petri nets are particularly suitable for modelling the failure and degradation of components in a system (Andrews, 2012), therefore, they are a potential method for modelling the asset management and life cycle cost of the OLE. A detailed description of how Petri nets work and how they can be used to model the asset management and life cycle cost of a system will be given next. Following this, an explanation outlining the advantages of Petri nets over other methods, for modelling such processes for the OLE, is provided.

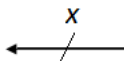
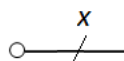
Petri Net Description

This section will describe Petri nets and their main features and elements using the terminology listed in the Petri net standards BS EN 62551:2012 (British Standards, 2012). Petri nets are bipartite graphs in which there are passive and active nodes. The passive nodes are called *places* and they represent local states or conditions. *Places* can be marked with *tokens* to indicate that the system is currently in this state or condition. The active nodes are known as *transitions*. These model the possible changes from one *place* to another to describe the potential events that can arise. *Places* and *transitions* are interconnected by directed *arcs*. These *arcs* represent inputs or outputs to *transitions*, according to the direction of their arrowhead, or an inhibitor to a transition. *Places*, *transitions*, *tokens* and *arcs* constitute all the elements used in a Petri-net and they are depicted by the symbols shown in Table 3-1.

The transitions enable changes of the system to occur through removing tokens from certain places and adding tokens to others. When a transition moves the tokens, according to its connected arcs, it is said to 'fire'. For a transition to fire it must first be enabled. A transition is enabled if all the places that its input arcs are connected to contain (at a minimum) the number of tokens specified by the input arc connecting that place to the transition. If the transition also contains inhibitor arcs, then the places that its inhibitor arcs are connected to must contain fewer tokens than the inhibitor arc specifies.

Once a transition is enabled, it can fire. Upon firing, the marking of the places connected to the transition is changed as follows: the places connected to the transition's input arcs will have the number, specified by the connecting input arc, of tokens subtracted from it and the places connected to the transition's output arcs will have the number, specified by the connecting output arc, of tokens added to it. If there is no weight attached to an arc, then its weight is simply one, i.e. one token will be added to or subtracted from a place. The number of tokens in a place is referred to the marking of the place.

Table 3-1 Description of Petri Net Elements

Token	Place	Transition	Input/ Output Arc (Weight = x)*	Inhibitor Arc (Weight = x)*
•				
*if weight = 1, then it is not written on the arcs				

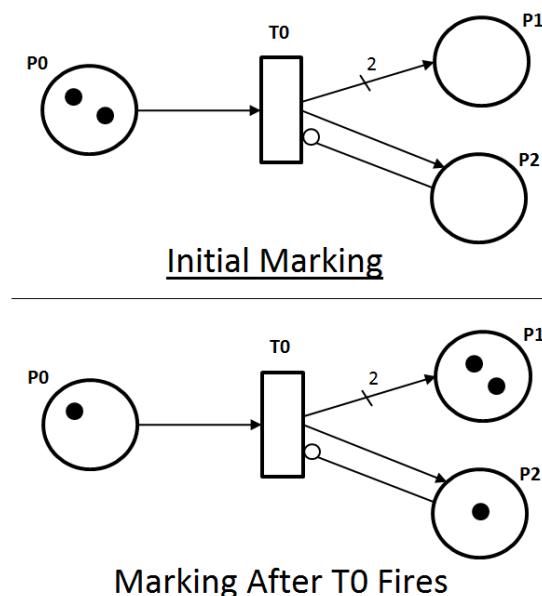


Figure 3-6 Simple Petri Net Example

Figure 3-6 shows a simple example of a Petri net containing one transition (denoted by T0) and three places (denoted by P0, P1 and P2). Transition T0 has one input arc connected to P0, with a weight of one. It has 2 output arcs to places P1 and P2, with weights of two and one respectively, and an inhibitor arc, with a weight of one, connected to place P2. In the initial marking, shown in the top part of the figure, T0 is enabled because there are two tokens in P0, meaning the requirements stipulated by the

input arc are met, and there are no tokens in P2 that inhibit the transition. When T0 fires, one token is absorbed from P0, because the weight of the input arc is one, two tokens are fired to P1 and one token is fired to P2. The bottom section of the figure shows the updated marking of the Petri net after firing. T0 is no longer enabled because there is now a token in P2 which inhibits the transition, due to the inhibitor arc, even though there is still one token remaining in P0.

With careful and methodical thinking, through the use of the Petri net elements (places, tokens, transitions and arcs), a Petri net can be created to model the main processes in most engineering systems. In a similar way to Markov models, the different places can represent different conditions of the system and the transitions can represent the processes that result in a change of the system's condition (such as failure or degradation). For large systems, with numerous processes, a hierarchical Petri net can be developed, where Petri net sub-nets are created to model some of the processes separately and then transitions can interlink the different sub-nets.

Timed Petri Nets

In a timed Petri net, when a transition becomes enabled, it can fire after a time delay, so the tokens remain in the input places during this period. This enables the Petri net to model how a system may reside in a certain condition or state for a length of time. After becoming enabled, the time duration that a transition will fire after can be a deterministic (fixed) time or a stochastic time. Deterministically timed transitions can be used to model discrete processes, where the timing of an event is fixed. The time for a stochastically timed transition to fire is calculated by sampling a time from the cumulative distribution function of the statistical distribution assigned to the transition, with the corresponding parameters (such as the shape and scale parameters for the Weibull distribution).

The Petri net can be evaluated using a Monte Carlo simulation. When a stochastically timed transition is enabled, a random number is generated and used to sample the transition's firing time. When a deterministic transition is enabled, its firing time is equal to the fixed time assigned to it. During the simulation of a Petri net, the firing times for transitions are calculated when they become enabled and the simulation time progresses to when the enabled transition with the shortest firing time will fire. Tokens will then move around the net according to the transitions that fire and the simulation will continue to progress through time until the study time is reached. During each simulation a variety of statistics can be collected, for example, the amount of time a certain place is marked in a given time frame, which can therefore relate to the amount of time the system spends in a certain condition. Simulations are then repeated until the statistics that are collected converge.

High Level Petri Nets

High Level Petri nets contain additional features that add further functionality to standard Petri nets to enable certain processes to be modelled more accurately and efficiently within the Petri net framework. A standard for High Level Petri nets has also been published by British Standards (2010).

Like standard Petri nets, High Level Petri nets contain tokens, which exist in places, and transitions, which move the tokens between the different places that their arcs are connected to. A distinct feature of High Level Petri nets is that the tokens can contain additional information in the form of data values, i.e. the tokens are no longer represented by a simple black dot. Different tokens can exist in the same place and can be distinguished according to information contained within their data values. This can allow different instances of each component or element of the system to be modelled using the same place. To allow the different tokens to be modelled concurrently, the transitions have different modes, where each mode of a transition will only become enabled and perform operations on certain tokens according to their data values. A transition's arc can also contain functions that can be based on the information stored within the tokens. The transitions themselves can therefore perform more complex operations than simply adding and subtracting tokens from places. For instance, the information within a token's data values can be altered by a function.

Allowing multiple tokens, that are distinguishable, to exist in the same place can be particularly advantageous because identical, or similar, processes do not require additional places and transitions to be modelled concurrently. This reduces the required number of required places for modelling certain systems and therefore keeps the net more concise. The use of transitions that undertake specified functions can also make High Level Petri nets more intuitive and efficient, in comparison to standard Petri nets.

Jensen & Kristensen (2009) also explained the concept and methodology of Coloured Petri nets, which are an example of High Level Petri nets, in detail. The British Standards publication for High Level Petri nets states that it encompasses the features that are used in Coloured Petri nets, but different terminology is used. Further research in the area of modelling engineering system behaviour has been undertaken using standard Petri nets that contain extended features, which have been developed to suit the particular problem studied. For instance, Andrews (2013) developed a conditional transition, where its firing time is chosen depending on the number of tokens in a certain place. Such features can be included within the framework stipulated by Coloured Petri nets or High Level Petri nets.

In this thesis, Petri nets containing additional enhancements to the standard Petri net technique (as described above) are referred to as High Level Petri nets and terminology synonymous with British Standards publications for Petri nets and High Level Petri nets is used.

Petri Nets Used to Model Asset Management

Petri nets are a relatively novel method for modelling the reliability and maintenance of a system. However, more recently, literature describing the use of stochastic Petri nets for modelling such processes has become more prevalent. For example, Dersin and Valenzuela (2012) described the use of Petri nets for modelling railway system maintenance for a signalling system. The failure, inspection and maintenance of components were considered, along with the availability of the resources needed to undertake the maintenance. The different processes modelled were split into different sub-nets that handle a specific set of actions. A case study showed how the model was used to calculate the expected availability of a system over a 30-year time frame and analyse the effect that increasing the number of maintenance operators has on the availability. The appropriate number of resources (in terms of the number of maintenance operators) required to ensure a suitable system availability were then found. These findings are particularly useful to asset managers and can be used to improve their asset management strategy.

Andrews (2013) described a Petri net that models the degradation of a railway track section, whilst also considering inspection, maintenance and renewal actions. The model contains several places representing different conditions (or states of degradation) of the track, in terms of its vertical geometry. The distributions of the times to reach different levels of degradation, under a given maintenance history, were obtained by analysing historical track geometry data. These distributions were then assigned to transitions that described the degradation process between the different condition places. The model also contained places describing the degraded conditions as being revealed and transitions representing the inspection process. Transitions describing the maintenance process then moved tokens from the revealed degraded places to a place representing the track as being in a repaired condition. A renewal process was also modelled, where the track section returns to a completely new condition.

Additionally, in this paper, enhancements to standard Petri nets were used to model how the degradation behaviour of a track section after maintenance will be different to that of a new track. To do this, a '*conditional transition*' was created where the distribution used to sample its firing time was chosen depending on the number of tokens in one of its input places. The tokens in this input place represented the number of times that maintenance has been undertaken. This was used to model the time it takes to degrade from a repaired state to the first degraded state. The advantage of creating

such a transition is that it removes the need to create numerous new places and transitions to represent the system for different maintenance histories, which would result in a rapid increase in the number of places and transitions. As part of the renewal process, a '*reset transition*' was developed that effectively resets the marking of all the places in the Petri net, so that the system exists in the new state with no previous maintenance having been undertaken.

A Monte Carlo simulation was used to evaluate the model and numerous statistics, describing the performance of the system over the 180-year period analysed, were calculated. These statistics include the expected number of maintenance interventions carried out on the track section and the number of times that speed restrictions and track closures were implemented. The amount of time the system spent in a condition where maintenance was required was also calculated and the number of simulated occurrences of these different times was plotted, to allow an insight into distribution of the expected time spent in a degraded condition. Such statistics can enable asset managers to predict and evaluate the future implications of their current strategies. Since there are costs associated with the various outcomes, such as the number of maintenance interventions, the outputs of the model can also be used to calculate the whole life cost of the system. Overall, this method represents a very detailed approach to modelling the asset management of the railway track over its life cycle. The flexibility of the method allows it to be readily applied to other systems, although ideally high quality degradation data is required to obtain the distributions to be used in the model. The additional, high level features developed allow the necessary processes to be modelled, whilst keeping the Petri net concise. This demonstrates one of the advantages of Petri nets over other methods, such as Markov modelling.

Other examples of Petri nets being used to model the reliability of other engineering systems are also of specific interest in this review. Volovoi (2004) described the use of coloured (high level) stochastically timed Petri nets with tokens that contain additional information, such as their age, that is not limited to changing discretely upon the firing of a transition. The transitions' behaviour, such as the distribution or method used to obtain its firing time, can then change depending on the information within the token. This feature can be particularly useful by allowing dependent processes to be modelled without the need for multiple additional places describing the system's history. Such dependent processes are common to many engineering systems, such as how the degradation of a repaired component may be different to that of a new component. It was shown that allowing the tokens to carry additional information can lead to more concise and accurate representation of various failure and degradation processes within the Petri net framework. Such a methodology could be used as an alternative to the conditional transition that Andrews (2013) developed, to allow transitions to change their characteristics based on the number of tokens in a place.

Fouathia et al. (2005) described a stochastically timed Petri net used to model the reliability of a high voltage distribution substation on the Belgian power system. An interesting feature included in the model was the consideration of imperfect preventative maintenance. A component's virtual age or the occurrence of a failure was the criterion for maintenance and after periodic inspections preventative maintenance was scheduled. The imperfect preventative maintenance resulted in the component's virtual age decreasing according to a factor that is based on a random number generated and the number of previously performed maintenances. After a certain number of previous maintenance events, the component can no longer be repaired. Although not explicitly stated, in order to implement this process, high level features must have been incorporated into the Petri net, such as the use of tokens containing additional information about the components' virtual age and maintenance history (as described by Volovoi (2004)). The model was used to calculate the expected availability and total cost (due to failure and maintenance costs) of the system over a 25 year operating period. Results for a system with a simple detection control system were compared to that of a double detection control system with redundancy (where the structural dependencies between the various components considered are changed within the Petri net).

Le and Andrews (2016) described a stochastically timed Petri net that modelled the degradation, failure, inspection and maintenance of a wind turbine. All of the main components within a single wind turbine were considered and the dependency between these different components and their influence on the overall wind turbine system were modelled. The system Petri net consisted of numerous sub-nets that modelled the relevant processes for the different sub-systems and their components in the wind turbine. The transitions representing component degradation and failure were assigned Weibull distributions. Various enhancements to standard Petri nets were also used to model the processes considered. For instance, different token types, that are distinguishable and can exist in the same place, were used to model the different components and some transitions contained enhancements, such as reset transitions, as first described by Andrews (2013). A Monte Carlo simulation evaluated the model over a 40-year period of operation and statistics were calculated at the sub-system and component level, as well as for the wind turbine system as a whole. The variety of statistics calculated were associated with future condition predictions (e.g. the probability of a component being in a certain condition), future failure predictions (e.g. the mean number of component failures or the distribution of the total downtime of the system) and future maintenance predictions (e.g. the mean number of maintenance interventions undertaken on the system). The whole life cost of the different components and sub-systems, as well as the system as a whole, was also calculated from the model (through consideration of the costs associated with maintenance and failure). The numerous output statistics, at different levels of granularity over the life cycle analysed,

allowed a detailed breakdown of the different performance measures and costs that are of interest to decision makers. The different maintenance strategies can be adjusted and the model can be used as an asset management tool to study the implications of different maintenance strategies. This paper clearly demonstrated the effectiveness of Petri nets for modelling the asset management of a system containing numerous components that have various dependencies between each other. It also shows how Petri nets can be used to obtain a large variety of statistics that are associated with the number of component failures and maintenance actions as well as the expected life cycle cost of the system.

Appraisal of Petri nets

The challenge for the work in this thesis is to model the asset management and life cycle cost of a system consisting of numerous components that may have various dependencies between each other. The models reviewed in this section have shown how Petri nets can be particularly suitable for modelling these processes.

Modelling the asset management and life cycle cost of the OLE requires a consideration of many different components and numerous different processes with various dependencies between them, such as maintaining a number of degraded components at the same time. The Petri net method is more capable of modelling such processes in detail than the other methods reviewed. Using a Monte Carlo simulation to evaluate a stochastically timed Petri net can allow the uncertainty associated with the degradation and failure of the components, which can be considerable, to be included in the analysis. The distributions that the transitions sample their firing times from can be found through the analysis of historical data, so that the model is based on the actual behaviour that has occurred on previous systems. Where a deterministic process (such as regular fixed interval inspections) is required to be modelled, deterministically timed transitions can be used. Similarly, the use of High Level Petri nets can allow the transitions to undertake higher level actions, which could be described by a given function.

Lifetime models, that use equations to model component lifetimes, can calculate the number of failures and maintenances over the time period analysed. However, this approach cannot model all the processes and different condition states required for accurate analysis of a component or system. The use of state-based models, like Markov models and Petri nets, allows numerous condition states to be considered and the different processes, that result in changes in the condition of a component or system, can be stochastically modelled by transitions.

Petri nets can be used to model a component or system in a more concise manner without the statistical limitations imposed on Markov models. For instance, the underlying distribution describing

the firing time of a Petri net's transition is not limited to the exponential transition. Therefore, Petri nets can model the behaviour of a system or component, and the dependencies between them, more accurately. In High Level Petri nets, multiple components, with similar behaviours, can be modelled concurrently by separate tokens that exist in the same place, thus reducing the state space explosion that occurs in Markov models. For large systems where many different components and processes need to be considered (like the OLE), Markov models may become excessively large, resulting in their analysis being cumbersome. However, Markov models have more prevalence in industry, meaning any research undertaken using Markov models might be more compatible with how a company implements its asset management strategy and gathers its data.

In order to compare the two types of modelling techniques, Le (2014) developed both a continuous time Markov process model and a Petri net model to analyse the asset management of railway bridges. The Petri net model's results for predicting long term future component conditions were shown to be similar to the Markov model's results. For a small number of bridge components, the Markov model was shown to be evaluated faster. However, once more components were analysed in the model, due to the increased state space required, the Markov model took considerably longer to be evaluated than the Petri net, even to the point that the calculations became unfeasible. Also, the Monte Carlo simulation of a Petri net model can be undertaken using parallel computing (since each simulation is independent), which reduces the computation time. A Markov model is therefore more applicable for a basic analysis, or the analysis of a single component or small system, where the durations of the main processes modelled are exponentially distributed. However, if a more accurate and detailed analysis is required then Petri nets are a more suitable alternative method.

3.4 Summary

This section provides a short overview of the main studies and methods described in this literature review. A discussion of the key findings and their relevance to this thesis are then outlined to conclude this chapter.

3.4.1 Overview of the Literature

Railway infrastructure organisations can improve their asset management capabilities by modelling the asset management and life cycle cost of a system to allow analysis of its expected performance, in terms of various performance indicators, such as the expected reliability or cost of a system, over its life cycle (Skinner et al., 2011) (International Union of Railways, 2010). This can be achieved through modelling the main processes that influence the behaviour of the system. For engineering systems,

like the OLE, these processes are the degradation and failure of components and the inspection and maintenance actions undertaken.

Numerous studies investigating the behaviour of the OLE have been undertaken using deterministic approaches, such as the finite element method and metallurgic analysis. These studies primarily concentrated on modelling the physical behaviour of the components, for instance the displacement of the contact wire or the force exerted on the contact wire by the pantograph. Within these models, the influence that different design parameters have on the system's behaviour and the interactions between different components during the operation of the system can be analysed. Railway infrastructure organisations use such modelling techniques to analyse the system behaviour and specify the design parameters, for example the dropper spacing or the span between structures, for new OLE installations (Railway Safety and Standards Board, 2007) (Bobillot et al., 2010).

Research describing reliability and risk analysis studies of the OLE has also been undertaken. A methodology based on FMEA was applied to OLE to analyse the reliability of components and specify suitable inspection regimes (Duque et al., 2009) (Zorita et al., 2010). This methodology can be useful for improving asset knowledge and specifying asset strategy but cannot be used to directly model the asset management and life cycle cost of an asset or system. Fault Tree Analysis was used to analyse the reliability of the overall railway electrification system, including OLE components (Chen, et al., 2007). The influence that the different components' reliabilities have on the overall system's reliability was investigated and a model that calculated the reliability of the system at a given time was described. Fixed interval preventative maintenance was considered within the equation, by improving the reliability by certain factors at the time intervals that the maintenance was scheduled for. This model allowed the system's reliability and associated maintenance costs to be calculated over time and the results for different intervals of preventative maintenance to be compared. However, the reliability model cannot accurately represent all the relevant processes and considers maintenance to occur at the system level rather than on individual components.

Studies investigating the maintenance and failure costs and reliability of the OLE over its life cycle have been undertaken using a Monte Carlo simulation of equations describing the lifetimes of the components (Ho et al., 2006) (Min et al., 2009). These equations also take into account fixed interval preventative maintenance and corrective maintenance after a failure. This method allows numerous statistics to be obtained (such as the expected reliability of the system over its life cycle) that can help asset managers to analyse the future performance of the system for a given asset management strategy. However, the equations are simply related to the lifetime distributions of the components (commonly represented by Weibull or exponential distributions), with additional expressions or

factors included to account for the improvements in reliability due to the maintenance actions considered. The equations do not accurately model all the processes in the system and the dependencies between different components are not taken into account. Furthermore, since Network Rail undertakes condition-based maintenance, where maintenance is scheduled based on the results of routine inspections, the equations used in such models would not be directly applicable to modelling the reliability and maintenance of OLE on the British railway network. Meier-Hirmer et al. (2007) described the analysis of inspection and maintenance data on the French railway network to fit distributions describing the lifetimes of OLE components. The Weibull distribution was shown to accurately represent the components' lifetimes.

Markov models have been widely used in a variety of different fields to model the reliability and asset management of a system (Remenyte-Prescott & Andrews, 2013). The different states considered in the model can represent different conditions of the system that are related to its performance and asset management. Numerous processes, such as component degradation, failure, inspection and maintenance can be modelled as transitions that describe how the system can move between the different states considered. The probabilities or rates of the various processes modelled (i.e. the probability or rate of movement between certain states) can be directly based on data. Since Markov models can be graphically represented as a state-based model, they can often describe the different processes considered in a more intuitive manner than an equation alone. Due to their stochastic nature, Markov models take into account the statistical variation associated with the different processes modelled. The results expressing the probability of the system residing in a particular state at a given point in time can be useful for asset managers, since they give an insight into the future behaviour of the system over its life cycle.

However, Markov models rely on the underlying assumptions that the future condition of the system, or a component, is dependent only on its current condition and the rate of moving between two states is governed by the exponential distribution. Such assumptions may not be valid for certain systems or processes. Additional states can be introduced to a Markov model to represent the system being in a state containing the required history. However, this can result in the number of states in the model increasing rapidly, which can increase the time taken to evaluate the model significantly (Prescott & Andrews, 2013). Similarly, modelling multiple different components, to analyse their dependencies in the same model can also result in a rapid increase in the state space. Consequently, Markov models may not be able to model all the processes associated with the asset management and life cycle cost of all the different OLE components in a detailed or efficient manner.

Literature reviewed in section 3.3.3.4 has shown the Petri net method to be particularly suitable for modelling the reliability and maintenance of various engineering systems. Stochastically timed Petri nets, which model a system's behaviour, have been shown to be capable of calculating numerous statistics, that are beneficial to asset managers (Andrews, 2012) (Fouathia et al., 2005) (Le & Andrews, 2016). In a similar manner to Markov models, the different places in the Petri net can be used to represent different states or conditions of the components or system modelled. The transitions, which can be deterministically or stochastically timed, can then describe the different processes that occur and move tokens between the different places. The use of High Level Petri net features can allow more complex processes to be modelled and reduce the required number of places and transitions, thus keeping the model more intuitive and concise.

3.4.2 Key Findings

Railway infrastructure organisations, like Network Rail, undertake life cycle cost modelling of their assets to determine appropriate asset management strategies, based on modelling results, and to estimate the future costs of the system. These life cycle cost models consider the degradation and failure of components, as well as their inspection and maintenance actions. The current model used by Network Rail for the OLE is based on a Markov chain approach, but it does not take into account component inspection and maintenance scheduling times, therefore the approach does not explicitly model the condition-based maintenance regime that Network Rail presently undertakes.

There has been limited research into OLE asset management to date. The majority of studies have focused on deterministic modelling of the components in order to better understand their physical behaviour for different design and loading characteristics. Literature has been reviewed describing the use of models that have been developed to analyse the expected number of failures and maintenance for the OLE components and calculate the life cycle cost of the system. These models are based on equations that represent the reliability or lifetimes of the different components and they do not sufficiently model all the processes associated with the asset management of the OLE components, such as inspection and condition-based maintenance.

Literature reviewed for state-based models, such as Markov models and Petri nets, have shown how the life cycle cost and asset management of other engineering systems can be effectively modelled. The Petri net method is a relatively novel approach in this field, but studies have shown it to be very applicable to modelling asset management processes due to its flexibility, where both deterministic and stochastically timed transitions can be used. The use of High Level Petri nets can also allow more complex processes to be modelled. An extensive range of outputs can be obtained, capable of

expressing the performance of the components or the system studied (in terms of the expected number of failures and maintenances), as well as the system cost over its life cycle.

As a result, in this thesis, Petri nets have been chosen to be used to model the degradation, failure, inspection and maintenance processes of the different OLE components. In particular, High Level Petri nets can be used to enable the complex processes and dependencies between the different components studied, to enable a whole system model to be developed, where all the main OLE components are modelled simultaneously. The model should calculate numerous outputs, that can help railway organisations evaluate and improve their asset management strategies, such as cost statistics and component maintenance and failure statistics. Such a model can, therefore, be used as a life cycle cost model which can help to improve OLE asset management, through estimating the future whole life cost of the system and evaluating maintenance strategies.

Chapter 4 Petri Net Model for OLE Asset Management

4.1 Introduction

A stochastically timed High Level Petri net has been developed in this study to model the asset management and life cycle cost of the OLE. The degradation, failure, inspection and maintenance processes of the main OLE components are modelled. Since the OLE system consists of many different components, which the inspection and maintenance regimes often address at the same time, a holistic approach has been undertaken whereby all the main components that influence the system's reliability are considered in the same model. This allows the interactions between the different components to be considered. High Level Petri nets were chosen in order to allow complex processes to be modelled and to also improve the efficiency and intuitiveness of the model.

Firstly, this chapter defines the different High Level Petri net features used in the model and then describes the methodology of developing the model and how it represents the different processes that are considered. Finally, features associated with the application of the model, in terms of how it is evaluated and used for analysis, are explained. The modelling results are presented in Chapter 5.

4.2 Model Definitions

High Level Petri nets work in a similar manner to standard Petri nets, but the higher level features allow the transitions to be associated with certain functions and the tokens can also contain additional data. This enables complex processes to be modelled more accurately and the overall model to be more concise and efficient (through reducing the number of transitions and places) in comparison to a standard Petri net. The High Level Petri net features in this research are described according to the terminology used in standards for High Level Petri Nets (British Standards, 2010) to allow better readability of the proposed model.

Firstly, this section describes how High Level Petri nets work, illustrated by a simple example. A description of how the tokens, places and transitions are used to model the processes considered in this research then follows.

4.2.1 High Level Petri Net Overview

In High Level Petri nets, the tokens are no longer represented by a simple black dot. A distinct feature is that the tokens can contain additional information in the form of data values. Each data value has a

specified property and can belong to a set of values, e.g. a data value could be an integer in the set {0,1,2,3,4,5}. The tokens can contain more than one data value, where the Cartesian product of the data values describes the set of data values contained within the token. In the coloured Petri net framework, described by Jensen & Kristensen (2009), the data values are referred to as colours and the set of data values (or colours) that a token contains is referred to as its colour set. Each place has a specified type, which refers to the set of data values that each token must contain to reside in the place (the required data values can be written next to the place). The different tokens can be distinguished according to their data values, which represent different instances of each component or element of the system being modelled. Note that some places can contain multiple instances of tokens with the same values, in which case the places contain a multiset of tokens.

In order to concurrently model the different tokens that can exist in the same place, the transitions can be enabled in different modes that operate independently on the different tokens. The arc expressions, listed on the transitions' arcs, contain variables that refer to the different data values that exist in the place that they are connected to. The variables within the arcs can bind to the corresponding data value within a token in its connected place (if such a token exists). If all the variables in the arc expressions can bind to the specified data values, then the transition is enabled in that mode for the successful binding. The transitions can also contain functions, involving the arc expressions' variables, which need to be evaluated to check if they are enabled. Since all the tokens that exist in the same place contain the same types of data values, the variables in the arc expressions can have different values to bind to the different tokens, so that the connected transition is enabled in different modes. The absorbing and firing of the arcs works in a similar format to standard Petri nets, however, some of the arc expressions can manipulate the data values contained within the token fired thus allowing higher level functions to be undertaken.

Figure 4-1 shows an example of a High Level Petri net that models a simple maintenance process for two components. There are four types of data value considered, three of which are integer values referred to as ID (used to distinguish between the different tokens, which represent different components), *PREV_MAINT* (which refers to the number of previous maintenance actions undertaken on the component) and *MAINT_DATE* (which refers to the date, in days relative to start date, that the component will be maintained). The *MAINT_STARTED* data value is a Boolean value that signifies whether maintenance of the system is underway.

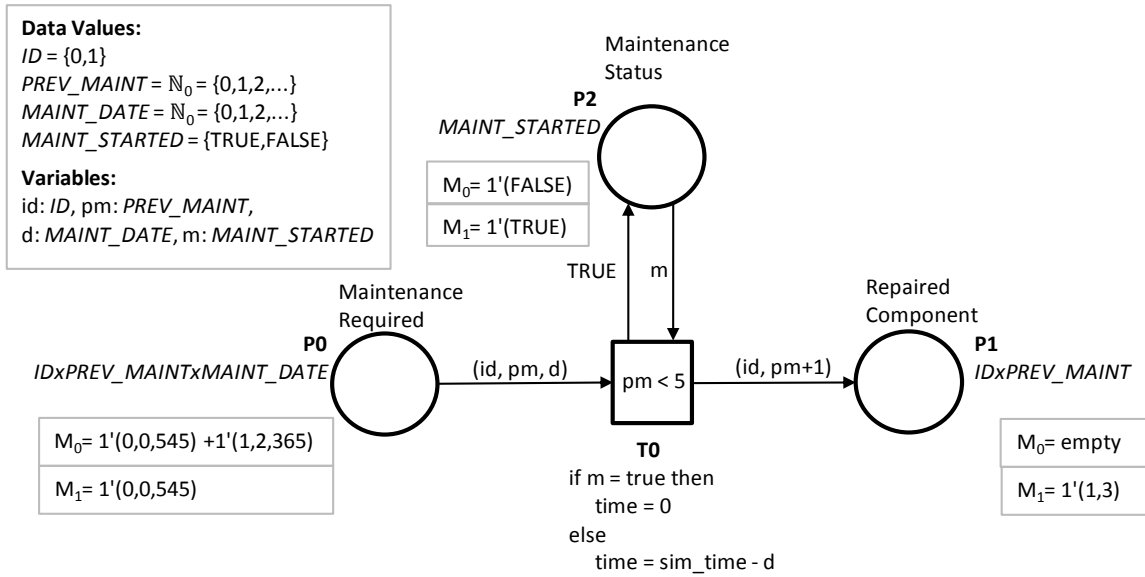


Figure 4-1 High Level Petri Net Example

Place P0 has a type $ID \times PREV_MAINT \times MAINT_DATE$ which means that the set of tokens that may reside in it must contain ID, PREV_MAINT and MAINT_DATE values (which are integers). When a token resides in P0 the component it represents is modelled to be in a condition where maintenance is required. P1 has a type $ID \times PREV_MAINT$ and, when a token resides in this place, it represents the component it models as being in a repaired condition. Place P2 has a type $MAINT_STARTED$ and if it contains a token with a $MAINT_STARTED$ data value of “TRUE”, then it represents the system as currently being maintained. The initial markings are listed in the boxes next to each place in the M_0 expression and the updated markings, after the transition fires, are listed in the M_1 expression. For example, Place P0 has an initial marking $M_0 = 1'(0,0,545) + 1'(1,2,365)$. This means that the place contains a token that has an ID value of 0, a $PREV_MAINT$ value of 0 and a $MAINT_DATE$ value of 545, and another token with an ID value of 1, a $PREV_MAINT$ value of 2 and a $MAINT_DATE$ of 365. In real terms, this means that there are two components in a condition that requires maintenance, one that has not been previously maintained and with a maintenance date of 545, and another component that has been maintained twice previously and has a maintenance date of 365.

The input arcs of transition T0 are connected to Places P0 and P2. The variables that are used in the transition’s arc expressions are id (of type ID), pm (of type $PREV_MAINT$), d (of type $MAINT_DATE$) and m (of type $MAINT_STARTED$). These variables bind to the corresponding data values contained within the tokens in the places that the arcs are connected to. Transition T0 is initially enabled in two separate modes, where the input arcs’ variables bind to the tokens, such that $id=0$, $pm=0$, $d=545$ and $m=\text{“FALSE”}$ in one mode, and $id=1$, $pm=2$, $d=365$ and $m=\text{“FALSE”}$ in the other mode (hence a different token is absorbed from Place P0 in the two different modes).

Transition T0 also contains a transition condition ($pm < 5$) written inside the transition. The transition condition is a Boolean expression which is true or false; if the value is true then the transition is enabled, otherwise it is not (even if there is a possible binding for the variables in the arc expressions). If no transition condition is stipulated, a transition is enabled (in a particular mode), as long as the variables in the input arc expressions can bind to the data values within the tokens in the input places (as described earlier). This ensures that the transition can only be enabled when the token's pm data value is less than 5. Such a transition could be used to model how maintenance can only be carried out 4 times, after which a replacement (modelled using another transition) must be scheduled.

Transition T0's firing time is determined through evaluating the expression listed below it. If m, which is the variable for the input arc connected to P2 (which refers to the *MAINT_STARTED* value of the token in P2), is equal to "TRUE" then the firing time is 0 (i.e. the transition will fire instantaneously). Otherwise, its firing time will be equal to the value of $d - sim_time$, where d is the *MAINT_DATE* value of the token in P0 (which refers to the date that maintenance was scheduled for this transition) and *sim_time* is the current simulation time. This expression makes the transition fire at the date that the maintenance was scheduled, for the component that the token represents.

The mode of T0, where $id=1$, $pm=2$, $d=365$ and $m="FALSE"$ will fire first because the maintenance date for the component that the token represents comes first (so the time calculated is sooner, as described above). The tokens that enabled the transition are absorbed from P0 and P2. A token containing the same ID value of $id = 1$ and a *PREV_MAINT* value of $pm + 1$, which is $2 + 1 = 3$, is fired to P1. Similarly, a token with a data value of "TRUE" is fired to P2. Therefore, the transition models how one of the components that was initially in a condition where maintenance is required was maintained and is now in a repaired condition. Note that the token's *PREV_MAINT* value was increased.

After firing, the updated marking means that T0 is only enabled in 1 mode, where $id=0$, $pm=0$, $d=545$ and $m="TRUE"$. In accordance with the expression beneath the transition, because $m="TRUE"$ the transition's firing time is equal to 0. Therefore, this transition will fire immediately afterwards and the remaining token in P0 will be absorbed and another token sent to P1. This models the fact that when maintenance has started (hence the token in P2 contains a TRUE value), other components that require maintenance will also be maintained at the same time.

This illustration shows how different tokens (that can be distinguished by their data values) can be used to represent different instances of a component or element in the system (e.g. insulators in different locations of the system). High Level Petri nets can concurrently model the different components, without the need for separate places and transitions for each token representing each component, as would be the case in a standard Petri net. The graphical representation is therefore

more concise and intuitive. In addition, the High Level Petri net transitions are not restricted to simply adding or subtracting tokens from places, they can also undertake functions that manipulate the data values within the tokens (as illustrated in Figure 4-1 by the function in the output arc that increases the number of previous maintenances). This can allow complex processes to be modelled, as demonstrated in later sections.

4.2.2 Transition Firing Times

The High Level Petri net developed is stochastically timed and a Monte Carlo simulation process is undertaken to evaluate it. Both fixed time and stochastically timed transitions are used in the model. When a transition becomes enabled in a given mode, its firing time is calculated. The transition with the smallest firing time is chosen to fire first and the simulation time progresses by this amount of time before the transition fires. After the transition fires, if any other transitions with previously found firing times remain enabled (in a certain mode), then their firing times are altered, such that their new firing time is equal to their previous firing time minus the time it took for the transition to fire. The firing times of the transitions that are no longer enabled (in a certain mode) are discarded. The firing times for any newly enabled transitions (in a certain mode) are calculated and the entire process repeats itself until the current simulation time exceeds the study time.

When a transition is enabled, its firing time can be a fixed time (which can also be instantaneous i.e. equal to zero) or a stochastically calculated time. A stochastically timed transition will sample its firing time from the cumulative distribution function (cdf) of a statistical distribution that has been assigned to the transition. The cdf for the Weibull distribution is shown in Equation 4-1 followed by its rearranged form in Equation 4-2. When the transition is enabled, a uniformly distributed random number between 0 and 1 is generated and the corresponding firing time is calculated.

$$F(t) = 1 - e^{-\left(\frac{t}{\eta}\right)^{\beta}} \quad \text{Equation 4-1}$$

$$t = -\eta[\ln(1 - x)]^{\frac{1}{\beta}} \quad \text{Equation 4-2}$$

Where $F(t)$ is the cdf of the Weibull distribution, β is the shape parameter, η is the scale parameter and x is a uniformly distributed random number (between 0 and 1).

In the area of asset management, fixed times are generally assigned to transitions that model inspection and maintenance processes (since these processes are commonly undertaken in fixed time intervals), whereas the stochastically timed transitions are used to model component degradation and

failure processes. Due to its flexibility, the Weibull distribution is commonly used to model such processes.

In High Level Petri nets, the transition firing times can also be based on the information that the tokens contain in their data values. The firing time can be calculated based on a function that uses some of the tokens' data values as parameters (as shown previously in Figure 4-1).

Each mode of a transition has a distribution or fixed time assigned to it, which is used to obtain the firing time. The distribution that is assigned to each mode of the transitions, which model component failure and degradation, is based on the behaviour of the component that the token (associated with the corresponding enabled mode) represents. The different behaviours associated with each token can be identified according to their data values. This allows the different instances of each component type, that the different tokens represent, to have different behaviours. This can allow different subtypes of components to be considered, such as porcelain or polymeric insulators, where their degradation and failure rates may vary.

In the case of transition firing time conflicts, transitions can be assigned priorities that enable the ordering of enabled transitions that are scheduled to fire at the same time to be established. For instance, if two or more transitions are scheduled to fire at the same time then the transition with the highest priority value is chosen to fire first. The use of such priorities is useful when modelling processes that cannot start until another process has been completed, for instance, a maintenance visit cannot be completed until all the maintenance actions have been completed. To model such a process, the transition that signifies that maintenance is completed will have a low priority to ensure that all the other transitions that represent the maintenance actions that are undertaken at the same time, fire first. Note that inhibitor arcs could be used instead of priorities. However, the number of inhibitor arcs could become excessive if the ordering is dependent on many different processes (e.g. many different maintenance actions) therefore the use of priorities is more efficient, due to fewer checks required when computing whether a transition is enabled or not.

In the case where the transitions also have identical priorities, the transition with the lowest transition id will fire first. In practice the Petri net should be developed in such a way that this situation rarely occurs or, when it does, the order that the transitions fire in is not important (such as during a scheduled inspection when all the different inspection transitions will fire at the same time).

4.2.3 Reset Arcs

Reset arcs are used to reset the marking of the tokens in their connected place to zero (e.g. remove all the tokens in the place), regardless of the place's initial marking. Reset arcs are significantly

different to regular arcs, since they change the marking of the place directly rather than absorbing/adding tokens from/to a place. They are particularly useful when modelling processes such as maintenance, where the transitions that model the maintenance do not know in which places the tokens that represent the components being maintained are currently residing. This is because when modelling other processes, such as degradation and failure processes, the tokens can move to other places. Reset arcs can be used as an alternative to creating multiple transitions with various inhibitor arcs, when it is necessary to identify which places contain the tokens that need to be cleared using input arcs. As a result, reset arcs make the model more concise and computationally efficient.

Reset arcs are not defined in High Level Petri net standards, however, there are a number of sources that studied their use (Billington, 1991), (Dufourd et al., 1998) or developed transitions specifically to undertake similar processes (Andrews, 2013) (Le & Andrews, 2016).

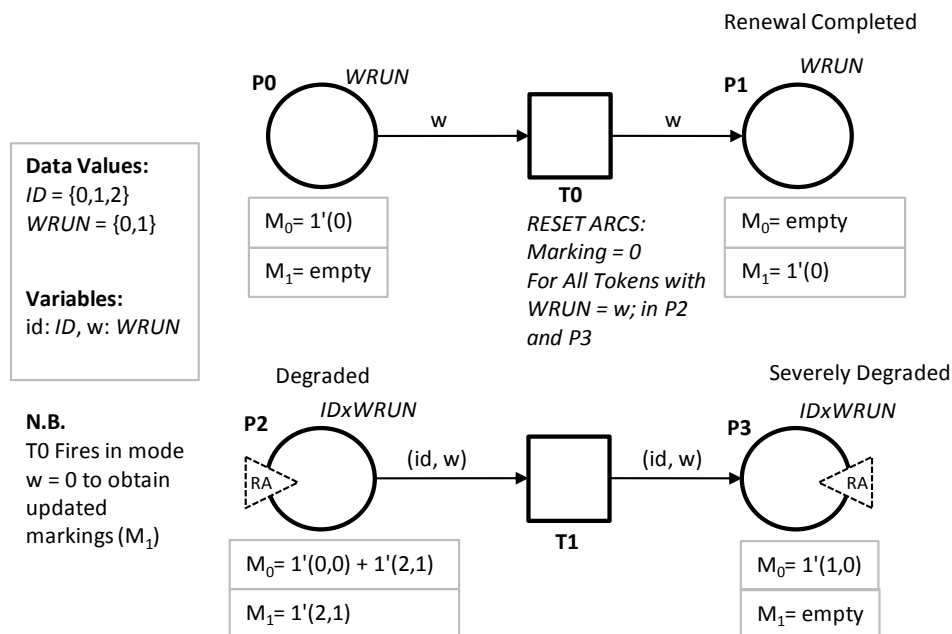


Figure 4-2 Example of a Simple High Level Petri Net with a Transition Containing Reset Arcs

Figure 4-2 shows two separate, simple processes; one process that models the renewal of components in a wire run, modelled by Place P0, Transition T0 and Place P1 (where the WRUN data value refers to the wire run) and another process that models the degradation of components from a degraded condition to a severely degraded condition, modelled by Place P2, Transition T1 and Place P3. Initially, P0 has a marking $M_0 = 1'(0)$, meaning that T0 is enabled in a mode where the variables bind such that $w=0$. This represents how wire run 0 is currently waiting for a renewal to take place. P1 is currently empty which means no wire runs have been renewed. P2 has an initial marking $M_0 = 1'(0,0) + 1'(2,1)$ which means T1 is enabled in two modes, where $id=0$ and $w=0$ and $id=2$ and $w=1$. This represents how two components are in a degraded condition, one is located in wire run 0 and the other in wire run 1.

P3 contains one token, where $id=1$ and $w=0$, meaning there is also a component from wire run 0 in the severely degraded condition. T0 contains reset arcs where the places and tokens to be reset are listed below the transition. In this research, reset arcs are represented this way, because in the High Level Petri net developed some transitions contain many reset arcs that interlink numerous places, and their pictorial representation can become too difficult to follow. In order to show which places are affected by reset arcs, triangles with “RA” written inside are used to label the places.

If T0 fires in the mode where $w=0$, then the token is absorbed from P0 and fired to P1. Reset arcs then force the marking of all the tokens with a WRUN value of 0 in P2 and P3 to be equal to 0 (as stipulated in the expression written below T0). Since P2 has a token with a WRUN data value equal to 0, this token is removed and P2’s updated marking is $M_1=1'(2,1)$. P3 also had a token with a WRUN data value equal to 0, so after this token’s removal P3 is empty. T0 therefore models how, during the renewal, all the tokens that represent components located in wire run 0 are removed from the degraded and severely degraded places. The reset arcs are necessary because T1 could move the tokens from P2 to P3 (to model how the components can degrade), meaning the current location of the tokens is unknown to T0 when it fires.

Note that in this research reset arcs can also be used to set the marking of a token in a place to any value, i.e. they don’t have to remove all the tokens in their connected place. The marking of the connected place (for the associated tokens) can be reset to any positive integer value (including 0) that is specified. Transitions containing reset arcs are used extensively in the model developed in this study, in particular when modelling the maintenance and failure processes, which are explained in later sections.

This section concludes the presentation of all the main definitions used to develop the High Level Petri net model in this study. The following sections will list the components and processes that have been studied and explain the overall modelling approach. A description of how the different processes considered are modelled within the Petri net is given along with the figures showing the developed sections of the Petri net. Finally, a description of the overall whole system model, and how the different processes and components that are modelled are interlinked, is provided.

4.3 Components and Processes Modelled

For the type of OLE system that is modelled, at or between each structure, the following components (including the structure) are always present: catenary wire, contact wire, a span of droppers, insulators (2 per structure), registration equipment and the return conductor wire. These are the main

component types that are modelled individually in the Petri net. Additionally, the requirement for adjustments of the components in the wire run, due to poor-system set up (such as excessive stagger or large fluctuations in the contact wire height) is also modelled.

The degradation, failure, inspection and maintenance processes are modelled for each of these components individually. Note that failure of structures is not considered in the model since data analysis has shown service affecting failures of structures to be extremely rare. Since a given length of the electrified railway will contain numerous instances of the same component type, each instance of each component type in the section of OLE studied is modelled individually. Additionally, the renewal of the catenary and contact wires, at the end of their service life, is also modelled.

It is assumed that the degradation and maintenance of other components, such as tensioning equipment and earthing and bonding (which also exist in every wire run of OLE) do not individually influence the life cycle cost of the system significantly. The failure of these other components are considered in conjunction with random failures that result in a service disruption, but were caused by some external influences and did not damage any of the components that are studied in detail, therefore, no maintenance is required after these failures. These external failure events are commonly caused by vegetation coming into contact with the OLE, random tripping of the system due to bird strikes and incorrect reporting of a failure when no fault existed. The prevalence and characteristics of these failures were explained earlier in section 2.4.8. The failure of the other components and random events are modelled in a separate process for each wire run of the OLE studied.

The way that the degradation, failure, inspection and maintenance processes are modelled is similar for each component type and a detailed explanation of how these processes are modelled is described in sections 4.6 to 4.9.

4.4 Modelling Approach

The Petri net developed is hierarchical, where a different subnet is constructed for each OLE component type studied. Each subnet models the degradation, failure, inspection and maintenance processes for the associated component type. The places denote different states of component condition and contain tokens that represent the different instances of the component type that the subnet is associated with. Each subnet also contains additional places that are used for calculating various statistics.

The number of different tokens that may reside in the places depends on the number of instances of the component type in the overall section of OLE that is studied. However, in the case of the contact

and catenary wires, since they are long components and their defects can occur locally, they are divided up further to express the length that a defect would affect or that maintenance would repair. For the catenary wire, each complete length of wire studied is split up into spans of wire between two structures and each of these spans of wire is assigned a unique token and modelled individually. Similarly, each wire run of the contact wire is split into 5 sections across its entire length.

It is possible to represent all the different component types in one net and use different transition arc expressions, containing functions, to model different behaviours or processes for the different tokens that represent different component types. However, the transitions would require many functions and transition conditions, which would make the model less intuitive. Modelling the different component types in separate subnets, which model the behaviour of the corresponding component type, can also make it easier to perform any changes or adjustments to the processes that are modelled for that component type.

The different subnets and different tokens that reside in each subnet are interlinked through the modelling of the intervention actions that are undertaken. This is primarily done through the maintenance scheduling, whereby the components that are known to require maintenance in the same access area are maintained at the same time. Similarly, opportunistic inspections can also be considered, such that when maintenance is being undertaken on one component, the other component types in the same location are also inspected. Additionally, if a failure occurs, a low-level inspection of all the components located in the wire run of the OLE where the failure occurred is undertaken. During some intervention actions, for instance renewals, other component types may also be maintained and renewed, e.g. the catenary wire and contact wire can be renewed together. The Petri net model is therefore intended to model every individual component that is located in the area studied. However, the separate subnets for each component type can also be run individually.

It is important to emphasise that the degradation of one component may influence the degradation and failure rates of other components. However, these relationships between the different components' degradations are very difficult to determine and quantify accurately, especially with the limited data available for this study. To show how this can be modelled using the proposed methodology, a simplistic case is considered where, when a wire run of OLE requires adjustments (of various components to ensure that the system is correctly set-up), an increased failure rate for the contact wire, catenary wire and registration equipment is modelled. These components were chosen to have increased failure rates because poor system set-up directly affects these components. The way that the different interactions between the components are modelled is explained in section 4.12, which describes the whole system model.

4.5 Representation of the OLE Components and System

In the proposed High Level Petri net model, the tokens are used to represent the OLE components, the wire runs that the components exist in and the access area that the wire runs are located within. In order to allow this representation, and to distinguish between the different tokens that represent these different elements, the tokens consist of data values containing additional information. The data values and their corresponding properties used in this research are listed in Table 4-1.

Table 4-1 Description of the Different Data Values Used

Data Value	Description	Type	Property
ID	Component ID	integer	{0,1,...,number of instances of component type-1}
SPAN	The span of OLE the component is located in	integer	{0,1,...,number of spans-1}
WRUN	The wire run of OLE the component is located in	integer	{0,1,...,number of wire runs -1}
AREA	The access area the component is located in	integer	{0,1,... number of areas-1}
INST_DATE	The installation date of the component	integer	Relative to the start of the simulation
LAST_MAINT_DATE	The date that maintenance was last undertaken on the component	integer	Relative to the start of the simulation
PREV_MAINT	The number of previous maintenance actions undertaken on the component	integer	$\mathbb{N}_0$ (Positive Integers including 0)
MAINT_DATE	The date maintenance of the component must be completed by	integer	Relative to the start of the simulation
MAINT_STARTED	Maintenance is currently underway	Boolean	TRUE if maintenance has started, otherwise FALSE
TIME_REMAINING	Number of time units remaining in a maintenance visit	integer	{0,1,..., number of time units in a visit}
COST	The cost associated with component failure or maintenance	integer	$\mathbb{N}$ (Positive Integers > 0)

Figure 4-3 illustrates how some of the data values contained within a token that represents an insulator component are directly related to the OLE in the area studied. For example, the ID data value is an integer used to distinguish between the different tokens (within the set of tokens representing insulator components). Each token that represents an insulator is assigned a unique ID starting from zero to the number of insulators in the area studied minus one (num of insulators -1). Similarly, each insulator is also assigned a SPAN data value, which refers to the span of OLE that the insulator is located in. Recall that a span refers to all of the OLE components that exist in the area just before one

structure until just before the following structure. A token's SPAN value can therefore be used to ascertain the location of the component that it represents. Similarly, the tokens contain a WRUN data value and an AREA data value which refer to the wire run and access area that they are located within respectively. The ID, SPAN, WRUN and AREA data values assigned are all constants because the components do not change location.

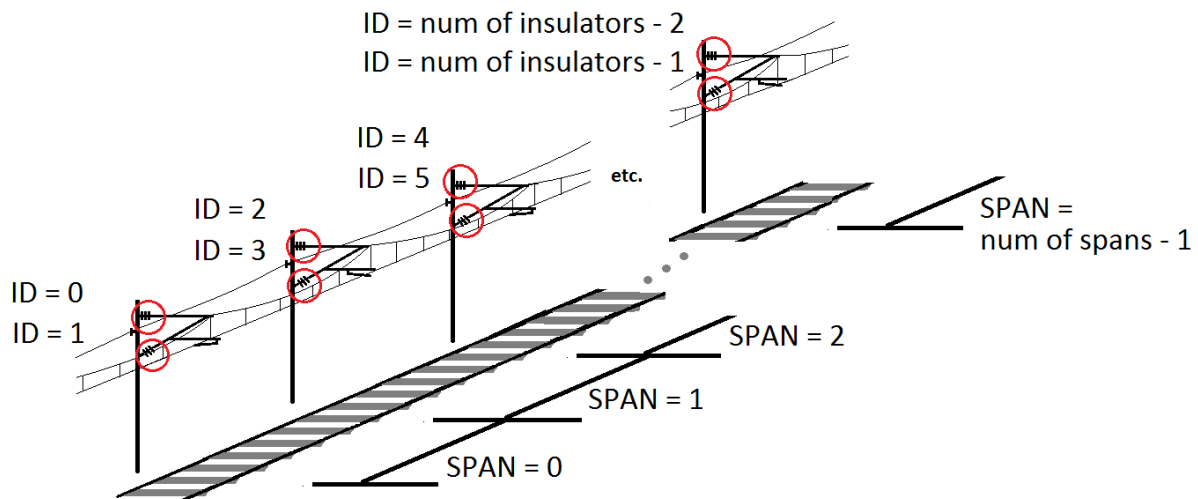


Figure 4-3 ID and SPAN Data Values for Tokens Representing an Insulator

The tokens that represent other components are defined in a similar manner. For instance, the set of tokens that represent the registration equipment relate to the registration equipment located in each span. The contact wire and catenary wire are both wires that span the entire length of the wire run. However, to account for local defects, separate sections of these components are considered. The set of tokens representing the catenary wire represent different spans (between 2 adjacent structures) of the catenary wire; hence the tokens' data values are assigned in a similar manner to the other components that exist in each span (such as insulators). For the contact wire, the overall wire run of each contact wire is split into 5 equal sections. The overall catenary component or contact wire component (which spans across the entire wire run) is modelled using tokens that represent the wire run.

The INST_DATE data value refers to the date that the component was installed. The LAST_MAINT_DATE and PREV_MAINT data values contain information regarding the maintenance history of the component. The maintenance of some components, such as insulators, simply involves a like-for-like replacement, in which case the set of tokens that represents these components does not contain LAST_MAINT_DATE or PREV_MAINT data values. Note that the data values that refer to a date (e.g. INST_DATE) contain an integer value that refers to the number of days since the start time

of the analysis (therefore negative values are possible). This allows the date to be easily compared to the current simulation time during the Monte Carlo simulation.

Table 4-2 Sets of Data Values Used in the Petri Net

OLE Component/ Element Modelled	Set of Data Values
Catenary Wire	ID x SPAN x WRUN x AREA x INST_DATE x LAST_MAINT_DATE x PREV_MAINT
Contact Wire	ID x SPAN x WRUN x AREA x INST_DATE x LAST_MAINT_DATE x PREV_MAINT
Dropper Span	ID x SPAN x WRUN x AREA x INST_DATE
Insulator	ID x SPAN x WRUN x AREA x INST_DATE
Registration Equipment	ID x SPAN x WRUN x AREA x INST_DATE x LAST_MAINT_DATE x PREV_MAINT
Adjustments to a Wire Run	WRUN x AREA
Return Conductor	ID x SPAN x WRUN x AREA x INST_DATE x LAST_MAINT_DATE x PREV_MAINT
Structures	ID x SPAN x WRUN x AREA x INST_DATE x LAST_MAINT_DATE x PREV_MAINT
External Influences in each Wire Run of OLE	WRUN
Set of Tokens in Places Recording Failure Statistics	WRUN x COST
Set of Tokens in Places Recording Maintenance Statistics for each Component Type	WRUN
Set of Tokens in Place Recording Maintenance Visits for the Access Areas	AREA
Set of Tokens in Place Describing Maintenance Status	AREA x TIME_REMAINING x MAINT_STARTED
Set of Tokens in Place Describing Opportunistic High Level Inspection of a Span Will Take Place	SPAN
Set of Tokens in Place Describing Opportunistic Low Level Inspection of a Wire Run Will Take Place	WRUN
Set of Tokens in Places Modelling the Timing of Renewals of Components in Each Wire Run	WRUN

Table 4-2 shows the set of data values that constitute each token that represents an instance of each of the different component types. There are various other places in the Petri net, e.g. those that collect the maintenance and failure statistics, which contain tokens with data values relating to the location of the component that is being maintained or failed (therefore, they may contain SPAN, WRUN or AREA data values). For the failure places the tokens also contain a COST data value that refers to the cost incurred due to the failure. The data values contained within the tokens in these places are related to a subset of the data values contained within the token that represented the maintained or failed component. For instance, during maintenance, the WRUN data value of the token representing the maintained component is fired within another token to a place that records the number of times that

the component type has been maintained in each wire run. Further illustration of the use of data values is given when describing the modelling of the degradation, inspection, maintenance, failure and large scale renewal processes in more detail in the following sections.

4.6 Modelling of Component Degradation

Each subnet, for each OLE component type, contains places that represent the condition of the component modelled. Each subnet contains a place that represents the component being in a working/good condition and places describing the degraded condition states of the component. Some components may have multiple degradation mechanisms, but, generally, rectifying the degradation would require the same maintenance action and it is also assumed that, in reality, a certain degradation mechanism will dominate, or the different degradation mechanisms can be grouped together to be modelled in the same process. Therefore, only one degradation process is modelled for each component type studied in detail.

As described earlier in section 2.4.4, often there is no quantifiable parameter that determines the exact condition of the OLE components. Since the degraded condition states refer to the component being degraded to the extent that maintenance is required, the rate of degradation can therefore be based on maintenance records, by considering the time it takes for a component to degrade to the extent that the maintenance was scheduled. Then, the statistical distributions for the time to reach a certain level of degradation are used in the transitions that represent the corresponding degradation. Section 2.6.3 described the methodology that can be used to obtain such distributions from historical data records. Due to the lack of quality data, the distributions of the time to certain levels of degradation have been assumed. The distributions used in this thesis are listed later in Table 5-1 in Chapter 5, which lists the values used in an example study.

The degradation states are defined according to the Network Rail maintenance policies, where the maximum time that maintenance must be completed by for different severities of degradation or component defects is specified. For each component type studied in detail there are two or three condition states defined as a working/good state, a degraded state and a severely degraded state. The difference between the degraded and severely degraded states is defined by the urgency of maintenance where the maximum maintenance time stipulated is less for a component in a severely degraded state. Note that some components do not have a severely degraded state because the maintenance standards only stipulate one maintenance time for the component based on its condition. The different condition states for each component type were shown earlier in Table 2-4 (on page 46 in section 2.5.5), along with the corresponding inspection regimes that reveal the state of degradation.

4.6.1 Example Petri Net for Catenary Wire Degradation

Figure 4-4 shows how the degradation of the catenary wire is modelled. The catenary wire's condition is described by three states; a good/working condition (P0), a degraded condition (P1) and a severely degraded condition (P2). The type 'CATWIRE' is defined as the set of data values {ID, SPAN, WRUN, AREA, INST_DATE, LAST_MAINT_DATE, PREV_MAINT}, the meaning of these data values was described earlier in Table 4-1. The variables that bind to the different data values are listed in the figure. The different tokens that exist in the places with type 'CATWIRE' represent different sections of catenary wire and are distinguished according to their data values. To provide further clarity, the value 'CW' in the various transitions' arc expressions refers to the set of variables that bind to the different data values within a token that represents a section of the catenary wire. The initial marking of the places has not been included in the figure, since it is dependent on the number of components studied in a particular scenario and is not needed for a general description of the model.

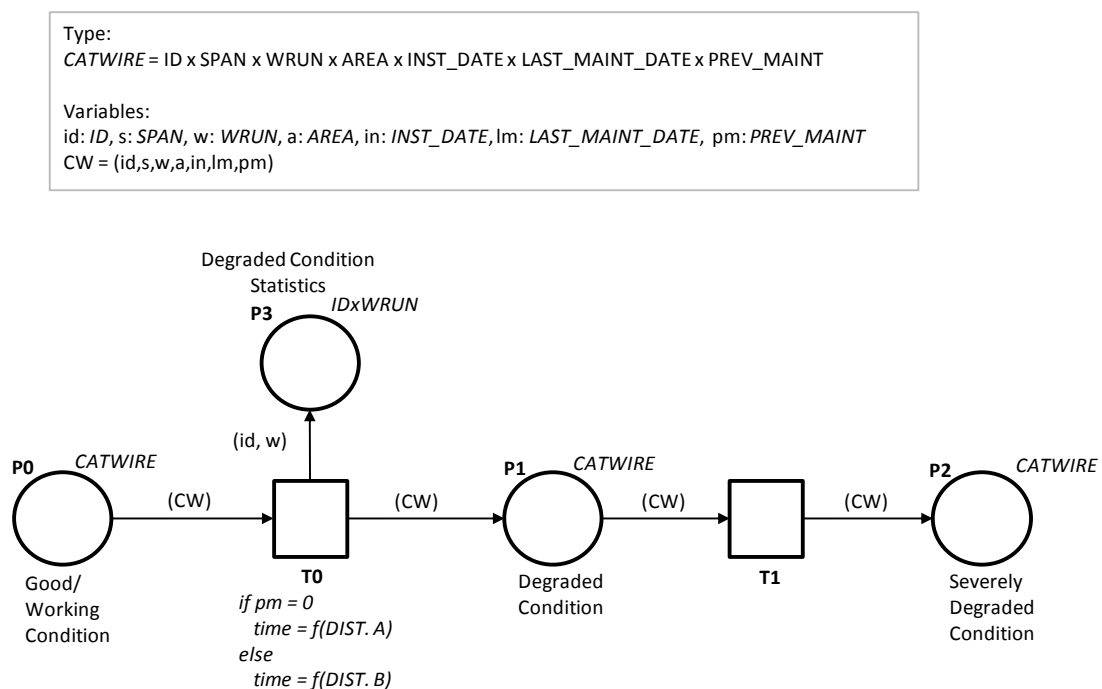


Figure 4-4 Places and Transitions Modelling the Degradation Process of the Catenary Wire

Transition T0 represents the degradation of the component where it moves from being in a good condition to a degraded condition, where the section of the catenary wire that the token represents has a single strand burst, or contains minor damage (such as caging or burn marks). Hence each mode of this transition absorbs the relevant token from P0 and fires an identical token to P1. The other output arc fires a token with the same ID and WRUN data values as the token representing the section of catenary wire to P3. This place is used to record the statistics associated with the condition of the

catenary wire and the amount of time that the different sections of the catenary wire spend in a degraded condition.

To allow different degradation behaviour after maintenance has been carried out to be modelled, T0's firing time is dependent on the maintenance history of the component that the token represents. This is described by the function written beneath T0. If the enabling token in P0 has a PREV_MAINT value that equals zero, then it means the component it represents has not been maintained yet and distribution A is used to sample the firing time. Otherwise, the component has been maintained (i.e. $pm \geq 1$) and it may not degrade at the same rate as it did before it was maintained, therefore a different distribution (distribution B) is used. The degradation behaviour after maintenance can depend on the component type and the maintenance action, therefore different degradation behaviour after maintenance is not considered for every component type. For example, the maintenance action of the catenary wire involves repairing the component, commonly by wrapping up the damaged part of the section or splicing it out. Therefore, it is assumed that because of this wrapped or spliced part of the section of the catenary wire, and the fact that the other parts will have continued to age, the overall section of catenary wire will degrade differently after the first maintenance, hence two different distributions are used before and after the maintenance. In comparison, the maintenance of insulators involves a like-for-like replacement, therefore, the degradation behaviour after maintenance is described by the same distribution. Details of distributions and parameters used in this thesis are listed in later in Table 5-1 in Chapter 5.

Transition T1 works in a similar way to T0. It models how a section of catenary wire can deteriorate from the degraded condition to the severely degraded condition, where the wire has multiple strands that have burst or it is damaged extensively and maintenance is required more urgently.

4.7 Modelling of Component Inspection

Inspections are undertaken at regular intervals to determine the condition of the OLE components, to reveal the extent of their degradation. Therefore, in addition to the places representing component degradation, there also exist places that represent the revealed state of degradation, at which point the maintenance is scheduled.

Table 2-5 (page 46 in section 2.5.5) listed the different inspection regimes and their frequencies for this study, in accordance with Network Rail's standards for a high category line. The inspection transitions' firing times are assigned based on these inspection frequencies. The transitions

representing inspection in each subnet will have the same frequency as the inspection regime that reveals the associated defect or degradation for the component type (as defined in Table 2-4).

The inspection process could be modelled using two places that describe whether an inspection is underway or not and then linking them with a transition that fires at repeated, fixed times matching the inspection interval. When a token enters the place that represents an inspection as being underway, other transitions that move the tokens from the places representing a component as being degraded to the places representing the component's degradation as being revealed can become enabled. Whilst this method is valid and has been used in the literature before (Andrews, 2013), it is not computationally efficient. This is because the transition that schedules the inspection will have to fire during every inspection interval for the entire simulation and every time it fires all the transitions that move a token from a component's degraded state to its revealed degraded state will have to be evaluated to see if they are enabled. In the case of OLE, the inspection interval is relatively frequent (such as every 28 days for a low level inspection). Therefore, such a transition would be firing every 28 days during the simulation. Furthermore, every time the transition fires and moves a token to the place signifying that an inspection is underway, many transitions will have to be evaluated (particularly if many components are studied in the same model, meaning many different transition modes need to be evaluated).

Instead, in the Petri net model developed, transitions representing inspection become enabled when a component is in the degraded place and their firing time is calculated by considering the date that the next inspection is due to occur at. This method of modelling inspection, removes the need for transitions regularly firing at a rate equal to the inspection interval, thus improving the efficiency of the model.

4.7.1 Example Petri Net Modelling the Inspection Process for the Catenary Wire

Figure 4-5 shows how the inspection process is modelled in this research for the catenary wire. The Petri net shown contains the degradation process described earlier in section 4.6.1. The data values and the variables used are also listed in the figure.

When a token first enters the degraded place (P1) an inspection transition (T2) is enabled. When the inspection transition becomes enabled, its firing time is calculated through consideration of the current simulation time and the inspection interval to find the amount of time until the next scheduled inspection. For instance, if the inspection transition becomes enabled when the current simulation time is 40 days and the low level inspection (which is assumed to reveal the degradation of the catenary wire) is scheduled to occur every 28 days (starting at 0 days), then the next inspection is

scheduled to occur on day 56. Therefore, there are 16 days until the next inspection, so the transition's firing time is 16 days.

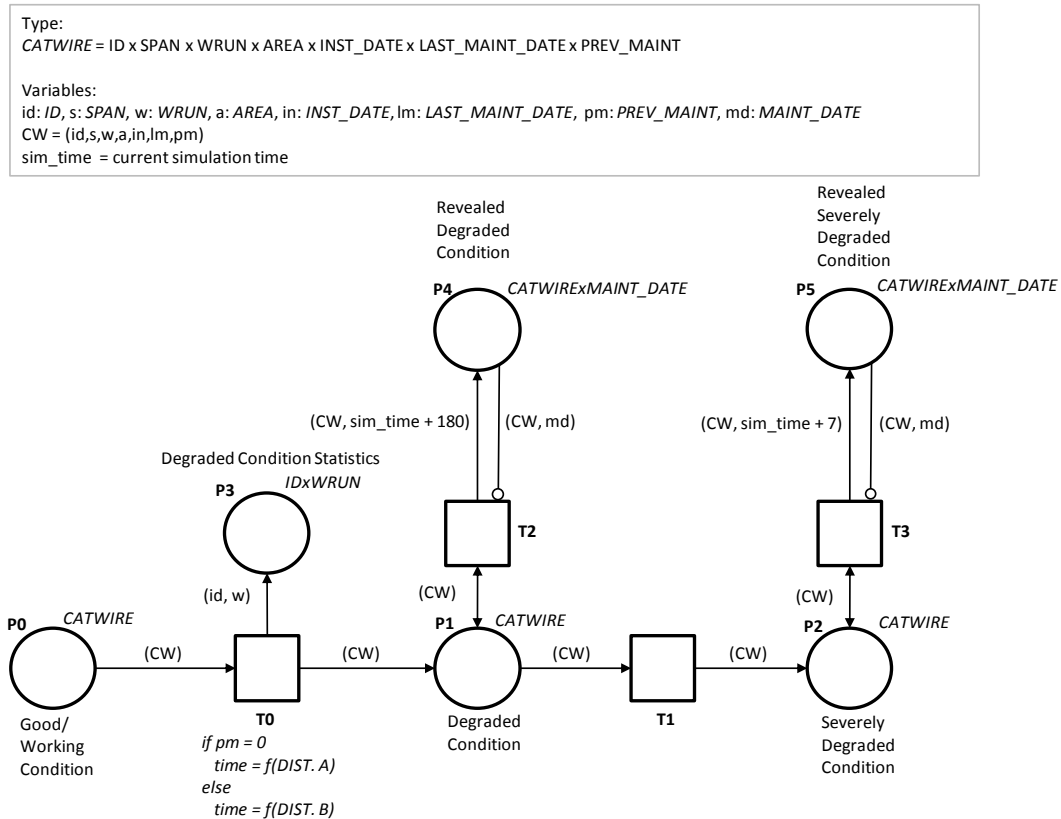


Figure 4-5 Places and Transitions Modelling the Degradation and Inspection Processes for the Catenary Wire

When transition T2 fires, the token that enabled the mode is absorbed from the input place and fired back immediately to ensure that all the other transitions that depend on the token being in this place (e.g. T1) remain enabled, in the associated mode, with the same firing time that was previously assigned. The same token is also fired to the place representing the component's degradation as being revealed (P4), in order to model how the inspection has found the component to be degraded. A *MAINT_DATE* data value, containing the date that the maintenance of the component must be completed by, is added to the set of data values in the token. Upon inspection of a degraded catenary wire, the standards state that maintenance must be undertaken within 180 days, therefore, the *MAINT_DATE* data value is equal to the current simulation time + 180 days (as shown by $sim_time + 180$ in the arc expression). An inhibitor arc then prevents T2 from becoming enabled again (in the same mode), as the degradation of the component is now revealed.

T3 works in the same way and it becomes enabled when a token is in the place representing the severely degraded condition (P2), where maintenance is more urgently required (within 7 days according to maintenance standards).

4.8 Modelling of Component Maintenance

As described previously, when a component has been inspected and it requires maintenance, its maintenance is scheduled according to the priority of the defect. The maximum time that a degraded component is scheduled to be maintained within, is dependent on the severity of the defect associated with the degradation. Network Rail maintenance standards specify the maximum maintenance times for the different defects or states of degradation associated with each component type.

The actual time scheduled to maintain a certain component defect is dependent on numerous processes. Due to access constraints and the fact that a maintenance team is responsible for a large section of electrified line, different maintenance actions are scheduled to occur at the same time. It is important to consider this fact in the model, since each maintenance visit to a particular access area has an associated cost, related to isolating the line and operational staff costs. Grouping together the maintenance of different components in the same access area can, therefore, reduce the number of maintenance visits required and reduce costs. Grouping the maintenance of the OLE components in this way is also necessary for logistical scheduling reasons, as gaining access to a particular access area can be problematic due to the numerous other railway assets present. However, the maintenance engineers aim to ensure that the components are not over maintained, therefore, not all the required maintenance actions will be grouped together for maintenance. For instance, component defects with a low priority, such that their maintenance is not required for over one more year, will not be maintained early. Furthermore, some component types' maintenance actions may take a particularly long time to complete, meaning there is less time during the scheduled access period to maintain other components requiring maintenance. Further information about the maintenance scheduling process is provided in section 2.5.3.

4.8.1 Maintenance Scheduling Rules

Due to the intricacies mentioned above, the maintenance scheduling process is a complex procedure to model. Various assumptions have been made with regards to what maintenance actions can be grouped to occur at the same time in the access area. It is assumed that when a component's maintenance is required, it is scheduled according to the latest date that it must be completed by (according to standards). However, if there are other maintenance actions already scheduled to occur in the same access area, but at an earlier date, then the component will be scheduled to be maintained at the same time as the other maintenance actions (if there is enough time available). Similarly, if the maintenance action is scheduled to occur at an earlier date than other maintenance already scheduled

in the access area, then the other maintenance actions will be brought forward and scheduled to occur at the same time, if there is enough time available.

To model this, each maintenance action is assigned a fixed amount of time to complete (expressed as time units) and each maintenance visit to an access area has a fixed amount of time available. When grouping the maintenance to occur at the same time, there must be enough time units available in the current maintenance visit to undertake the maintenance action (otherwise the maintenance action cannot be completed). The maintenance actions with a higher priority, meaning their maintenance scheduling time (the time until the maximum date that the maintenance must be completed by) is shorter, are considered for grouping first.

Table 4-3 lists the different maintenance actions that are undertaken for each component along with the maximum time that the maintenance of each component defect, or state of degradation, must be completed within (according to Network Rail's standards for a high category line). The amount of time units required to undertake each maintenance action are listed in the final column. These values are all assumed, and the time units are relative to the amount of time available during a maintenance visit, which is set as 10 time units. Note that the actual time taken to complete the maintenance visit is not considered in the model, since it is undertaken during the night out of service hours.

Table 4-3 Details for the Different Maintenance Actions for Each Component Type

Component/ Process Modelled	Maintenance Action	Maximum Time Maintenance Must be Scheduled Within		Time Units Required
		Degraded	Severely Degraded	
Catenary Wire	Repair - wrap or splice out degraded section	0.5 years (180 days)	7 days	3
Contact Wire	Repair - splice out degraded section	1 year (365 days)		4
Droppers	Replacement	7 days		1
Insulators	Replacement	2 years (730 days)	7 days	2
Registration Equipment	Repair- readjustment, occasionally replacement of subcomponents	2 years (730 days)		1
Return Conductor	Repair (wrap or splice out degraded section)	2 years (730 days)	28 days	2
Structures	Repair	2 years (730 days)		3
Adjustments to the Wire Run	Repair- readjustment	2 years (730 days)		2

4.8.2 Example Petri Net Modelling the Maintenance of the Catenary Wire

In Figure 4-6, Transitions T4 and T5 model the maintenance process of the catenary wire. The degradation and inspection processes, which have been described previously, are also present in this figure, since the maintenance process is dependent on these processes. The data values and variables used are also listed in the figure. Supplementary information associated with some of the transitions' features is provided in Table 4-4, beneath the figure. The places affected by reset arcs are labelled (with triangles containing "RA") and Place P0 is reset by a transition representing the renewal of the catenary wire (which is described later in section 4.11).

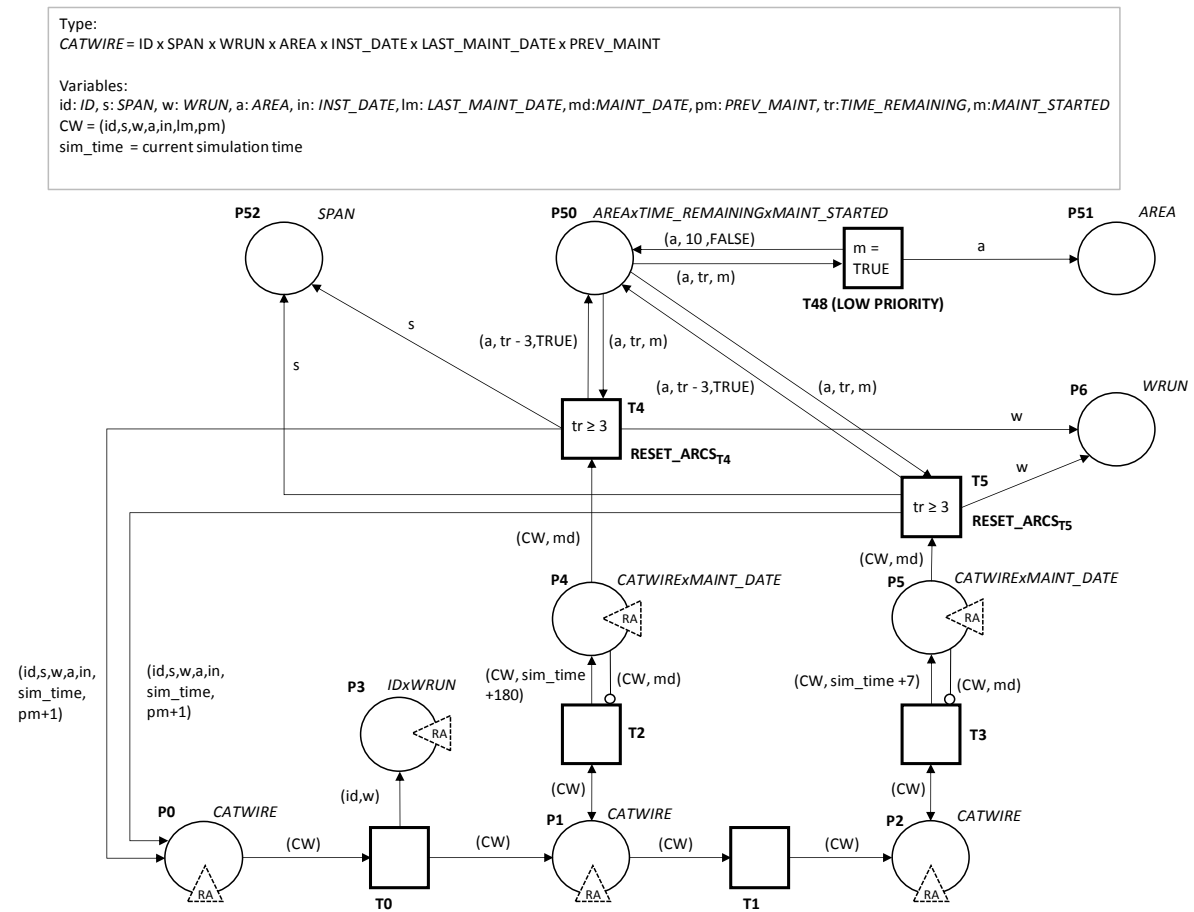


Figure 4-6 Petri Net for the Degradation, Inspection and Maintenance Processes for the Catenary Wire

Table 4-4 Information Regarding the Firing Times and Reset Arcs for T4, T5 and T48

Transition	Function/ Feature	Information
T4 & T5	Firing Time	If $m = 'TRUE'$ Fire Time = 0 Else Fire Time = $md - sim_time$
T4	$RESET_ARCS_{T4}$	Marking = 0 for all tokens with $ID = id$ in: P1, P2, P3 and P5
T5	$RESET_ARCS_{T5}$	Marking = 0 for all tokens with $ID = id$ in: P2, P3 and P4
T48	Firing Time	= 0 (has a LOW PRIORITY, meaning it fires after every other transition that is scheduled to fire at the same time)

When a token enters place P4, which represents the section of catenary wire being known to be degraded (hence maintenance is scheduled), transition T4 becomes enabled. Because T4 represents maintenance, the calculation of its firing time is intended to replicate the maintenance scheduling process. When a section of catenary wire is degraded, Network Rail's standards state that maintenance must be undertaken within 180 days to rectify the issue, however if other maintenance is scheduled in the same access area at an earlier date then this maintenance can be undertaken at same time, if there is available time.

Place P50 is another input place for T4 and it is a global place that is linked to each component subnet. This place signifies the maintenance status for each access area studied. It contains a set of tokens that contain an *AREA* data value, corresponding to the access area, a *TIME_REMAINING* data value, indicating the amount of available time to perform maintenance during a visit to the access area, and a *MAINT_STARTED* data value, a Boolean value signifying whether maintenance is being undertaken in the corresponding access area. T4 has function for finding its firing time that is based on the value of the variables *tr* and *m*, which bind to the *TIME_REMAINING* and *MAINT_STARTED* data values respectively in the token in P50, and *md*, which binds to the *MAINT_DATE* data value in P4. This function is listed in Table 4-4 and states that if *m* equals 'TRUE' then the transition firing time is equal to 0, i.e. it fires immediately. Otherwise, the firing time is equal to the amount of time until the date that maintenance has to be completed by. This is calculated by subtracting the current simulation time from the *MAINT_TIME* data value in the token in P4 ($md - sim_time$).

The following description clarifies how this function is used. Initially, before any maintenance has started, P50 would contain one token for each access area, the *TIME_REMAINING* data value would be equal to 10 (signifying there are 10 available time units when a maintenance visit is scheduled) and the *MAINT_STARTED* data value would be equal to 'FALSE' (i.e. maintenance has not begun). When a token enters P4 and T4 becomes enabled, according to the function listed in Table 4-4, if *m* is 'FALSE' then the transition's firing time (in that mode) is simply equal to the amount of time that the maintenance must be undertaken within. This is calculated by subtracting the current simulation time from the maximum date that maintenance must be completed by, which is given in the *MAINT_DATE* data value in the token in P4 ($md - sim_time$). When T4 fires in a given mode, the token for the corresponding access area is absorbed from P50 and fired back with a *MAINT_STARTED* data value of 'TRUE', to denote that maintenance is underway. All previously enabled modes of T4 are no longer valid, since the variable *m*, on the arc to P50, has changed (because the token belonging to the same access area now has the *MAINT_STARTED* data value equal to 'TRUE'). The number of time units available is also reduced by 3 ($tr - 3$) because the maintenance of a section of catenary wire is modelled to require 3 time units (out of 10 time units that are available during a maintenance visit). Newly

enabled modes of T4 then exist for each token that is in P4 within the same access area as the token that initially fired through T4. Now, according to the function for finding their firing time, because m is equal to 'TRUE', then the transition's firing time (for that mode) is equal to 0. Therefore, this can model how the maintenance has been grouped to occur at the same time because there is time available. Note, since P50 is a global place, the maintenance transitions in the other component types' subnets can link to it (in the same manner as T4 and T5) if that component type is also considered to be grouped for maintenance in the same access area.

However, for T4 to be enabled there must also be enough time units available for the maintenance to be undertaken, as specified by the transition condition, $tr \geq 3$ (written inside the transition) which states that there must be at least 3 available time units available in the current maintenance visit. This information is contained within the *TIME_REMAINING* data value in the token that describes the current maintenance status in P50. Note that the firing times of maintenance transitions, like T4, are evaluated based on the urgency of their maintenance. For example, a component requiring maintenance within 4 days will be scheduled for maintenance with higher priority than a component requiring maintenance in 200 days, meaning this component will be opportunistically maintained first (provided that there are enough time units available).

The other output arcs associated with T4 fire a token containing the wire run information into P6, which records the statistics associated with the maintenance of the catenary wire. A token with a *SPAN* data value, equal to the span that the section catenary wire is in is fired to P52, a global place that enables opportunistic inspections of other components in the same span to take place (which is modelled in another process). A token is also fired back to P0, to model how the component has been repaired to the good condition. Since the maintenance action undertaken on the catenary wire involves wrapping up or splicing out the damaged section, after this repair action the *PREV_MAINT* data value of the token is increased by one (to denote that maintenance took place) and the *LAST_MAINT_DATE* data value is made equal to the current simulation time (the date that the maintenance took place). This is shown in the arc expression of the output arc that fires to P0 ($id, s, w, a, in, sim_time, pm + 1$). The variable pm is bound to the *PREV_MAINT* data value of the token that enabled the mode of the transition that fires, therefore, the *PREV_MAINT* data value of the token fired to P0 will be increased by one (thus adding to the number of times it has been maintained).

Note that for maintenance actions that involve a like-for-like replacement (such as for insulators), the *INST_DATE* data value (which represents the installation date of the component) is changed to be equal to the current simulation time.

T4 also contains reset arcs to remove the tokens representing the section of catenary wire that is being maintained from the degradation process. Reset arcs are very useful, since it is not known where the token may have moved to in the degradation and inspection processes. Therefore, for all the places that it could exist in, the marking of the token that represents the component being maintained is set to zero. Table 4-4 lists the properties of T4's reset arcs. The marking of tokens that contain the same ID data value as the token representing the section of catenary being maintained is set to zero in P1, P2, P3 and P5. T5 works in a similar way to T4 and it represents maintenance of a severely degraded section of catenary wire where maintenance is required more urgently (the maximum time it must occur within is 7 days).

When maintenance is underway in the access area the *MAINT_STARTED* data value of the token representing the access area is equal to 'TRUE'. Therefore, T48 is enabled (as stated by its transition condition, because $m = \text{'TRUE'}$). T48 has the firing time of zero, but a low priority so it will not fire until all maintenance transitions that are linked to P50 have fired, such as T4 and T5. When it fires, a token with an *AREA* data value is fired to P51, which records the statistics about the number of maintenance visits (hence the transition fires after all the maintenance transitions). The token that is fired back to P50 has a *TIME_REMAINING* data value equal to 10, so that 10 time units are available for the next maintenance visit, and a *MAINT_STARTED* data value of 'FALSE' to signify that maintenance is no longer underway.

4.9 Modelling of Component and System Failures

In the Petri net model developed, a component failure is considered to be an event where a component's condition has led to an interruption to the timetabled train service, hence it is a service affecting failure. Note, a component may not have completely failed, but its degradation could be so severe that the line has to be closed to electrified trains (or speed restrictions put in place), in order to prevent the risk of more serious failures occurring. Because such events disrupt the train service and result in delay minutes, which are included in the historical failure records analysed in this thesis, they are classified as component failures.

When modelling the consequences of a service affecting failure, attempting to estimate the amount of time that the line will be unavailable for and then estimating the cost according to the amount of delay minutes incurred could be undertaken within the Petri net framework. However, this process is complex to model as it involves many factors, such as the time of day that the failure occurred and the number of trains affected. This approach would also require accurate data for maintenance response times, which was not available for this study. Instead, in the model developed, the cost of

the failure, as a result of fines imposed on Network Rail due to the service disruption and the cost of the repair work, is used to account for different severities of failure.

The transitions that represent a service affecting failure have an output arc, containing a function within its arc expression, which calculates the cost incurred due to the failure. As described previously in section 2.6.2.2, the distributions of costs associated with the failure of each component type have been found through the analysis of failure records. The function within the arc expression calculates the failure cost by sampling it from the corresponding distribution of the failure costs for the associated component type. The arc then fires a token with the failure cost as the value for the token's *COST* data value, to the place that represents the component as being failed, which records statistics associated with the component's failure. Since downtime of the system is not considered, after a failure event the failed component is immediately repaired and the simulation continues.

In addition to component failures, the model developed also considers failures caused by external influences, which are failures associated with the OLE but are not caused by the failure of the OLE components and do not result in damage to the OLE components. Examples of such failures include bird strikes or encroaching vegetation, resulting in the electrical supply short circuiting. As discussed earlier, the degradation of one component in the system may influence the degradation and failure rates of other components. To show how this can be modelled using Petri nets, this study considers how the failure of the contact wire, catenary wire and dropper can occur due to poor set-up of a wire run, where the wire run required adjustments.

Firstly, a description of how component failures are modelled is given in section 4.9.1, followed by a description of how the failures of other components due to poor set-up of the wire run are modelled in section 4.9.2. Finally, a description of how failures caused by external influences are modelled is given in section 4.9.3.

4.9.1 Modelling Component Failures

In the model it is assumed that the components can fail even if they are in the good/ working condition. It is assumed that these failures are due to random events, such as extreme weather, manufacturing defects, vandalism or rail users, for instance where a train's pantograph is defective and critically damages the components. It is assumed that these failures occur at a constant rate that is relatively low compared to the failure rate of a component when it is degraded. When the components are degraded, their failure rate is greater because the presence of defects reduces the strength of a component making it more susceptible to failures. For example, when the catenary wire is stranded, its tensile strength will decrease meaning its chance of failure is increased.

As described earlier, the cost incurred due to a failure is sampled from the distribution of failure costs, for the component that failed. In the model developed, the failure cost is used as an indicator of the effect and severity of the failure, rather than the amount of system downtime that occurred. Since the model considers days (expressed as integers) as the smallest unit of time in the simulation, when a failure occurs it is modelled to be rectified in the same day. Historical data records show that the majority of service affecting failure events that are associated with the OLE are rectified before the next day of time tabled train service. For more extreme failure events, such as where the OLE has been damaged extensively, the failure may not be rectified completely for several days. Such situations are not considered within the model because downtime is not modelled. However, the severity of such extreme failures is taken into account through considering the costs incurred due to the failure. Another issue associated with extreme failure events, that is not considered, is the influence the failure of a component has on the other components in the nearby area, i.e. the failure of one component may result in the damage or failure of others.

These complexities could be considered by adding additional transitions to model certain processes. For instance, when the failure cost sampled is large, it could be assumed that the line will be unusable for electrified trains for perhaps up to one week meaning no other OLE component failures can occur during this time. Additionally, transitions representing maintenance of some of the components in the nearby spans could be enabled to model how a large scale repair rectifies the extensive damage. Including these processes in the model would make the subnets much more complex, and, since the processes modelled would be heavily reliant on assumptions (due to lack of quality data) and their occurrence is rare anyway, they are not included in this study.

Figure 4-7 illustrates how the failure of a section of the catenary wire, from a good/working condition (denoted by place P0), is modelled by transition T6. The data values and variables used are listed in the figure. For clarity, the other places and transitions in the catenary wire subnet are not shown in this figure. The output arc that fires a token to place P7 contains a function in its arc expression that is listed as $FAIL_{CATWIRE}$ and is described by Equation 4-3, which describes how the failure cost is sampled from the lognormal distribution of failure costs for the catenary wire. The token that is fired contains the *WRUN* data value, which refers to the wire run that the section of failed catenary wire belongs to, and the *COST* data value, which was calculated using Equation 4-3. P7 records statistics about the number of failures of the catenary wire and the costs incurred.

$$FAIL_{CATWIRE} = \exp(\mu + \sigma Z) \quad \text{Equation 4-3}$$

Where μ and σ are the location and scale parameters for the lognormal distribution of failure costs for the catenary wire, and Z is a number sampled from the normal distribution, which can be done

using a Box-Muller transform as described by (Gentle, 2003). At the request of Network Rail, information about the real cost values are not provided in this thesis, therefore, the values of these parameters are not revealed.

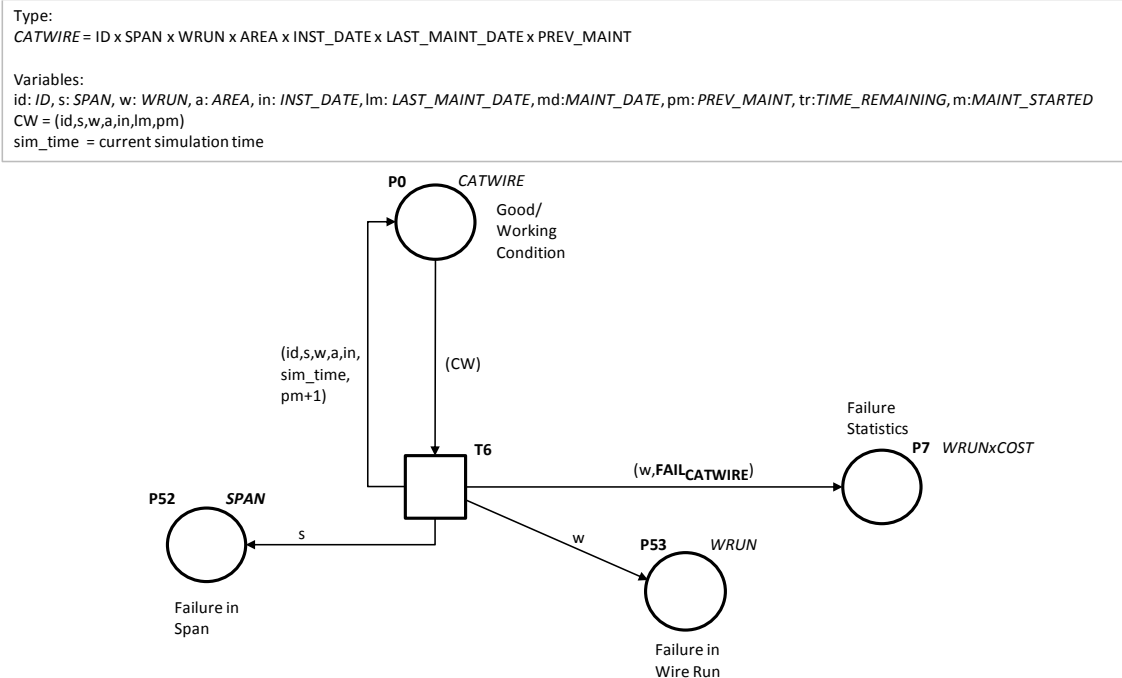


Figure 4-7 Petri Net Showing the Failure of a Section of Catenary Wire from the Good / Working Condition

Another output arc fires a token to P0, in order to model how a repair has been undertaken to rectify the issue, so that after the failure the component is returned to the good/working condition. The relevant manipulations are made to the token's data values in accordance with the maintenance action that is undertaken for the component type. In the case of the catenary wire, a repair is undertaken, therefore, the *LAST_MAINT_DATE* data value is set to equal the current simulation time and the *PREV_MAINT* data value is increased by one. Therefore, the output arc that fires to P0 contains an arc expression $(id, s, w, a, in, sim_time, pm + 1)$. This arc expression works in the same way as the arc expression in the transitions representing repair in the maintenance process, as described earlier in section 4.8.2.

In a similar way to the maintenance transitions, a token containing the *SPAN* data value, that corresponds to the span of OLE that the component that has failed is located in, is fired to P52 (a global place) to signify that maintenance is being undertaken in the span. This can enable the transitions that represent a high level inspection of the other components, located in the same span. Similarly, a token containing the *WRUN* data value, that corresponds to the wire run that the component that failed is located in, is fired to P53 (a global place) that represents the occurrence of a failure in the wire run. When a token enters this place, various inspection transitions are enabled to

model how after a failure the wire run of OLE, that the failure occurred in, would be subject to a low level inspection. The opportunistic inspection processes are described later in section 4.12.1.

As shown in the complete subnet for the catenary wire (shown later in Figure 4-10, in section 4.10), there are additional transitions that represent the section of the catenary wire failing from the degraded and severely degraded states. These transitions work in the same way as the process described above. It is assumed that when a component fails from a working or good condition it is due to random process such as extreme weather events. Therefore, an exponential distribution is used to sample the firing time of T6. The transitions representing a component failing from the degraded and severely degraded condition, have an increased failure rate as the components are now more likely to fail due to their degraded condition.

4.9.2 Failures Caused by Poor Set-Up of a Wire Run

When a wire run requires adjustments, in order to alleviate poor set-up issues (such as excessive stagger or large fluctuations in the contact wire height), the failure of the catenary wire, contact wire and registration equipment is modelled to occur as a result of the poor set-up. The rate of these failures occurring is assumed to be constant and equate to 20% of the random failure rate of the respective component types (when they are in the good/working condition). Therefore, when all the components are in the good/working condition, if the wire run they are in requires adjustments, their failure rate will increase by 20%. In order to have a more accurate failure rate for this process and include other relationships between the different components' degradation and failure rates, more detailed failure data, describing the last known condition of the different components before the failure and the exact cause of the failure, would need to be analysed. This process is considered in this study, with the failure rates assumed, to show how dependencies relating the failure of components to another process can be modelled using Petri nets.

Figure 4-8 shows the subnet that models the adjustments of the wire run. Place P46 describes the wire run being in a good/working condition and place P47 describes the wire run as being in a condition where adjustments are required, i.e. the set-up is poor. This section concentrates on describing how the catenary wire can fail as a result of poor set-up of the wire run therefore only transition T53, and the places connected to its arcs, are described in detail. The other places and transitions model the inspection and maintenance of the wire run, in terms of performing adjustments to rectify poor set-up, and these processes are modelled in the same way as for the catenary wire, as described earlier.

Type:
CATWIRE = ID x SPAN x WRUN x AREA x INST_DATE x LAST_MAINT_DATE x PREV_MAINT

Variables:
id: ID, s: SPAN, w: WRUN, a: AREA, in: INST_DATE, lm: LAST_MAINT_DATE, md: MAINT_DATE, pm: PREV_MAINT, tr: TIME_REMAINING, m: MAINT_STARTED
CW = (id,s,w,a,in,lm,pm)
sim_time = current simulation time

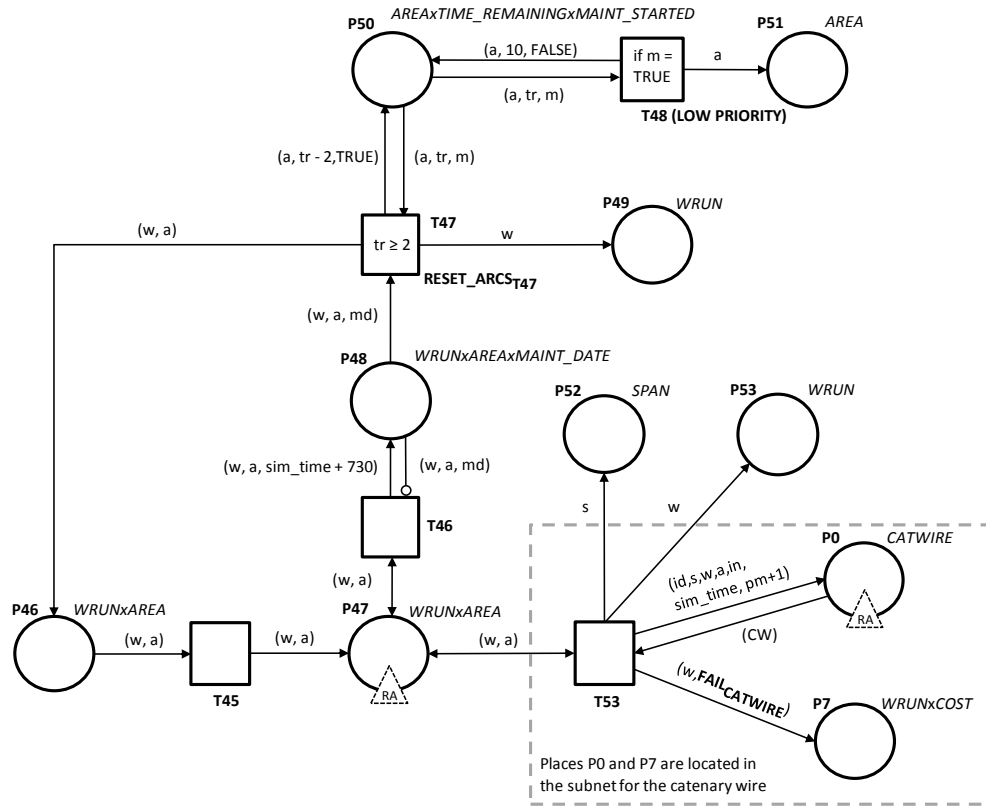


Figure 4-8 Adjustments to Wire Run Subnet Showing Transition for Failure of the Catenary Wire

When a token is in place P47, the wire run requires adjustments and transition T53 becomes enabled if a token representing a section of the catenary wire in the same wire run is currently in place P0, which represents the section of catenary wire being in the working/good condition. T53 will be enabled in a different mode for each token that is in P0 that has the same *WRUN* data value as the token in P47, i.e. for all the tokens that represent a section of catenary wire located in the wire run that requires adjustments. T53 works in the same way as the failure transition described previously in section 4.9.1. The cost of failure is sampled from the distribution of failure costs, and sent to place P7, which records statistics associated with the number of failures and failure costs for the catenary wire. The component is also repaired after the failure so a token is also fired to P0. Note that other transitions exist for the failure of the catenary wire from the degraded and severely degraded conditions and failure of the contact wire and registration equipment, due to poor set-up of the wire run. These transitions are not shown in the figure, but are shown in the complete component subnets which are presented in the appendices.

4.9.3 Failures Caused by External Influences

The analysis of the failure records showed that there are a significant number of service affecting failures caused by external influences. These are failures that are not caused by the failure of the OLE components and do not result in damage to the OLE components, but they are associated with the presence of the OLE. Examples of such failures include bird strikes or encroaching vegetation, resulting in the electrical supply short circuiting. During a failure caused by external influences, a system failure will have occurred without one of the OLE components failing, therefore, these failures are different to component failures due to random events (where a component failure does actually occur). The consequences of these failures are low, as their rectification commonly involves simply re-connecting the circuit to allow the trains to travel down the line. However, their occurrence is frequent in comparison to other failures associated with the OLE. During such a failure event it is also assumed that maintenance engineers would inspect the wire run that the failure was located in to ensure that a more serious failure had not occurred and there is no damage to the OLE components.

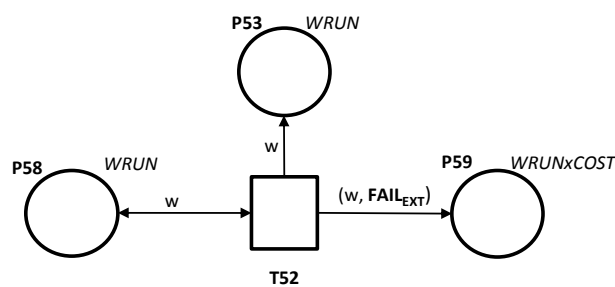


Figure 4-9 Petri net Modelling Random Failures due to External Influences

External influences are modelled in a separate subnet, which is shown in Figure 4-9. These failures are modelled for each wire run of OLE that is studied. Place P58 contains different tokens, that contain a *WRUN* data value, corresponding to the different wire runs in the area of OLE studied. The firing time of Transition T52 is sampled from the exponential distribution, because it is assumed that the failure rate is constant for the failures caused by external influences. Different wire runs may have higher failure rates than others (e.g. wire runs in closer proximity to vegetation may be more prone to trips caused by overgrown branches). The different modes of T52, for tokens in P58 (with different *WRUN* data values) can have different exponential distributions for their firing time (depending on the wire run's susceptibility to these external issues). When T52 fires, a token is fired back to P58 and a token is fired to place P53, a global place that signifies that a failure has occurred in the wire run (this place enables various inspection transitions, as described later in section 4.12.1). In a similar manner to the transitions that represent component failure, the output arc to P59 contains a function (*FAIL_{EXT}*) that calculates the cost incurred due to the failure (because of the ensuing delay minutes) by sampling the

cost from the distribution of failure costs for external failures. A token is fired to P59 with its *COST* data value equal to the calculated cost. P59 records the statistics associated with the failures caused by external influences.

4.10 Complete Subnet for the Catenary Wire

Figure 4-10 shows the complete subnet that represents the degradation, failure, inspection and maintenance of the catenary wire, as shown previously. In addition, there are transitions representing the failure of a section of catenary wire that was in a degraded condition (T7) and a severely degraded condition (T8). There is also an additional transition that models the failure of the section of catenary wire when the wire run of OLE it is located in requires adjustments. To provide clarity this transition is not included in the figure as this process was explained previously in section 4.9.2, note that these transitions are shown with the subnets presented in the appendix. The catenary wire can also be renewed, but this process is modelled in a separate subnet that contains various reset arcs that reset the marking of the tokens in this subnet. The renewal process is explained in section 4.11. Information about the different data values and variables used, what each place represents and the functions and firing times associated with the transitions is listed in Table 4-5, Table 4-6 and Table 4-7. The initial marking of the places is dependent on the initial condition of the catenary wire in the system studied and the number of tokens that may reside in each place is dependent on the number of components that are studied (which is dependent on the length of electrified line that is studied). Therefore, the analysis of different lengths of electrified line will result in a different number of tokens in the model.

Places P50, P51, P52 and P53 are all global places that the different component subnets are connected to. As previously explained, P50 is used to enable the maintenance transitions (such as T4 and T5 in the catenary wire subnet) to fire at the same time, to model how the maintenance actions can be scheduled to occur during the same maintenance visit. The transitions representing maintenance and failure of the section of the catenary wire fire a token, which consists of a *SPAN* data value corresponding to the span of OLE that the component was located in, to P52. This is a global place that enables transitions that model a high level inspection of the other components that are located in the same span to take place. Similarly, for the transitions representing a component failing, a token containing a *WRUN* data value, corresponding to the wire run that the failed component was located in, is fired to P53. This is a global place that enables transitions that model a low level inspection of the other components that are located in the same wire run as the failed component to take place. To provide clarity, these opportunistic inspection transitions are not shown in Figure 4-10 and a more detailed description of their use is given in section 4.12.1, when describing the whole system model.

Each OLE component that is studied in detail contains places and transitions that model the degradation, failure, inspection and maintenance in a similar way to what has been described for the catenary wire. Each subnet records statistics associated with the condition, maintenance and failure of the component type. For example, in Figure 4-10, P3 collects statistics associated with the amount of time a section of the catenary wire is degraded, P6 collects statistics associated with the number of maintenance actions and P7 records statistics associated with the cost and occurrence of failures. The global place, P51, collects statistics associated with the number of maintenance visits to an access area. Each subnet interacts with the other global places in a similar way, in order to model various dependencies between different components. Dependencies therefore exist between different instances of the same component type, as well as different component types.

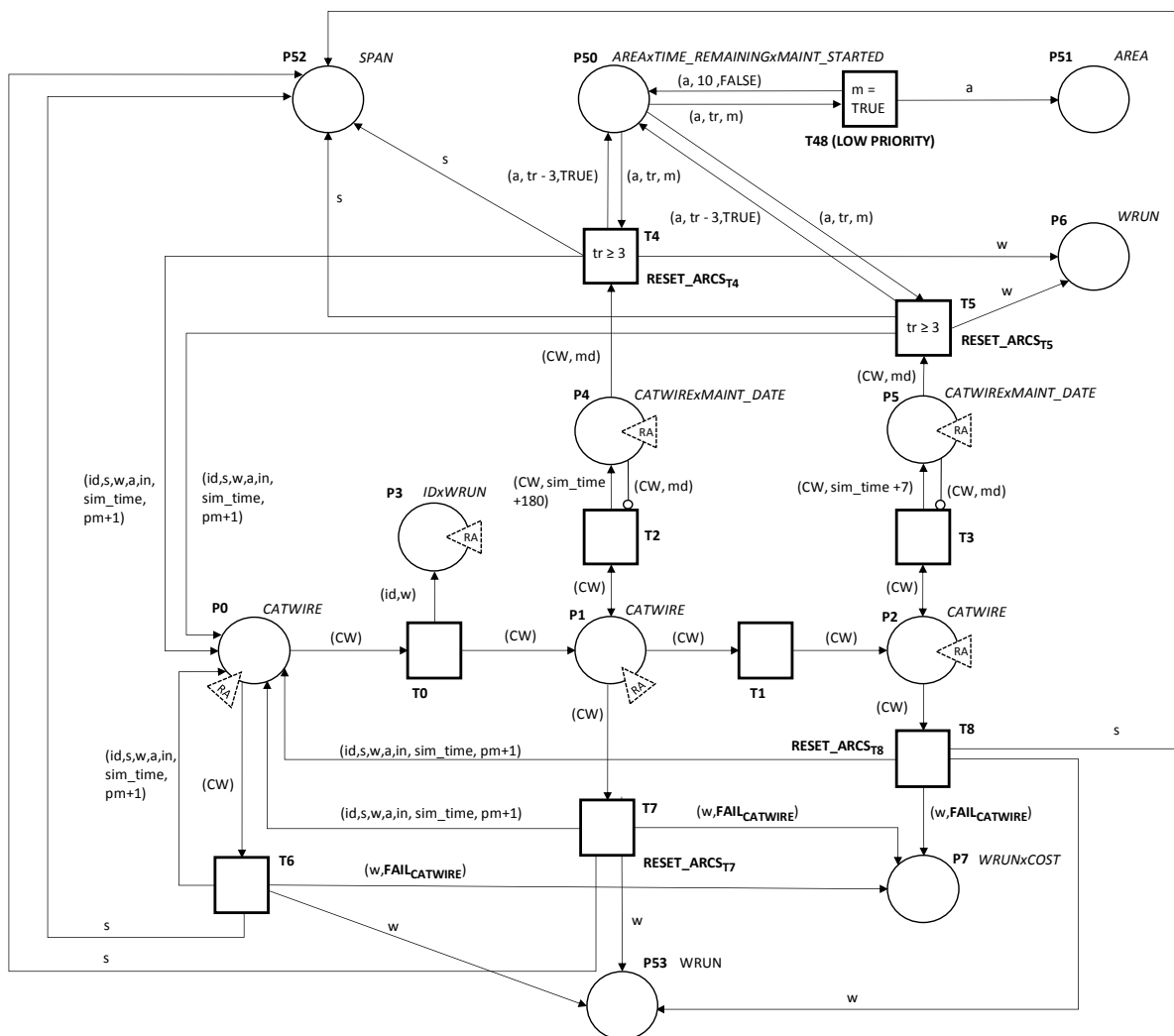


Figure 4-10 Example Subnet for the Catenary Wire (including the various global places)

Table 4-5 Different Variables used in the Catenary Wire Subnet

Variables	Data Value It Binds to
id	<i>ID</i>
s	<i>SPAN</i>
w	<i>WRUN</i>
a	<i>AREA</i>
in	<i>INST_DATE</i>
lm	<i>LAST_MAINT_DATE</i>
pm	<i>PREV_MAINT</i>
md	<i>MAINT_DATE</i>
tr	<i>TIME_REMAINING</i>
m	<i>MAINT_STARTED</i>
CW = set of variables: (id, s, w, a, in, lm, pm)	
sim_time = the current simulation time	

Table 4-6 Description of the Places in the Catenary Wire Subnet

Place	Description	Type
P0	Good / Working Condition	CATWIRE*
P1	Degraded Condition (section of catenary wire has a single strand of wire burst or minor damage).	CATWIRE*
P2	Severely Degraded Condition (section of catenary wire has multiple strands of wire burst or extensive damage).	CATWIRE*
P3	Records statistics associated with the number of degraded sections of catenary wire for a certain wire run.	ID x WRUN
P4	Revealed Degraded Condition (the maintenance engineers are aware of the degradation and maintenance is scheduled).	CATWIRE* x MAINT_DATE
P5	Revealed Severely Degraded Condition (the maintenance engineers are aware of the degradation and maintenance is scheduled).	CATWIRE*x MAINT_DATE
P6	Records statistics associated with the number of maintenance works undertaken on the wire run of catenary wire.	WRUN
P7	Records statistics associated with the number of service affecting failures of the catenary wire and the corresponding costs incurred.	WRUN x COST
P50 (global)	Describes the current maintenance status of the access area.	AREA x TIME_REMAINING x MAINT_STARTED
P51 (global)	Records statistics associated with the total number of maintenance visits to an access area.	AREA
P52 (global)	The span of OLE is currently undergoing maintenance. This is an enabling place for transitions that represent opportunistic high level inspection of components located in this span.	SPAN
P53 (global)	The wire run of OLE contains a failed component. This is an enabling place for transitions that represent opportunistic low level inspection of components located in this wire run.	WRUN
*CATWIRE = ID x SPAN x WRUN x AREA x INST_DATE x LAST_MAINT_DATE x PREV_MAINT		

Table 4-7 Additional Information for the Transitions in the Catenary Wire Subnet

Transition	Function/ Feature	Information (all times given in days)
T0	Firing time	If pm = 0 then Sampled from Weibull distribution: $\beta=2.5$, $\eta=43800$ Else Sampled from Weibull distribution: $\beta=1.5$, $\eta=36500$
T1	Firing Time	Sampled from Weibull distribution: $\beta=3$, $\eta=1825$
T2 and T3	Firing Time	= sim_time - date of next low level inspection (every 28 days)
T4 and T5	Firing Time	If m = 'TRUE' then Fire Time = 0 Else Fire Time = md – sim_time
T4	RESET_ARCS _{T4}	Marking = 0 for all tokens with ID = id in: P1, P2, P3 and P5
T5	RESET_ARCS _{T5}	Marking = 0 for all tokens with ID = id in: P2, P3 and P4
T6, T7 and T8	FAIL _{CATWIRE}	= $\exp(\mu + \sigma Z)$ Samples from lognormal distribution μ and σ are location and scale parameters respectively, on the request of Network Rail the values are not shown. Z is a standard normal random number
T6	Firing Time	Sampled from exponential distribution: $\lambda=4.6 \cdot 10^{-7}$
T7	Firing Time	Sampled from exponential distribution: $\lambda=2.7 \cdot 10^{-4}$
T7	RESET_ARCS _{T7}	Marking = 0 for all tokens with ID = id in: P3 and P4
T8	Firing Time	Sampled from Weibull distribution: $\beta=3$, $\eta=500$
T8	RESET_ARCS _{T8}	Marking = 0 for all tokens with ID = id in: P3, P4 and P5
T48	Firing Time	= 0 LOW PRIORITY, so fires after every other transition that is scheduled to fire at the same time)

4.11 Modelling of Large Scale Renewals

Large scale renewals, or improvement works, that involve the renewal or maintenance of a large number of components (of the same or different types) take place according to the asset management strategy. A separate subnet exists to model the timing of such renewals or improvement works. When such work is scheduled to occur, various transitions that model the maintenance or renewal work, become enabled. The model can be used to test different strategies, with respect to the timing of renewal or improvement works. In this thesis, the renewal of the catenary and contact wire in an access area are modelled to occur at the same time, after a fixed time period of 70 years (which represents the predicted service life of the components), although in practice the exact timing of the renewal will vary based on access restrictions and maintenance resources (such as available staff) that are not considered in this study. Since there is a large amount of work required, the section of line has to be shut for a prolonged period to allow the work to be completed. In practice, this type of work

is commonly undertaken when the railway is less used, such as over the Christmas period, to reduce disruption.

Figure 4-11 shows the subnet that models the renewal process. At the start of the simulation, a token for each access area will be in place P54 to show that a renewal is scheduled in the future. Transition T49 represents the renewal process and it fires when it is time to undertake the renewal, therefore, its firing time is 70 years (25550 days). This transition contains various reset arcs that result in all the tokens that represent a contact wire and catenary wire in the access area undergoing renewal, being cleared from all the places that they exist in their subnets. Tokens that represent each new section of the catenary wire and contact wire in the access area being renewed are then added to the places representing the component as being in a working/ good condition in the catenary wire and contact wire subnets (P0 and P8). This is done using output arcs, containing a for loop, that will fire each token in the access area for the contact and catenary wires to the working/ good condition place, with updated information about their installation date (which is equal to the simulation time) and the number of previous maintenance actions (which is now zero since the components have been replaced). Therefore, a token for each id that belongs to the area being renewed is fired and the tokens *INST_DATE*, *LAST_MAINT_DATE* and *PREV_MAINT* data values are changed, as shown in the arc expression (id, s, w, a, sim_time, 0, 0). A token is also fired to P55 which records the cost of the renewal.

It is assumed that maintenance of the other OLE components will also be undertaken opportunistically during the period that the renewal is undertaken. This works in a similar way to the maintenance process, described earlier, however, there is more available time to perform the maintenance due to prolonged access to the area whilst the renewal is undertaken. When T49 fires, a token for the access area being renewed is also fired to P50 with a *MAINT_STARTED* data value equal to “TRUE”, which shows how maintenance is currently underway in the access area. The token also has its *TIME_REMAINING* data value equal to 30, which means 30 time units are available to perform opportunistic maintenance of other degraded components in the access area being renewed. Recall that P50 is a global place, describing the current maintenance status, and the different components’ maintenance transitions schedule their maintenance according to this information. After the renewal, and the completion of all the opportunistic maintenance that occurs at the same time (which takes place in the other component subnets), T50 fires, which updates the current maintenance status for the access area in P50. Note, that T50 has a low priority to allow all the maintenance transitions, representing the opportunistic maintenance, to fire first. T48 is inhibited by P56 because a renewal of the catenary and contact wires is not recorded as a maintenance visit.

CATWIRE = ID x SPAN x WRUN x AREA x INST_DATE x LAST_MAINT_DATE x PREV_MAINT
CONWIRE = ID x SPAN x WRUN x AREA x INST_DATE x LAST_MAINT_DATE x PREV_MAINT

Variables:

id: ID, s: SPAN, w: WRUN, a: AREA, in: INST_DATE, lm: LAST_MAINT_DATE, md: MAINT_DATE, pm: PREV_MAINT, tr: TIME_REMAINING, m: MAINT_STARTED

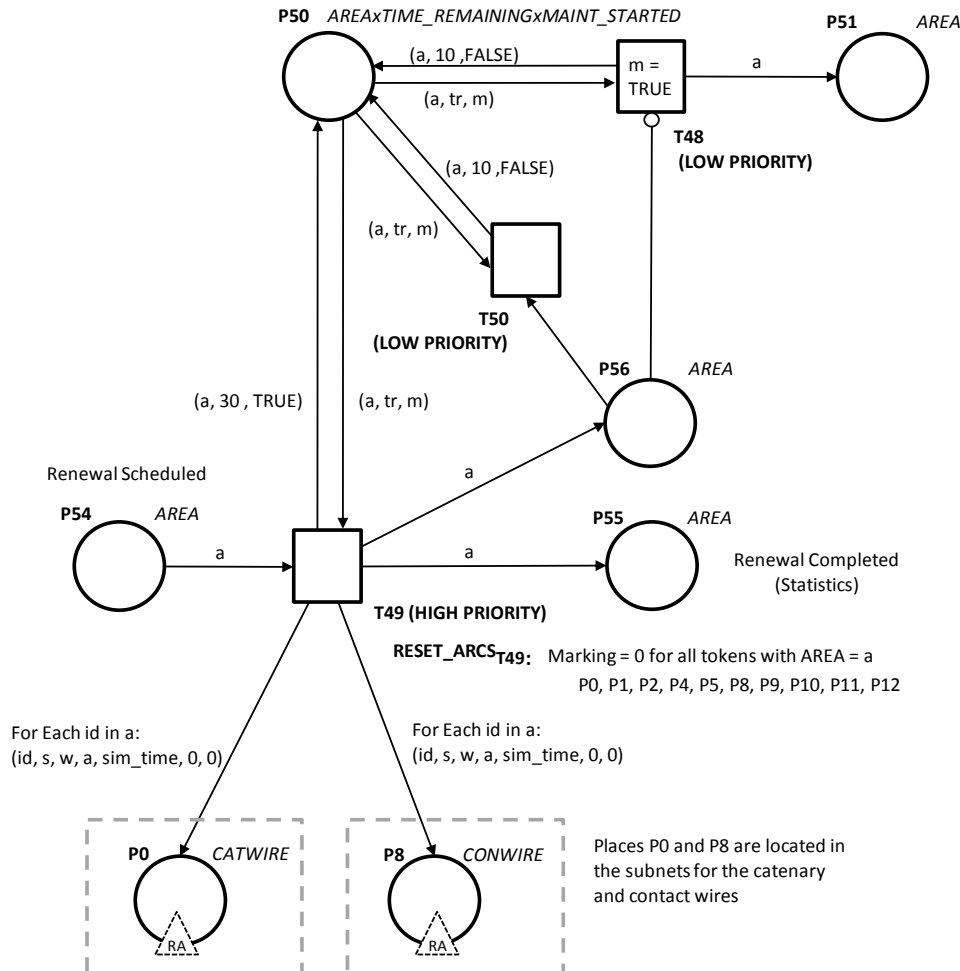


Figure 4-11 Petri Net Modelling the Renewal of the Catenary and Contact Wires

4.12 Whole System Petri Net Model

As described previously, a number of different Petri nets that describe the degradation, failure, inspection and maintenance of the different OLE component types were developed. In the whole system Petri net model, these Petri nets represent separate subnets that concurrently model all the different instances of each of the component type in the area of OLE studied.

Additionally, there is a subnet that models the adjustments to a wire run that must take place to address poor set-up of the wire run, for instance when there is excessive stagger or large fluctuations in the contact wire height across the wire run. A process that models the failure of the system due to external influences, where the components are not damaged but delays are incurred (such as

encroaching vegetation or bird strikes leading to the system short-circuiting), is also included in the model.

Various dependencies are considered between the different components modelled. As described earlier in section 4.8, the component maintenance can be grouped together to occur during the same maintenance visit to the same access area. Additionally, two forms of opportunistic inspection are also considered, which introduce further dependencies between the components. Firstly, when maintenance is undertaken on a certain component, during scheduled maintenance or when rectifying a service affecting failure, an opportunistic high level inspection is modelled to occur on the other components in the same span, since the maintenance engineers will be directly next to the components and can, therefore, assess their condition. Similarly, after a service affecting failure has occurred, a low level walking inspection of the wire run that the failure occurred in is modelled to take place. The whole system model, therefore, considers the dependencies between the inspection and maintenance of the different components in the area studied, independent of whether they are different instances of the same component type or different component types.

There are also dependencies modelled between the failure of the catenary wire, contact wire and registration equipment and the set-up of the wire run of OLE that they are located in, as described earlier in section 4.9.2. If the wire run requires adjustments to correct the set-up, then transitions representing the failure of the catenary wire, contact wire or registration equipment due to the poor set-up of the wire run become enabled.

A detailed description of how the opportunistic inspection process works is now given, followed by an overview of the whole system model where the main features that model the dependencies between the different components are explained.

4.12.1 Opportunistic Inspection Processes

Figure 4-12 shows the subnet for the registration equipment, which models the degradation, inspection, maintenance and failure of the component. The subnet is similar to the catenary wire subnet, previously presented in section 4.10. Additional transitions, which model how opportunistic inspection is undertaken on this component during maintenance actions and after service affecting failure events, are also shown in this subnet. The different tokens in the places with type REG represent different instances of the registration equipment at each span of OLE that is studied.

Table 4-8 defines the different variables that are used in the figure and Table 4-9 describes what the different places represent. The purpose of this figure and description is to give an understanding of how opportunistic inspection is modelled. The detailed information about the transition's firing times

and functions is not required to understand how the process is modelled (this information is provided in the appendix with all the other component subnets).

After the maintenance or failure of any component (in any component subnet), a token is fired to P52 (a global place). This token consists of a *SPAN* data value that refers to the span of OLE that the component that is being maintained is located within. In Figure 4-12, when P52 is marked, T68 becomes enabled if a token containing the same *SPAN* data value is present in P29 (the degraded place) and not present in P31 (the revealed degraded place). T68 will then fire immediately (with a high priority). When it fires, it mimics the normal inspection transition (T29), so a token is removed from P29 and a token fired to P31, in order to model how the degradation of the component is now revealed. The token with the same *SPAN* data value is also fired back to P52, so that any other opportunistic inspection transitions in the other component subnets remain enabled. Once all of the modes of the opportunistic inspection transitions that have P52 as an input place (in all the different component subnets) have fired, T74 absorbs the token from T52. T74 fires immediately, but it has a low priority to ensure that it fires after all the opportunistic inspection transitions, which require a token in P52 to be enabled (like T68), have fired.

Opportunistic inspection after failure events is modelled in a similar way. It is assumed that after a service affecting failure, a low level walking inspection of the wire run will take place. Transitions that represent a component's failure fire a token, which consists of a *WRUN* data value, that represents the wire of OLE that the failed component is located in, to P53 (a global place). When this place is marked, the transitions that represent this low level opportunistic inspection can become enabled in certain modes. T69 represents such a transition for the registration equipment. This transition will be enabled in multiple modes for each token that resides in P29 with a *WRUN* data value that is the same as the token in P53. T69 works in a similar way to T68 and after all the transitions representing opportunistic inspection have fired, T75 absorbs the token from P53.

All the different component subnets are connected to the global places, P52 and P53, in a similar way. However, the degradation of some components (such as the amount of wear on the contact wire) is not revealed through a low level walking inspection. Therefore, for these components, an opportunistic inspection is not modelled to occur after a service affecting failure of another component.

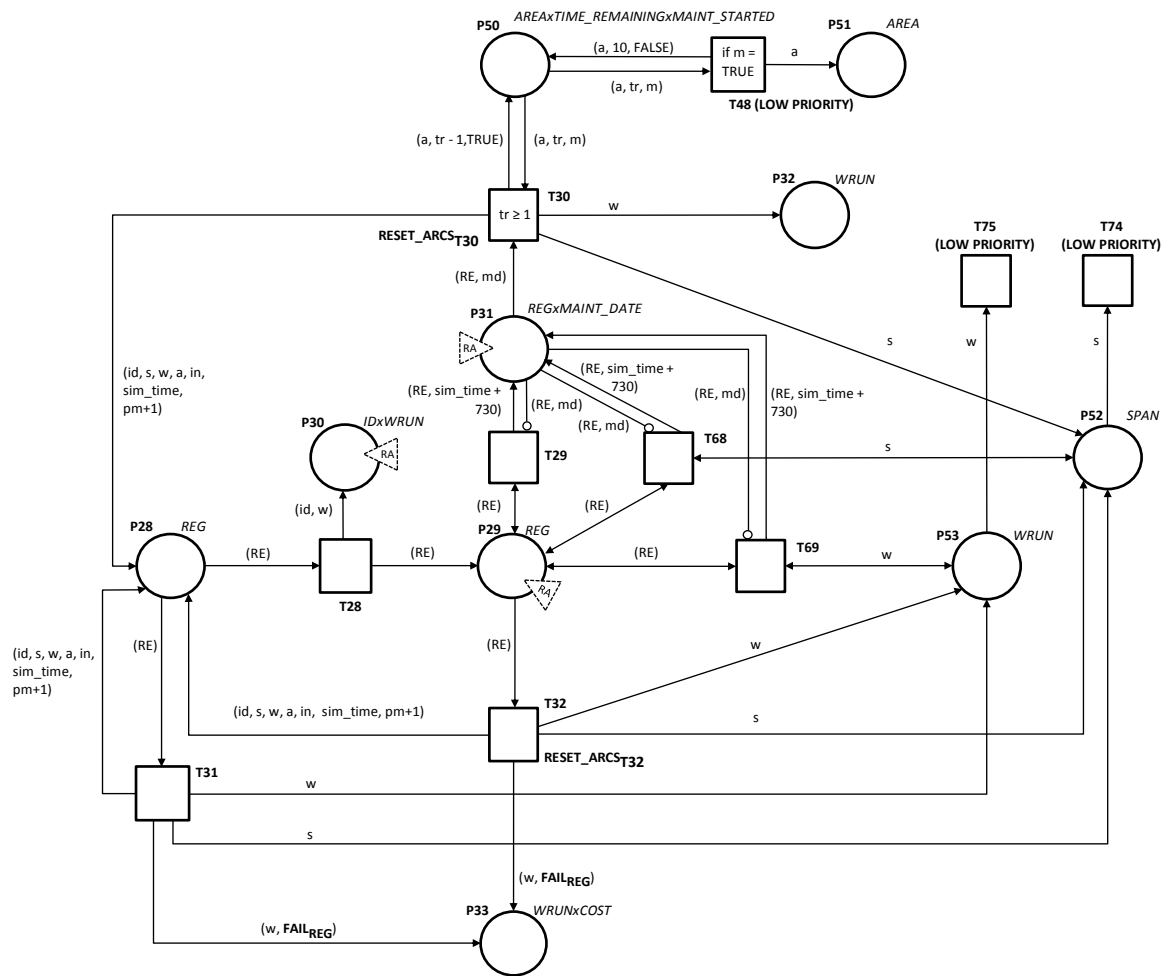


Figure 4-12 Registration Equipment Subnet with Opportunistic Inspection Transitions

Table 4-8 Different Variables used in the Registration Equipment Subnet

Variables	Data Value It Binds to
id	ID
s	SPAN
w	WRUN
a	AREA
in	INST_DATE
lm	LAST_MAINT_DATE
pm	PREV_MAINT
md	MAINT_DATE
tr	TIME_REMAINING
m	MAINT_STARTED
RE = set of variables: (id, s, w, a, in, lm, pm)	
sim_time = the current simulation time	

Table 4-9 Description of the Places in the Registration Equipment Subnet

Place	Description	Type
P28	Good / Working Condition.	<i>REG*</i>
P29	Degraded Condition (registration equipment is damaged, seized or loose).	<i>REG*</i>
P30	Records statistics associated with the number of degraded registration equipment components in a wire run.	<i>ID x WRUN</i>
P31	Revealed Degraded Condition (the maintenance engineers are aware of the degradation and maintenance is scheduled).	<i>REG*</i>
P32	Records statistics associated with the number of maintenance works undertaken on the registration equipment.	<i>WRUN</i>
P33	Records statistics associated with the number of service affecting failures of the registration equipment and the corresponding costs incurred.	<i>WRUN x COST</i>
P50 (global)	Describes the current maintenance status of the access area.	<i>AREA x TIME_REMAINING x MAINT_STARTED</i>
P51 (global)	Records statistics associated with the total number of maintenance visits to an access area.	<i>AREA</i>
P52 (global)	The span of OLE is currently undergoing maintenance. This is an enabling place for transitions that represent opportunistic high level inspection of components located in this span.	<i>SPAN</i>
P53 (global)	The wire run of OLE contains a failed component. This is an enabling place for transitions that represent opportunistic low level inspection of components located in this wire run.	<i>WRUN</i>
*REG= <i>ID x SPAN x WRUN x AREA x INST_DATE x LAST_MAINT_DATE x PREV_MAINT</i>		

4.12.2 Overview of the Whole System Model

Figure 4-13 shows the overall system model drawn as a hierarchical Petri net. This figure shows the main features of the whole system model and how the different processes that are modelled are interlinked. As described previously, there are separate subnets for the component types and processes that are studied in detail, where the degradation, failure, inspection and maintenance are modelled. Failures due to external influences (i.e. system failures that were not caused by the OLE components studied in detail and did not cause any damage) and the renewal of the catenary and contact wires are also modelled in separate subnets. In Figure 4-13, each subnet is represented as a super transition, denoted by double lined squares. These subnets can be viewed as functions and the places that are connected (by arcs that will connect to transitions within the subnets) are input or output events of the processes modelled within the subnets. Note, every subnet is presented in the appendix.

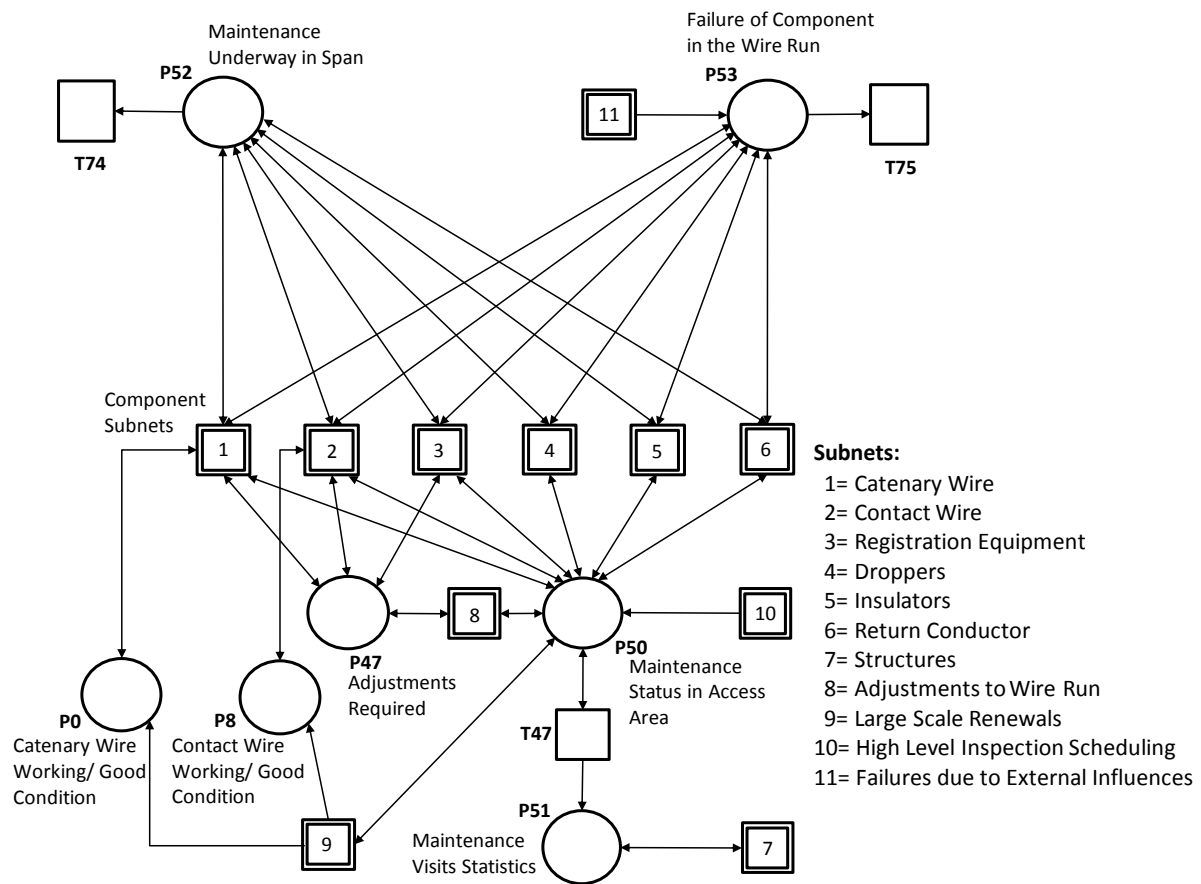


Figure 4-13 Whole System Hierarchical Petri Net

Each of the components' subnets, that model the degradation, failure, inspection and maintenance of their associated component, contain transitions that connect to place P50, the global place that holds the information about the current maintenance status in the access area. The maintenance transitions then obtain their firing time based on this information. Immediately after maintenance has been completed, a token is fired to P51 which records statistics associated with the number of maintenance visits to the access area. Transition T47 will fire a token to P51 after all the maintenance transitions, representing all the work scheduled to occur during the maintenance visit, have fired. When a high level inspection is undertaken, a token is also fired to place P50 to enable component maintenance transitions to occur at the same time as the inspection. This models how maintenance is also undertaken during high level intrusive inspections. The token is fired from the high level inspections scheduling subnet (Subnet 10) at regular intervals equal to the inspection frequency.

Note, the structures subnet is not connected to P50 because the structures are not opportunistically maintained at the same time as the other OLE components, as they are dealt with by the civil engineering team (not the OLE maintenance engineers). However, within the structures subnet, the maintenance of structures in the same access area are modelled to occur at the same time.

The maintenance transitions in the different component subnets also fire a token to P52, which signifies that maintenance is currently underway in the span that the component being maintained is located in. When a token enters P52, the opportunistic high level inspection process is enabled. Similarly, the transitions that represent failure in each of the component subnets also fire a token to P52, to enable an inspection to be undertaken of the components located in the same span as the failed component. Additionally, a token is fired to P53, which signifies that a failure has occurred in the wire run. This will enable the opportunistic low level inspection process to take place for the wire run that the failed component was located in. The random failures of the other OLE components and external influences are modelled in a separate process (Subnet 11) that also fires a token to P53 to enable a low level inspection of the wire run affected to take place.

Subnet 8 models the adjustments of a wire run to rectify poor set-up. As described earlier, in section 4.9.2, when a wire run requires adjustment, there is an additional failure mode modelled for the catenary wire, contact wire and registration equipment. Place P47 represents the wire run as requiring adjustments and the transitions representing the failure of the catenary wire, contact wire, and registration equipment, which exist in the component subnets, are connected to this place (as shown by the arcs linking P47 to Subnets 1, 2 and 3). Subnet 8 is also linked to P50 to model how the adjustments of the wire run can also take place at the same time as the maintenance of other components.

Finally, there is also a large scale renewal subnet (Subnet 9), which models the renewal of the catenary and contact wires. The transition representing the renewal contains various reset arcs that change the markings of the places in Subnets 1 and 2 to model how the components are renewed. Output arcs fire to P0 and P8, which represent the good/working condition of the catenary wire and contact wire respectively, to model how the renewal has improved the component's condition. This subnet is also linked to P50, to model how opportunistic maintenance of the other OLE components will take place at the same time as the renewal.

4.13 Building and Evaluating the Model

A bespoke software program that undertakes the Monte Carlo Simulation of the Petri net developed in this study and calculates the statistics has been coded using the C++ programming language. The program is capable of simulating any Petri net (providing it does not have any high level features that weren't described earlier). The program reads in one text file containing information about the places and tokens in the Petri net and another text file containing the transition information. Using this

information, the program undertakes the Monte Carlo simulation of the Petri net. The statistics that are calculated are written to csv files, which can then be accessed easily using Microsoft Excel.

C++ has proved to be a useful language to code the Petri net simulator in due to its object orientated nature and features, such as polymorphism, which allow the different functions that the transitions perform to be executed efficiently. Since the simulations have no influence on one another, the code has also been made to perform the simulations in parallel to reduce the run time. By doing this the runtime is reduced by approximately the inverse of the number of processors available to run the code on. In the example study, presented in Chapter 5, an access area consisting of two wire runs was analysed using the model. This resulted in 380 components/processes being considered concurrently in the model developed for a 100-year simulation period. The model was able to undertake 100,000 simulations in approximately one minute, using a computer with a dual core Intel i3 processor.

A document to create the Petri net and its input files has been made using Microsoft Excel. User forms and VBA macros are used to allow fast and predominantly automated generation of the input files needed for the C++ code to undertake the simulation. Attempting to create the input files manually would be arduous due to the sheer number of places and transitions in the model. There are also macros that can be used to easily edit and enhance the Petri nets created. Each subnet (for each component type) is saved in a different document and then a master document can be used to incorporate the different subnets to be used in the same model. The user selects the components that exist in the area to be studied and the input files for the transitions and places are created automatically. The overall model is able to change size dynamically in terms of the amounts and types of components that the user chooses to study with different tokens, and therefore different transition modes, created depending on which components are studied. User forms are used to help the user to input which component types (and subtypes) are present at or between each set of structures in the area studied. A library that contains all the behaviours for the different transitions' firing times has been created, so that the degradation and failure distributions for each component type and subtype is added to the associated transitions for each component chosen. Similarly, the firing information for the transitions that represent intervention actions, like inspection and maintenance, is added according to the components selected. These values can also be altered to allow different intervention strategies to be tested within the model.

The overall practical use of the model is illustrated in Figure 4-14. The Petri net is built in Excel and the number of tokens, that represent the different components studied for a particular analysis, can change dynamically. Similarly, the different intervention actions, such as the inspection interval or the component maintenance scheduling times, can also be changed. These are listed as user inputs

because when the model is used, the user will specify the components in the area studied, e.g. the number of a specific component type and the sub-type of components, their corresponding degradation and failure behaviour and the intervention strategy considered. Macros in Excel then adjust the number of tokens, transition firing times, transition modes and place marking in the Petri net accordingly. The actual Petri net model can also be edited within Excel.

Text files are then generated for the current configuration of the Petri net and these are read into the C++ software which will generate the model, based on the input information, and evaluate it using Monte Carlo simulation. Various events are recorded for each simulation and after 100,000 simulations have been completed, numerous statistics are calculated. Further information about how these statistics are obtained are described in the following section. The statistics are calculated at number of granularities, for each component type and for the system as a whole, for an individual wire run and for the entire section of OLE studied. These outputs contain statistics that refer to the number of component/system maintenances and failures and the cost of maintenance and failure. A thorough explanation of all the different statistics that are obtained is provided in Chapter 5, where the application of the model is presented.

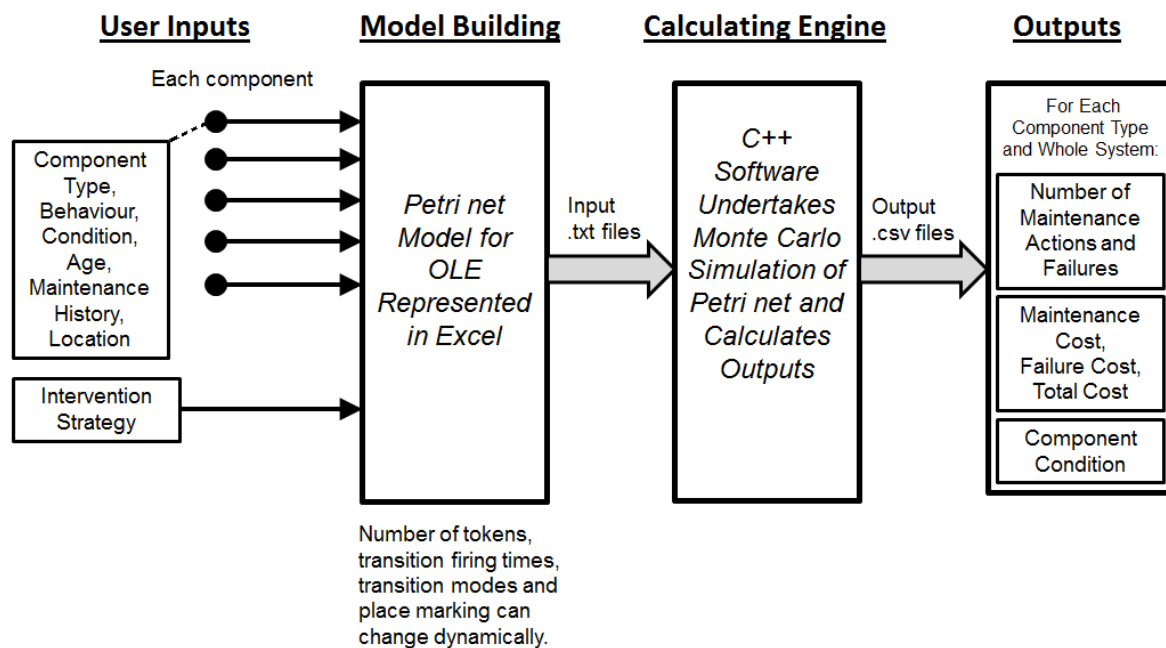


Figure 4-14 Overall Framework for the Model as Life Cycle Cost and Asset Management Tool

The model can be used as an OLE life cycle cost and asset management analysis tool, where component information and the controllable asset management decisions are provided as inputs to the model, which is then evaluated to obtain outputs that describe the impact of the asset management decisions, in terms of the performance and cost of the components and the system. The

overall modelling framework developed is, therefore, similar to the framework used by Network Rail for its life cycle cost model, as described earlier in section 3.2.5 and outlined in Figure 3-2 (page 64 in the literature review).

4.13.1 Obtaining Statistics from the Petri Net

In the Petri net there are various places used to record the occurrence of certain events of interest, such as when a maintenance action or failure occurs. Numerous outputs, that contain statistics associated with the occurrence of these events, e.g. the mean number of failures per year for a certain component type, are then calculated. This section explains how maintenance and failure outputs for the different component types are obtained and how higher level outputs for the overall system, such as the number of system failures and the total cost of the system, are calculated. Outputs that describe component condition are also explained.

Maintenance and Failure Outputs

In each subnet there are places that record various statistics associated with maintenance and renewal costs, failure costs or component condition. For places that collect statistics for maintenance, a token is fired into the place when maintenance of this component type takes place. When this occurs, the current simulation time is recorded. This is done throughout the entirety of each simulation. Once the model has stopped simulating, for each simulation that was completed, the times that a token entered the place (representing each time maintenance of this component type was undertaken) are grouped into the year of the simulation (1-100). The grouping into years is done to allow annual statistics to be expressed, so that the outputs can be analysed over the life cycle of the system. By considering the results for all the simulations, various statistics describing the number of maintenance actions per year, including the mean, median, upper and lower quartiles, are obtained.

Since the maintenance of a component has an associated cost, the cost of maintenance for a component type and the system as a whole (by summing the different components' maintenance costs) can also be calculated. The cumulative number of times a token enters a specific maintenance place per year is also calculated for each simulation from which, through considering all the simulations, statistics associated with the cumulative maintenance costs can be calculated for a given year. Note that other than the mean, the statistics for the cumulative number of maintenance actions cannot be calculated directly from the number of yearly maintenance actions. Therefore, the cumulative number of times that the place is entered is calculated for each simulation to allow the full range of cumulative statistics to be obtained.

Places that obtain statistics for failures work in a similar way. When a token is fired into the place the current simulation time is recorded. The token that is fired into the place contains a data value describing the cost of the failure (as described in section 4.9), and this failure cost is also recorded. Upon the completion of all the simulations, for each simulation completed, the failure costs are grouped into the year of the simulation that they occurred (1-100). Additionally, for each simulation, the number of failures per year are calculated and split into 3 different categories (minor service affecting, average service affecting and major service affecting) according to the failure cost that was incurred. The same approach is also repeated for cumulative failure costs. Then, by considering all the completed simulations, detailed statistics can be calculated for the yearly failure costs, the yearly cumulative failure costs and the number of failures per year.

Whole System Outputs

The maintenance, renewal and failure cost statistics are also collated, so that the model provides a higher level of output granularity. For each component type, outputs regarding its maintenance, renewal and failure costs are provided at both the wire run level and for the total area studied. The statistics collected are collated further to obtain outputs for the total maintenance, renewal and failure costs for the section of OLE studied. The collation of statistics is done by combining the information recorded for each simulation. The higher level granularity outputs (e.g. outputs concerning the total maintenance costs for the area studied) are then calculated by considering all the simulations undertaken. This enables many more statistics to be calculated than if the mean values for the different cost types were added together. This allows statistics that help express and quantify uncertainty, such as the standard deviation and inter quartile range, to be provided at all the different levels of output granularity.

This process is carried out by recording the occurrence of an event for the system at the same time as recording the event for the component that the event is associated with. For example, when a component fails, the place representing the failed component records information about the times and costs of the component's failure, and the information about the overall number of system failures and system costs is updated.

Component Condition Outputs

There are also places that record statistics associated with component condition. Since the component degradation rates describe how an individual component's condition is expected to change over time, condition outputs are provided at the wire run level or for the entire area studied. The condition of a group of components within a wire run is expressed by considering the number of components in the

wire run that are degraded. Network Rail developed different condition thresholds depending on the number of degraded components in a wire run. For instance, 0 degraded insulators in a wire run would be a perfect condition, between 1 and 3 could represent a good condition, between 3 and 5 satisfactory and greater than 5 poor. When a component degrades, a token, containing a data value describing the wire run that the component is located in, is fired to the place that records condition statistics. By considering the token types present in the place, the condition can be evaluated by calculating the number of components in the wire run that are degraded. Similarly, upon maintenance, the token is removed and the condition score is re-evaluated. The amount of time spent in each condition, during each year of each simulation, is recorded and then the average times calculated. This allows the expected amount of time that the overall wire run condition of a component type will spend in the different conditions each year to be calculated.

Additionally, outputs expressing the number of components in a wire run, and the entire area studied, that have degraded (to the extent that maintenance is required) each year are also recorded. Such outputs can help to show the effectiveness of maintenance and inspection regimes by comparing them to the outputs calculated for the maintenance activities. This is because the inspection frequency and the grouping of maintenance influence how soon a component is maintained from the moment it requires maintenance. Component age can also be used as a proxy for condition. By considering the installation date of the components, the average age of a component type in a wire run, or the area studied, can also be calculated for each year.

4.13.2 Verification and Validation of the Model

The coding of the model was verified by creating smaller Petri nets containing many of the features used in the developed whole system model and checking that the transitions fired the tokens as intended. For example, the use of reset arcs was verified by considering the Petri net shown earlier in Figure 4-2. The desired behaviour of the reset arcs was confirmed by stepping through the code when the transition with reset arcs was scheduled to fire and ensuring that the marking of the net was updated correctly. Different initial markings, before the transition with reset arcs fires, were also tested. A similar process was done for all the functions that the code implements. The majority of the functions are associated with transitions but they are verified by considering the change in the marking of the places. However, when verifying that the transition firing times were calculated properly and that the transitions fired at their scheduled time, the random numbers sampled to calculate the firing time, the firing time calculated and the actual time the transition fired were written to a csv file for each transition that fired in a test scenario. Analysis of the csv file was then undertaken to ensure that the firing time calculations and the time at which the transitions fired at were correct.

An advantage of Petri nets is that the model consists of numerous instances of the same elements: tokens, places, transitions and arcs. Therefore, after ascertaining that all the functions that are associated with these elements in the code are working correctly for smaller Petri nets, the code should remain valid for larger Petri nets since the same functions are used. To further verify the code after the whole system model was created, the firing of several transitions in a sequence, at numerous stages in the simulation was examined. This involved stepping through the code and verifying that the marking was updated properly and the current list of enabled transitions and their firing times were correct, for the first 5 transitions to fire, the first 5 transitions to fire after a simulation time of 15000 days and the first 5 transitions to fire after a simulation time of 30000 days (where the total simulation time was 36500 days which equals 100 years).

The results obtained from the overall model were used for validation by considering the plausibility of the values. Firstly, the results are explainable in terms of the change in values over the life cycle of the system, e.g. the change in the number of maintenance actions. Secondly, the results obtained are similar to the results calculated in the life cycle cost model developed by Network Rail (as demonstrated later in section 5.4) and also similar to the values revealed through analysis of historical data. For instance, the model's outputs describing the number of failures for the different components are similar to the values witnessed on the actual railway network. Chapter 5 describes the application of the model developed and the numerous outputs, discussed above, are presented using graphs and figures and their significance is discussed.

4.14 Summary

A High Level Petri net model has been developed to model the main processes associated with the asset management and life cycle cost of the OLE. The main processes considered are the degradation, failure, inspection and maintenance of the components. These processes are modelled individually for each instance of each component type in the section of OLE studied. The components studied in detail are the catenary wire, contact wire, droppers, insulators, registration equipment, return conductor, and structures. The additional process of performing adjustments to components in the wire run, in order to alleviate poor set-up issues, is also modelled. The other OLE components are not studied in detail because they were deemed not to influence the life cycle cost of the system significantly.

High Level Petri net standards have been followed during the construction of the model, which has enabled the model to be intuitive and concise, whilst also allowing more complex processes, which could not be considered in standard Petri nets, to be modelled. In High Level Petri nets, the tokens consist of a set of data values that can contain additional information. This allows numerous tokens,

that are distinguishable according to their data values, to exist in the same place. These different tokens are used to represent different instances of the different components that are studied. Additional component information can also be stored within the data values, such as the component's location and maintenance history, and the transitions can change this information (e.g. increase the number of previous maintenance actions after a maintenance action is completed) and obtain their firing times based on the information. Higher level functions can also be used, for example, when a component fails the cost incurred due to the failure is calculated using an equation that samples the failure cost from a distribution of failure costs that have been found using data analysis of previous failure events. This allows the large uncertainties associated with the cost of component failures (due to different severities of component failure) to be considered in the model.

The Petri net developed models the condition of each component that is studied in detail. Therefore, the model contains places representing the current condition of a component, such as good/working or degraded. The places denoting a degraded component refer to the component being degraded to the extent that maintenance is required. For the OLE this commonly results in the presence of a defect or identifiable degraded feature, e.g. for the catenary wire a degraded section of the wire is identified by signs of burst or caging strands of the wire. The different states of degradation considered for a component type are chosen to replicate the different degraded conditions that Network Rail's maintenance standards state that maintenance must be undertaken to rectify. The maintenance standards also specify the maximum time that the maintenance must be completed by. The Petri net models the condition-based maintenance policy implemented by Network Rail, where component maintenance is scheduled based on the condition of components, revealed during routine inspections. The maintenance modelling in the Petri net is, therefore, more sophisticated than simple fixed time interval preventative maintenance, which other studies modelling OLE asset management in the literature considered. To model this, there are also places that represent the degraded condition of a component as being revealed, where maintenance is then scheduled. Finally, component failure is also modelled. It is assumed that a component may fail from a good/working condition, predominantly due to random processes, and also from degraded conditions, where the rate of failure will increase due to the presence of defects.

The firing times of the transitions representing component degradation and failure are stochastically timed, where the firing time is sampled from a distribution of times to degradation or failure for the component. As described earlier, when a failure transition fires, the cost incurred, due to downtime caused by the failure, is fired to a place that records statistics about the number and costs of failures. The failed component is also maintained as a result of the failure. Transitions representing inspection are scheduled to fire at the same time as the fixed interval inspections are scheduled. The inspection

transitions then move the tokens from the degraded place to the revealed degraded place, where maintenance is scheduled. When a maintenance transition is enabled, the maintenance status of the access area, that the component being maintained is located in, is evaluated in order to obtain its firing time. If maintenance is not currently being undertaken, then it is scheduled to occur at the time that the maintenance standards specify, for rectifying the corresponding component type's degradation. If maintenance is currently underway, then the maintenance of other components in the same access area can be scheduled to occur during the same maintenance visit (i.e. at the same time), provided that there is enough time available in the maintenance visit. Priority is given to the components that require maintenance sooner, according to their originally scheduled maintenance dates, which were determined by the maintenance standards. The use of High Level Petri nets allows this process to be modelled in an intuitive and concise manner.

The whole system model developed is hierarchical, where a separate subnet exists for each OLE component type, where the processes considered (e.g. degradation and inspection) are modelled for each instance of the component type. Therefore, tokens representing different instances of the same component type may exist in the same places in the same subnet. These tokens contain data values describing their location relative to one another, where the span, wire run and access area that they are located in are provided. This chapter described the processes in the subnet for the catenary wire specifically, the other component subnets work in a similar way and they are presented in the appendix. Other subnets also exist to model the renewal of the catenary and contact wires and the occurrence of random external failure events (which result in service disruption but none of the OLE components are damaged or caused the failure, examples of such failures include bird strikes causing the electrical supply to short-circuit).

The different subnets are then linked by various dependencies. For example, dependencies are introduced for the intervention actions, where opportunistic maintenance and inspection are modelled. As described earlier, when a maintenance visit takes place in an access area to undertake maintenance of a component, if other components in the same area require maintenance then they can be opportunistically maintained during the same visit if there is time available. When maintenance of a component takes place, an opportunistic inspection of the other components in the same span is modelled to take place. Similarly, after a service affecting failure, a low level inspection of all the components that are located in the same wire run that the failure occurred in is modelled to take place. This represents how maintenance engineers will assess the wire run to check for other damage after a failure event. Global places are used to communicate the current maintenance status of an access area to the different subnets, where the maintenance transitions can then obtain their firing time based on this information, so that the opportunistic maintenance can be modelled. Similarly,

global places are used to contain information about which spans are being maintained or which wire run has failed, in order to enable transitions representing opportunistic inspections, in the different component subnets, to fire. Other dependencies are introduced when the components in a wire run require adjustments, due to poor-set up of the system (e.g. excessive stagger or large fluctuation in the contact wire height). When a wire run requires adjustments, the failure (due to the poor set-up) is modelled for the catenary wire, contact wire and the registration equipment that are located in the same wire run. This feature, therefore, models how the failure of certain components is influenced by the condition of another component or process that is modelled.

The Petri net developed is evaluated using Monte Carlo simulation and various statistics are recorded in certain places, such as the number of maintenance actions for a component type or the number and cost of failures for a component type.

Finally, a Microsoft Excel document has been created to represent the Petri net and create input text files that describe the configuration of the model. These text files are read into bespoke C++ software that has been developed to undertake the Monte Carlo simulation of the Petri net and calculate the various outputs, which are written to csv files. Using macros in Excel, the number of tokens and transition modes, the transition firing times and the initial marking of the Petri net can be changed dynamically, depending on the input information that relates to the components and asset management strategies that are considered for analysis. The framework developed demonstrates how the model can be used as an OLE life cycle cost and asset management analysis tool.

Chapter 5 Results of the Proposed Methodology

This chapter discusses the main ways that the model developed can be used to study the asset management of the OLE. Various output results from an example analysis are provided, along with a description of their characteristics and relevance to the field of asset management.

5.1 Application of the Model

The main purpose of the OLE model developed in this thesis is to calculate the expected costs, maintenance work volumes and number of failures for the various component types over the life cycle of the system.

As described in Chapter 4, dependencies between the components that are located within the same access area (which is assumed to be 2 to 3 wire runs of OLE) are modelled by considering how their maintenance works can be grouped together. The Petri net does not exclusively model any interactions between components in different access areas. Therefore, for illustrative purposes, the model is run for just one access area of OLE. The results for a number of different access areas can still be collated to obtain the statistics for a larger section of an electrified railway. Note that the subnets for the individual component can also be run separately, but the interactions between different component types in the same access area would not be considered in this case. For example, results for only insulators can be obtained (with no opportunistic inspection or maintenance due to the presence of the other component types).

As an asset management tool, the model can be used for multiple purposes, since it calculates statistics associated with the behaviour and expected cost of the OLE over the system's life cycle. First of all, it can be used to provide statistics associated with the expenditure and performance of the OLE for a section of electrified line. More simplistically, various outputs can be found for each component type in a typical wire run. These outputs can then be multiplied by the number of wire runs that exist in an entire electrified line. The process of multiplying the results for each component type could be done within Network Rail's existing whole life cost modelling framework, where software has been developed that collates the life cycle cost profiles of various railway assets. Secondly, the model can also be used for a more detailed analysis, for instance to help maintenance engineers predict the amount of work required for a specific access area and the expected costs, so that they can allocate the resources required (such as spare components and staff) and budget accordingly. Different asset management strategies can be tested in the model to predict the system's behaviour or the expected costs over its life cycle. Thirdly, for future projects, requiring substantial capital expenditure, such as

new electrification schemes or major upgrades, the model can be used to calculate the expected whole life costs of different options (e.g. using different OLE types or maintenance policies). An informed decision on what option is best for investments can be based on the statistics obtained from the model (that also take into account and expresses the degree of uncertainty).

Furthermore, a sensitivity analysis, whereby certain parameters of the model (such as the parameters within the components' degradation and failure distributions) are varied, can also be undertaken. This process can enable the factors that most heavily influence the life cycle costs and have the most uncertainty to be revealed and quantified. Following such analysis, particular attention can then be applied to the components associated with these factors, especially during the stages in the corresponding components' life cycles where the expected costs increase or other issues (e.g. increased failure rates) are more prevalent. Further details about the use of a sensitivity analysis are explained in section 5.3.7.

In addition, optimisation of the various asset management intervention actions can also be performed using the model. The optimum inspection intervals, component maintenance scheduling times and timings of large scale renewals can be found to minimise the expected total cost of the system. Further details about the optimisation of the model are given in Chapter 6.

5.2 Granularity of the Outputs

Each instance of each component type in the section of electrified line studied during the analysis is modelled individually. However, the statistics associated with each component type are expressed at a higher level. The various outputs of the model are calculated for each component type for a particular wire run and also for the entire section that is studied during an analysis. For instance, an example output of the model would be the mean number of maintenance actions for insulators in the entire section studied.

Similarly, by combining the outputs for the different component types, outputs are provided for the overall system's failure costs, number of failures, maintenance costs and total costs (the combination of failure and maintenance costs) for the entire section of OLE that is studied.

The outputs are annualised to provide yearly summaries of the statistics, associated with each component type or the overall system, to analyse the change in values over the components' life cycles. These outputs are expressed as both yearly values and cumulative yearly values, providing a comprehensive set of statistics that describe the expected behaviour and cost of the different component types and the overall system. Note that in addition to the mean values that are calculated,

a comprehensive range of statistics that help quantify the uncertainty associated with the system's behaviour, are obtained such as the maximum, minimum and upper and lower quartiles for the different outputs.

The different outputs that are obtained are as follows:

- Maintenance Outputs
 - Number of Component Maintenance Actions
 - Number of Maintenance Visits to an Access Area
 - Component Maintenance Cost
- Failure Outputs
 - Number of Component Failures
 - Component Failure Cost
 - Number of System Failures
- Condition Outputs
 - Number of Degraded Components
 - Component Age
- System Cost Outputs
 - System Maintenance Cost
 - System Failure Cost
 - System Total Cost

A detailed description of the various outputs that are obtained from the model is given in sections 0 to 5.3.6. The methodology of obtaining these outputs during the Monte Carlo simulation of the Petri net model was described earlier in section 4.13.1.

5.3 Example Analysis

The model is used to simulate 100 years of operation for all the main OLE components in one access area, which was assumed to contain two wire runs, with 26 structures in each (representing approximately two miles of electrified railway). The 100-year timeframe is chosen to allow the entire life cycle of most of the components to be witnessed, as the OLE component lifetimes are typically between 40 and 80 years.

Further details about the components and the asset management strategies considered in the access area that is studied are provided next, before a comprehensive description of the various outputs statistics that were obtained through analysis of the model is given in the following sections. At the request of Network Rail, all values that express a cost, which are used as inputs to the model (e.g. a component's maintenance cost) or outputs that are obtained from the model (e.g. the system total cost), have been multiplied by a factor. Note that the cost outputs obtained are un-discounted so the reader can view the change in the cost values over time without interference from the discount rates

(which would result in the yearly costs being reduced significantly by the end of the 100 year period studied). Note that the results obtained by the model can be multiplied by the discount rates easily if required.

5.3.1 Selection of Components Studied and Asset Management Strategies

The system studied is a newly installed section of OLE consisting of one access area, containing two wire runs, where maintenance engineers can address different components requiring maintenance during the same scheduled maintenance visit. Table 5-1 lists detailed information for each component type studied, including the number of instances of the component and details for the parameters used by the transitions that model the component's degradation, failure and maintenance. It is possible to include different sub-component types at different locations across the area studied. For example, some sections of the registration equipment could be in a tunnel, where their configuration would be slightly different and their degradation and failure rates increased. For simplicity, each instance of each component type is the same, representing the typical sub-types of each component type, in this example study. Note that the degradation distributions used were estimated by taking into account information obtained from various internal Network Rail sources and discussions with maintenance engineers to establish the characteristic life of the components and their degradation behaviour. Similarly, the failure distributions were estimated so that the component failure rates are similar to what Network Rail data analysis has revealed. Since the degraded component conditions represent degradation to the extent that maintenance is required, then the distribution of times to the different levels of degradation and times to failure can be found using maintenance data collected in the format suggested earlier in section 2.6.3.

At the request of Network Rail, all of the cost data used in the model has been adjusted by a factor. The different maintenance and renewal costs have been gathered from various internal Network Rail sources. As described previously, when a failure occurs in the model, the cost incurred is sampled from a distribution of failure costs that has been found for each component type using historical data. To hide details about the costs, the parameters of these distributions are not listed in this thesis.

The asset management intervention strategies that are considered in this example study are intended to replicate those which Network Rail currently implements for a high category line. A cab patrol inspection takes place every 14 days, a low level walking inspection takes place every 28 days and a high level intrusive inspection (where maintenance can also be scheduled to occur at the same time) takes place every four years. The maximum time that maintenance must be scheduled to be completed by for each component (listed in Table 5-1) is set according to the current maintenance standards. It is also assumed that during the first two years, maintenance that is normally scheduled

to take place within a time period greater than 180 days (e.g. for a degraded insulator, it is normally within 730 days) is instead scheduled to take place within 180 days, in order to model how early component issues are rectified sooner for a newly installed system. Due to the lack of data, the amount of time that each maintenance action takes (listed in Table 5-1) and the amount of time that is scheduled for each maintenance visit to the access area have been assumed. Therefore, it is assumed that 10 time units of maintenance may occur during a scheduled maintenance visit because the maintenance will generally be completed during small periods of time at night, when there is no time tabled train service. Note that the concept of time units was described earlier in section 4.8.1.

Table 5-1 Information about the Components and Processes Modelled in the Example Study

Component or Process	Number of Instances Modelled	Degradation and Failure Distributions (all time units in days)	Max Maint. Scheduling Times	Time Units	Maint. Cost (factored)
Catenary Wire	52 sections of wire (each section represents span between 2 structures)	Good → Degraded: Weibull $\beta=2.5$, $\eta=43800$ After 1 or more maintenances: Weibull $\beta=1.5$, $\eta=36500$ Degraded → Severely Degraded: Weibull $\beta=3$, $\eta=1825$ Good → Failed: Exponential $\lambda=5.07E-07$ After 1 or more maintenances: Exponential $\lambda=6.75E-7$ Degraded → Failed: Exponential $\lambda=2.74E-04$ Severely Degraded → Failed: Weibull $\beta=3$, $\eta=1825$	180 days for degraded, 7 days for severely degraded.	3	£640 (Renewal = £80000 per Wire Run renewed)
Contact Wire	10 sections of wire (2 wire runs each split into 5 sections)	Good → Degraded: Weibull $\beta=2.5$, $\eta=40150$ After 1 or more maintenances: Weibull $\beta=1.5$, $\eta=21900$ Good → Failed: Exponential $\lambda=7.12E-06$ After 1 or more maintenances: Exponential $\lambda=9.49E-06$ Degraded → Failed: Weibull $\beta=1.5$, $\eta=1460$	365 days*	4	£800 (Renewal = £52000 per Wire Run renewed)
Droppers	52 spans of droppers (between 2 structures)	Good → Failed: Exponential $\lambda=2.26E-05$ Probability clear of contact wire = 0.93 Degraded → Failed: Weibull $\beta=2$, $\eta=365$	7 days	1	£120
Insulators	104 (2 at each structure)	Good → Degraded: Weibull $\beta=1.3$, $\eta=32850$ Degraded → Severely Degraded: Weibull $\beta=3$, $\eta=3650$ Good → Failed: Exponential $\lambda=7.00E-08$ Degraded → Failed: Exponential $\lambda=5.48E-05$ Severely Degraded → Failed: Weibull $\beta=3$, $\eta=1095$	730 days* for degraded condition, 7 days for severely degraded condition	2	£320
Registration Equipment	52 (1 at each structure)	Good → Degraded: Weibull $\beta=2.5$, $\eta=25550$ Good → Failed: Exponential $\lambda=2.85E-07$ Degraded → Failed: Weibull $\beta=2$, $\eta=3650$	730 days*	1	£400
Return Conductor	52 sections of wire (each section represents span between 2 structures)	Good → Degraded: Weibull $\beta=1.5$, $\eta=91250$ Degraded → Severely Degraded: Weibull $\beta=2$, $\eta=5000$ Good → Failed: Exponential $\lambda=4.58E-07$ Degraded → Failed: Exponential $\lambda=1.52E-04$ Severely Degraded → Failed: Weibull $\beta=2$, $\eta=1825$	730 days* for degraded, 28 days for severely degraded.	2	£960
Structures	52	Good → Degraded: $\beta=1.5$, $\eta=54750$ After 1 or more maintenances: $\beta=1.5$, $\eta=14240$	730 days*	3	£960
Adjustments to Wire Run	2 Wire Runs	Good → Degraded: Exponential $\lambda=3.42E-04$	730 days*	2	£80
External Failures	2 Wire Runs	$\lambda=2.74E-05$			
Isolation and Access Costs for a Maintenance Visit (including High Level Intrusive Inspection) = £800, time units available = 10					
Isolation and Access Costs for Large Scale Renewal = £200000, time units available = 50					
*During first 2 years, component maintenance scheduled to take place within 730 days is scheduled to take place within 180days so that any prematurely defective components are rectified.					

A renewal of the contact and catenary wire is scheduled to take place at 70 years and other necessary maintenance, of the other components in the access area, will also be undertaken at this point. It is assumed that during the large scale renewal works 50 time units of additional maintenance may occur because the line will be closed for all time tabled train services to allow the large quantity of work to be undertaken (typically for 1 to 2 days). Due to the increased service disruption, the cost of access to the line, to undertake the large scale renewal works, is assumed to be substantial.

5.3.2 Convergence of Outputs

Since the Petri net model is solved using the Monte Carlo simulation method, the outputs can be regarded with higher confidence if more simulations are undertaken. However, running a large number of simulations can be time consuming and after a certain number of simulations the output statistics should converge, such that any subsequent simulations result in negligible changes to the output statistics. 100,000 simulations of the model were undertaken and through the analysis of various statistics, the results appear to have converged sufficiently.

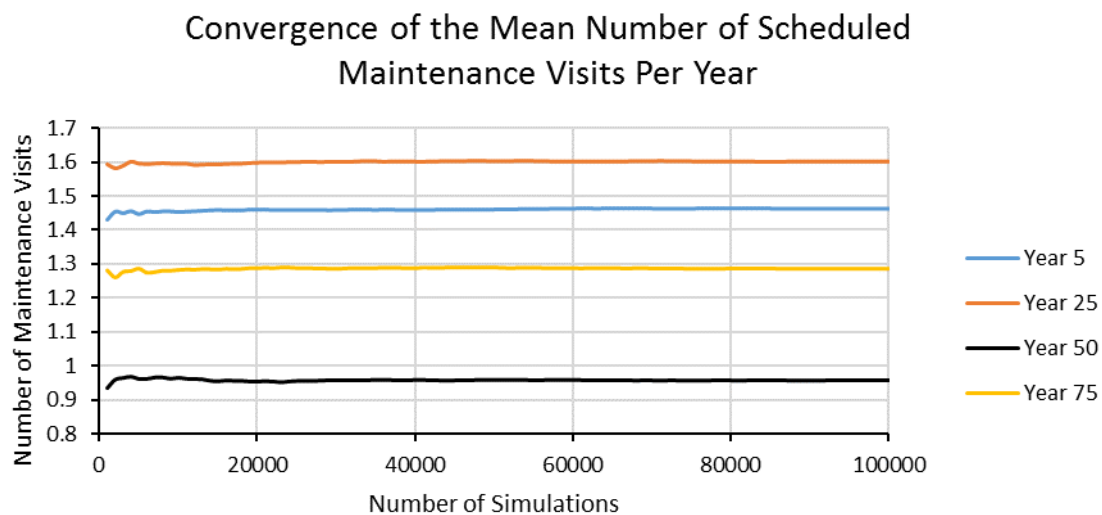


Figure 5-1 Convergence of the Mean Number of Scheduled Maintenance Visits for Various Years

Many of the statistics that are collected and used for analysis are associated with the yearly number of maintenance visits and the yearly number of failures. The change in the mean yearly number of maintenance visits and the mean yearly number of system failures with the number of simulations undertaken, can be examined to check for convergence. Figure 5-1 and Figure 5-2 show the convergence of the mean number of system maintenance visits and the convergence of the mean number of system failures for various years (within the 100-year period analysed) respectively. For every data series (e.g. Year 5, Year 25 etc.), it is clear that after initial fluctuations the results appear to have converged. A description of the significance of the actual results and the change in values over time is explained when the main outputs of the model are presented in sections 0 to 5.3.6.

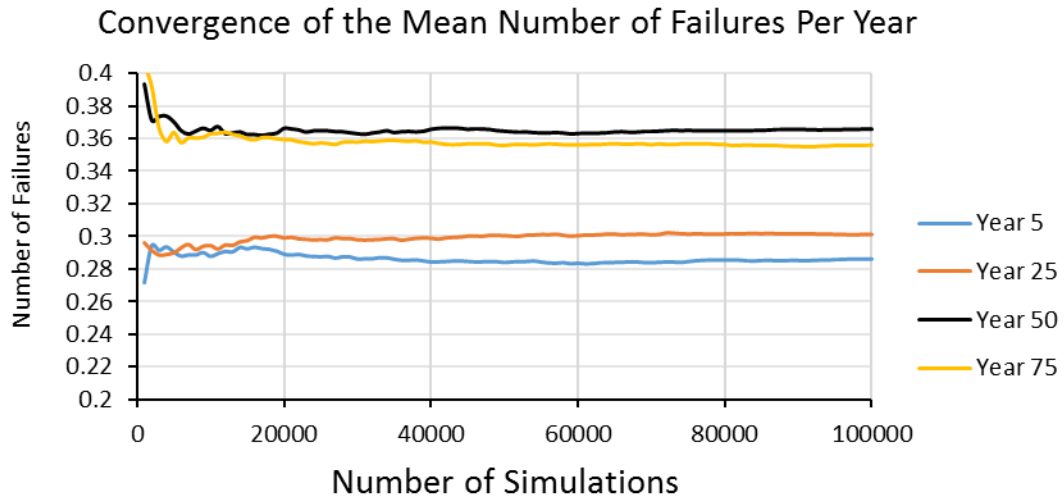


Figure 5-2 Convergence of the Mean Number of Service Affecting Failures of the System per Year for Various Years

The costs that are considered within the model are related to maintenance costs (including renewal costs) and failure costs. These costs are broken down further for each component and for different types, e.g. preventative maintenance costs for the catenary wire. The access/isolation costs (associated with gaining access to undertake scheduled maintenance) and large scale renewal costs are included within the maintenance costs. The total system cost in each year, which consists of all the maintenance and failure costs for each component in the area studied, is a good indicator of overall convergence, since it takes into account all the different processes with associated costs and events with higher associated costs can influence the convergence even if their occurrence is less frequent. The failure costs, which are the key component of the total system cost, take the longest to converge because they are dependent not only on the occurrence of failures, but also on the severity of the failure, which is taken into account by sampling the cost of failure from a distribution of the component's failure costs. Figure 5-3 shows the convergence of the mean total cost for various years. Note that these statistics take longer to converge than those in Figure 5-1 and Figure 5-2 but after 100,000 simulations the changes in the mean cost are minimal.

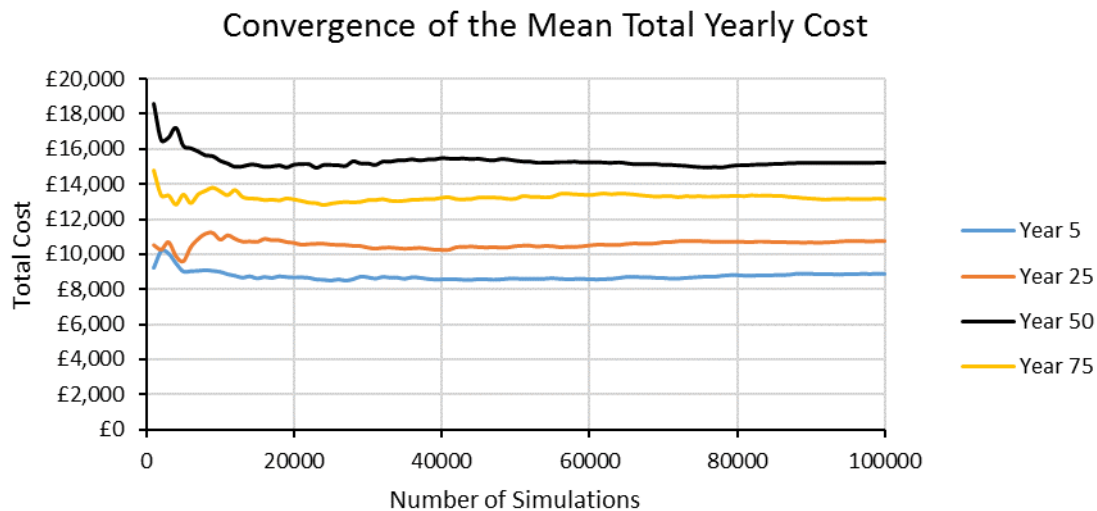


Figure 5-3 Convergence of the Mean Total Yearly Cost for Various Years

The cumulative statistics, such as the mean cumulative total system cost over the 100-year period analysed, converge faster than the annual (non-cumulated) statistics. This is because the cumulated values are greater, meaning if a random event occurs in one simulation it will not have a large influence on the overall mean value for all the simulations undertaken. Generally, the events simulated occur in certain time periods (over the system's life cycle), but they do not necessarily occur in the same year during each simulation.

5.3.3 Maintenance Related Outputs

Various statistics that describe the number of expected maintenance actions for the different component types and the system as a whole are calculated. The expected cost of maintenance can be calculated by considering the costs associated with the different maintenance actions. The number of maintenance actions and the maintenance cost can be expressed for each year over the 100-year period modelled. This allows the behaviour of the system and the different component types to be analysed, demonstrating the expected maintenance requirements over the life cycle of the system and the associated components. Cumulative statistics are also provided. This section explains the maintenance statistics obtained and presents the results for certain component types.

Number of Yearly Component Maintenance Actions

For each component type studied, statistics associated with the number of yearly maintenance actions are obtained for all the components in a wire run and all the components in the entire access area that is studied.

Figure 5-4 and Figure 5-5 show the mean number of maintenance actions per year that address component degradation, for the catenary wire and insulators respectively, for all instances of these component types in the access area studied. These charts also show the number of components that have a new defect occurring each year. This shows the number of sections of the catenary wire, or the number of insulators, that changed from being in a good condition to being in a degraded condition, where maintenance is required. The comparison between the number of new defects occurring and the number of maintenance actions can give an insight into the effectiveness of the maintenance regime.

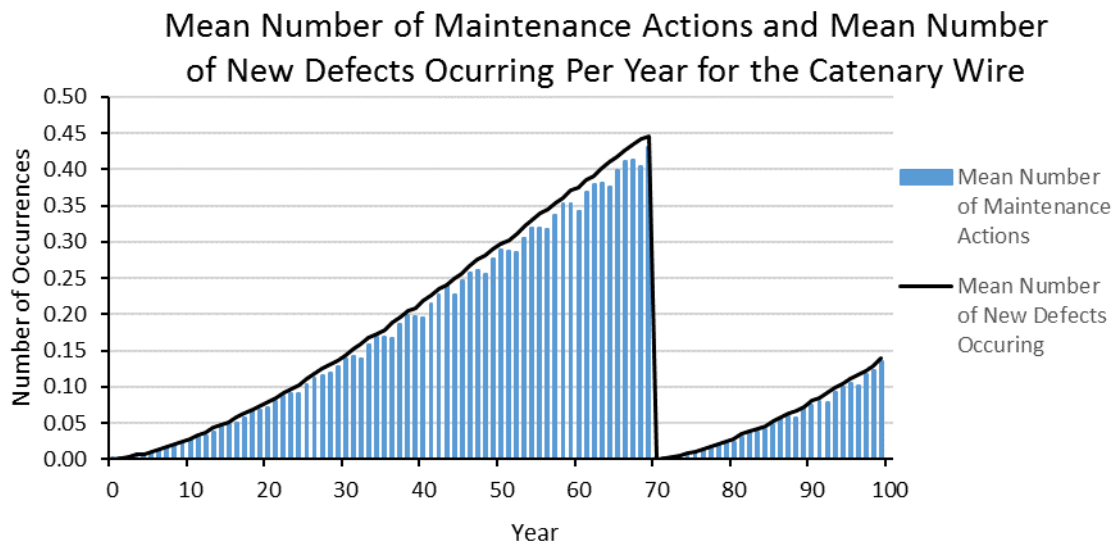


Figure 5-4 Mean Number of Maintenances and Number of new Defects Occurring per Year for the Catenary Wire

For the catenary wire, Figure 5-4 shows that the yearly number of maintenance actions increases each year as the wire ages. At the start of year 71, i.e. after 70 years, both wire runs of the catenary wire in the access area are renewed. Therefore, after year 70 the component is in a new condition where it is less likely to require maintenance. The number of maintenance actions closely follows the curve for the number of new defects occurring, i.e. the number of sections of the catenary wire that have moved from a good condition to a degraded condition. Since the maximum maintenance scheduling time for the catenary wire is 180 days for a degraded section and 7 days for a severely degraded section, any new defects that occur should be maintained within a year. Therefore, the number of maintenance actions per year should be similar to the number of new defects that occur per year. The small shortfall in the number of maintenance actions relative to the number of new defects occurring per year, is due to the occurrence of component failures, where the rapid response maintenance to rectify the failure is not included in these maintenance statistics. Also note that the small fluctuations in the number of maintenance actions is due to the occurrence of the high level intrusive inspections,

scheduled to take place every 4 years, where the components requiring maintenance will be opportunistically maintained at the same time. This is discussed in more detail when describing the maintenance of insulators. The figure shows the maintenance regime to be effective because the majority of defects are maintained before a failure occurs.

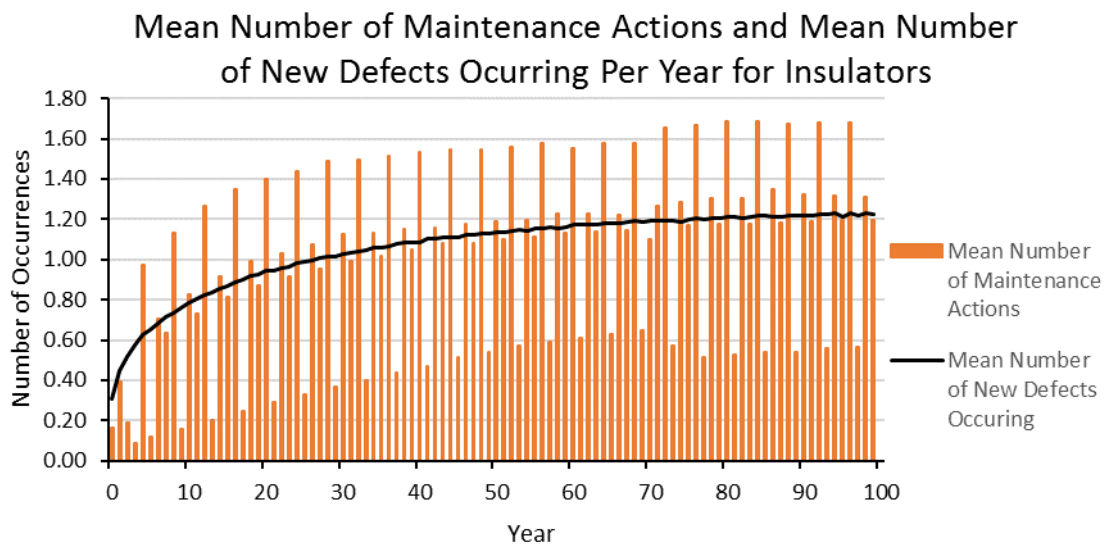


Figure 5-5 Mean Number of Maintenances and Number of new Defects Occurring per Year for Insulators

Similarly, for the insulators, Figure 5-5 shows that the yearly number of maintenance actions increases as the components age. However, when an insulator becomes degraded, i.e. a defect occurs, it is scheduled to be maintained in two years' time, unless it is opportunistically maintained earlier with the maintenance of other components. Therefore, the scheduling of high level intrusive inspections, where the insulators can be opportunistically maintained, influences the number of yearly maintenance actions significantly. Every 4 years when a high level inspection occurs, the number of insulator maintenance actions is higher due to their opportunistic maintenance. The spikes in Figure 5-5 therefore refer to the years where the opportunistic inspection occurs, e.g. in year 5 (after 4 years). Because many of the components that were previously degraded (of any component type in the access area studied) were maintained during the high level intrusive inspection, the year following the inspection has fewer maintenance actions for the insulators. This is because previously degraded insulators are more likely to have been maintained whilst any newly degraded insulators have had less chance of being maintained opportunistically at an earlier date, therefore, they will be maintained in two years' time. The year following this there is a large increase in the number of maintenance actions because there is a higher chance of opportunistic maintenance of the components and the following year the number of maintenance actions is similar to the number of new defects occurring. Note that during the first two years, the maintenance of degraded insulators is scheduled to take place within 180 days to rectify early component issues therefore there is an increase in maintenances occurring

in the first two years relative to the following two years. After 70 years, in year 71 there is a slight increase in the number of maintenance actions because, during the renewal of the catenary and contact wires, many components are opportunistically maintained. The overall increase in the number of insulator maintenance actions with time, or the number of new defects occurring, is not as steep as for the catenary wire because the underlying distributions chosen to represent the degradation of the insulators describe the degradation as being more random. The overall number of insulator maintenance actions is also greater than for the catenary wire. More information about the cumulative number of component maintenance actions is given later in this section.

Number of Yearly Maintenance Visits

In addition to the number of component maintenance actions, statistics describing the number of maintenance visits to the access area were also collected. Note, since the maintenance of different components is grouped together to be addressed during the same maintenance visit, multiple component maintenance actions are undertaken during the same maintenance visit. Estimating the number of expected maintenance visits that will be required is beneficial to asset managers. Knowing how often engineers are likely to be required to visit the access area over the system's life cycle can help determine the number of resources that are required (e.g. maintenance staff) and gain a better understanding of the future logistical requirements for maintenance.

Figure 5-6 shows the mean number of yearly maintenance visits to the access area. The general trend for the number of maintenance visits per year over the 100-year period analysed is similar to the trend for the number of maintenance actions per year for the insulators, as shown in Figure 5-5. The number of maintenance visits steadily increases, as the components in the system age and require maintenance. The fluctuations occurring every 4 years are due to the high level intrusive inspections (modelled to occur every 4 years), where the maintenance engineers will visit the access area and undertake maintenance (if time allows) in addition to the inspection. These high level inspections are recorded as a maintenance visit, therefore, in the years that they occur there is always at least one maintenance visit recorded. As described previously, for the number of insulator maintenance actions, the year following a year where a high level inspection occurs contains a lower number of maintenance visits. This is because many of the components will have been maintained the year before, during the high level inspection, meaning that the system will be in a better condition so there is a lower chance of maintenance being required. In year 70, because there is a large scale renewal of the contact and catenary wire scheduled and other components will be opportunistically maintained too, there is a reduced chance of a maintenance visit being required. Because the large scale renewal generally leaves the system in a better condition, the number of maintenance visits required per year

is reduced afterwards. During the first two years, the maintenance of components that are degraded and normally have a maintenance scheduling time greater than 180 days are scheduled to be maintained within 180 days to rectify early issues. This results in a greater number of maintenance visits in the first two years relative to the following two years.

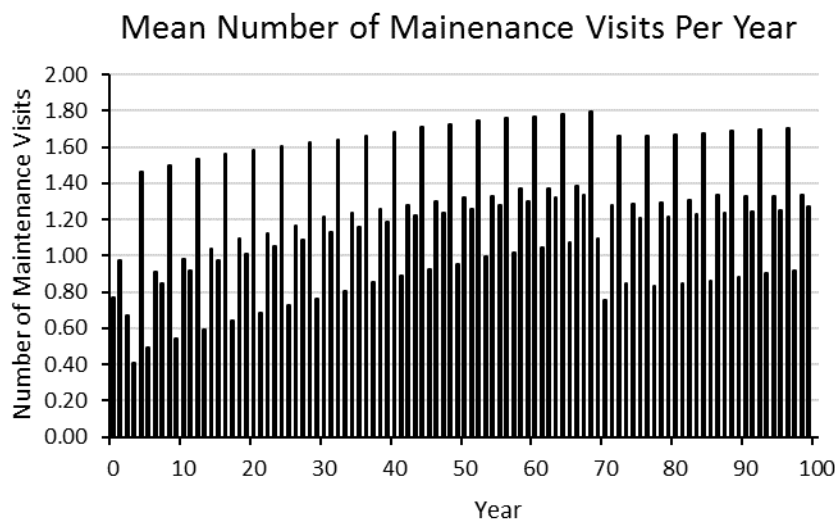


Figure 5-6 Mean Number of Yearly Maintenance Visits to the Access Area

Cumulative Number and Cost of Component Maintenance Actions

Whilst the outputs describing the yearly number of component maintenance actions can give a detailed insight into how the maintenance volumes change over the components' life cycles (for example, as shown previously in Figure 5-4), outputs describing the cumulative number of maintenance actions and the cumulative maintenance cost can provide an overall summary of the expected maintenance volumes and their associated costs over a certain period. Note that the maintenance cost is simply the number of maintenance actions multiplied by the cost of the maintenance action. The renewal of the catenary and contact wire is not included in these maintenance outputs.

An example of the outputs for the statistics associated with the number of cumulative maintenance actions of the different components in the access area studied and the number of maintenance visits, for the first 50 years, is shown in Table 5-2. The variety of statistics provided, such as the standard deviation and upper and lower quartiles, allows the associated uncertainties to be accounted for and quantified. These cumulative statistics are calculated for each year studied. Figure 5-7 and Figure 5-8 show the mean cumulative number of maintenance actions and the mean cumulative maintenance costs respectively, for the different component types for different years.

Table 5-2 Number of Cumulative Maintenance Actions for Each Component Type up to the end of Year 50.

	Cat. Wire	Con. Wire	Dropper	Insulator	Reg. Equip.	Wire Run Adjust.	Return Cond.	Structures	Maint. Visits
Mean	5.62	1.36	20.33	43.01	17.51	10.93	4.21	9.05	55.40
Median	5	1	20	43	17	11	4	9	55
Max	18	11	41	71	34	25	16	24	76
Min	0	0	3	20	5	1	0	0	36
Std. Dev.	2.39	1.21	4.50	6.17	3.61	2.85	2.01	2.90	4.78
Upper Quartile	7	2	23	47	20	13	5	11	59
Lower Quartile	4	0	17	39	15	9	3	7	52

In Figure 5-7 insulators are the most maintained component. This is due to the fact that there are more insulators in the access area than any other component and their expected service life is 70 years, therefore, within the 100-year period analysed the majority of the insulators should be replaced during maintenance actions. Similarly, the amount of maintenance actions for the registration equipment is high due to the large number of these components. Note that the number of maintenance visits refers to the number of visits to perform maintenance of any component type. Since the catenary and contact wires were renewed after 70 years, the number of cumulative maintenance actions does not increase significantly for these components between years 75 and 100. This is because the components are in a better condition after the renewal and therefore require less maintenance.

In Figure 5-8, the cumulative cost of maintenance of insulators is also the greatest for all the component types studied. However, the cost of a maintenance visit to the access area is significantly greater than all the component maintenance costs. This is because during a maintenance visit, the cost are incurred for isolating the line, staff and operating the road rail vehicle, which are considered to total a factored cost of £800 in the model. Relative to some of the other components, droppers require a large number of maintenance actions. However, because their maintenance is relatively cheap, their cumulative maintenance cost is not as large as many of the other components. In comparison, because the maintenance of structures is relatively expensive, assumed to be a factored cost of £1200, the cumulative maintenance cost for structures is one of the largest maintenance costs. The overall total maintenance cost is discussed in detail in section 5.3.6 where the overall system level outputs and total costs are presented.

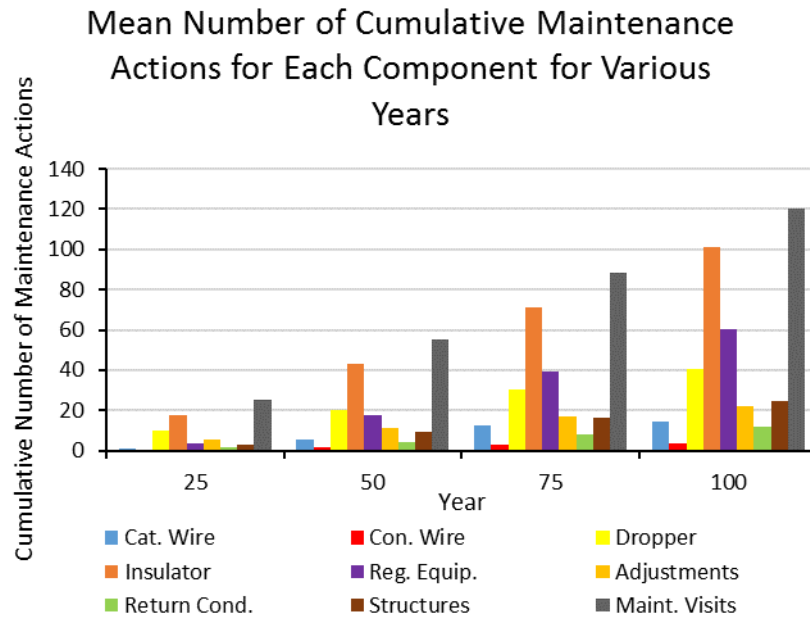


Figure 5-7 Mean Number of Cumulative Maintenance Actions for Each Component for Various Years

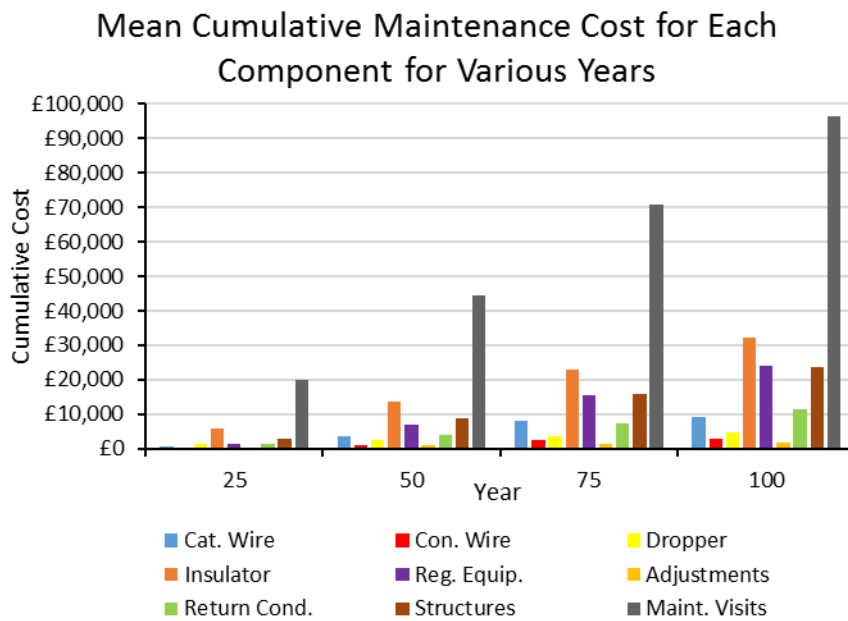


Figure 5-8 Mean Cumulative Maintenance Cost for Each Component for Various Years

5.3.4 Component Failure Related Outputs

Recall, that in the Petri net model, component failures were considered to be failures or severe levels of degradation that result in a disruption to scheduled train services. To account for different severities of failure, the cost that was incurred due to the occurrence of a failure was sampled from a distribution of failure costs for each component type. The results therefore take into account the variability in the costs of failure. Statistics associated with the yearly costs or number of failures and the cumulative yearly costs and number of failures are calculated for each component type and the system as a whole.

Number and Cost of Component Failures per Year

Figure 5-9 shows the mean number of component failures per year for each component type in the entire area studied. Note that failure of the structures was not considered in the model because such events occur extremely rarely. Similarly, failures due to external influences (such as bird strikes that result in service disruption but no damage to the OLE and were not caused by the OLE components studied in detail) are not included in Figure 5-9 because they occur at a significantly greater rate than the component failures. The external failures are assumed to occur randomly with a constant hazard rate and there were approximately 0.2 failures caused by external influences per year, for the access area studied.

It can be seen that the general trend, for each component type, is for the number of failures to increase over time as the components age and their condition therefore deteriorates making them more likely to fail. Following the renewal, after 70 years, the number of failures per year of the catenary wire and contact wire decreases back to their initial starting level where the majority of the failures are due to random events (e.g. a defective pantograph damaging the components). A momentary decrease in the number of failures for the other components is also seen after year 70, because during the renewal of the catenary and contact wires a full inspection of the other components will take place and degraded components will be maintained. Fluctuations occur every 4 years for the component failure rates, due to the scheduling of the high level intrusive inspection. In the years when a high level inspection occurs, the number of failures is reduced because any component defects are more likely to be identified and maintained.

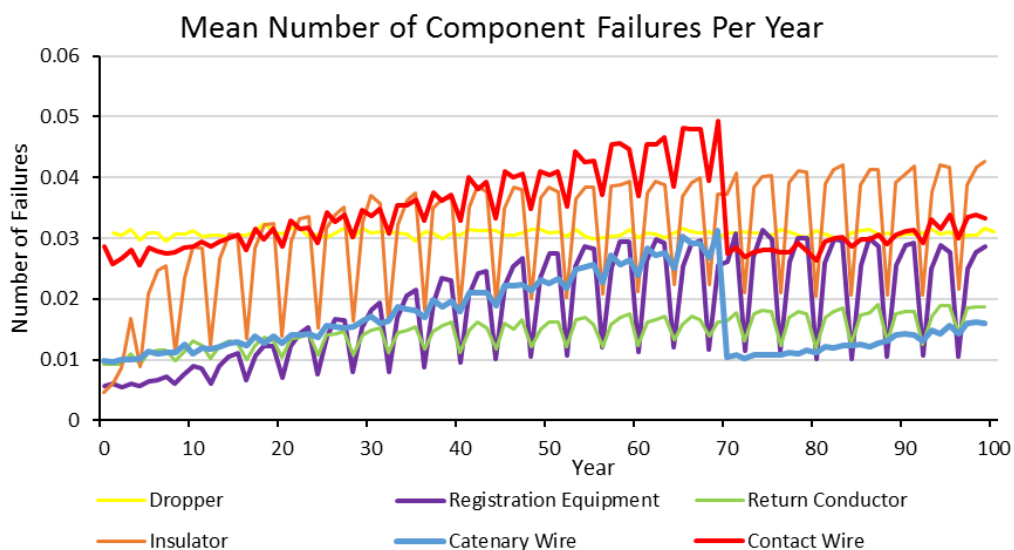


Figure 5-9 Mean Number of Component Failures per Year

Figure 5-10 shows the mean number of failures and the mean failure cost per year for the catenary wire. The statistics shown in the chart can be used by asset managers to predict the behaviour of different components, in terms of the expected number of failures and failure costs, over their life cycles. Different component types may have a lower failure rate, but higher costs associated with their failures and vice versa. A comparison between the failure costs of the different component types is given in the following outputs that are described in this section.

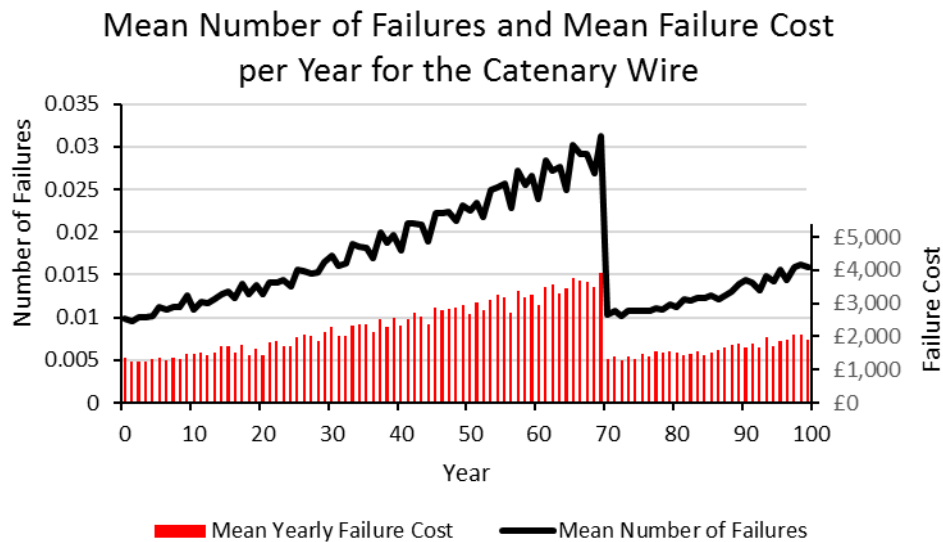


Figure 5-10 Mean Number of Failures and Mean Failure Cost per Year for the Catenary Wire

Cumulative Number and Cost of Component Failures

Outputs describing the cumulative number and cost of component failures can give an insight into the reliability of the components and help to understand which components have the largest expected failure cost over the time period studied. Figure 5-11 shows the mean number of cumulative failures for each component for various years and Figure 5-12 shows the mean cumulative failure costs for each component for various years. Other statistics associated with the cumulative number and cost of failures are also calculated using the model, e.g. the median and interquartile range, for each year over the period studied.

Figure 5-11 shows the number of failures due to external influences to be the greatest. Since these failures do not cause damage to the OLE, they are commonly resolved easily (by simply re-connecting the power supply), therefore, their cumulative failure cost is relatively low (as shown in Figure 5-12). The contact wire has the greatest number of failures out of all the OLE component types. Additionally, because the cost associated with a failure of the contact wire is very high, due to an increased risk of a dewirement, the cumulative failure cost of the contact wire is significantly higher than the other components. The cumulative number of failures for droppers and insulators is only just less than that

of the contact wire, but these failures are less likely to result in severe disruption to the timetabled service. For example, the failure records show that many insulator failures simply involve the insulator being flashed over such that the circuit trips, but can be re-set soon after and the insulator replaced out of service hours. Therefore, the failure cost of the droppers and insulators is not too large. Despite the relatively low occurrence of catenary wire failures, a failure of this component is more likely to result in a large disruption to service and therefore the cumulative failure cost for the catenary wire is large. The overall system failure cost and number of failures is discussed in detail in Section 5.3.6 where the overall system level outputs and total costs are presented.

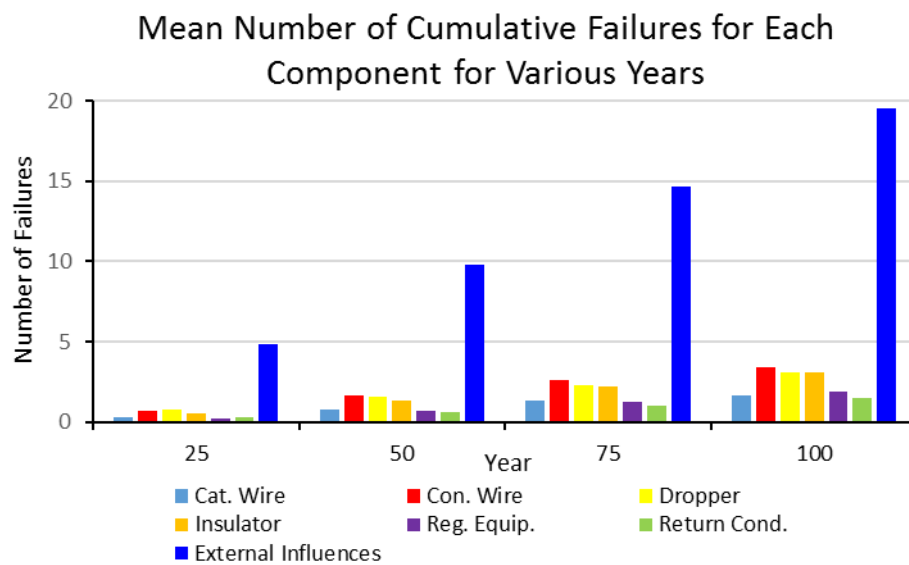


Figure 5-11 Mean Number of Cumulative Failures for Each Component for Various Years

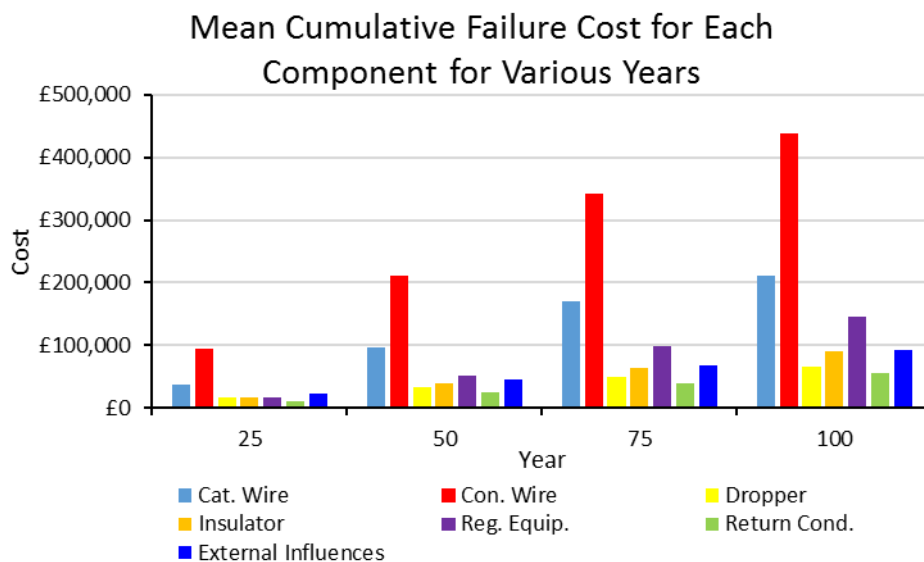


Figure 5-12 Mean Cumulative Failure Cost for Each Component for Various Years

5.3.5 Component Condition Related Outputs

Statistics related to the condition of the different components over the period analysed are also calculated. Network Rail expresses the overall condition of a component type over a wire run according to the number of degraded components (of the same type) that exist in that wire run. Predicting when a wire run is likely to contain a particularly high number of degraded components, for a given maintenance strategy, can be useful for asset managers. For instance, when the condition of a certain component type across a wire run is predicted to be intolerable, a renewal of the component type, or a change in the asset management strategy, can be proposed.

In the model developed, the time that a component type, in a particular wire run, spends in the different condition bands each year was recorded, where each condition band refers to a number of degraded components (of the same type) in the wire run. For instance, for the contact wire the first condition band, signifying a good condition, refers to 0 sections of the overall wire run of contact wire being degraded (e.g. being excessively worn) or containing a splice (that was put in to rectify previous degradation or failure of that section of the wire). The second condition band, signifying a satisfactory condition, refers to the wire having 1 or 2 degraded or spliced sections. The third condition band, signifying a poor condition, refers to the wire having 3 degraded or spliced sections. Finally, the fourth condition band, signifying a very poor condition, refers to the wire having 4 or more degraded or spliced sections. Note a section of the contact wire containing a splice is still considered degraded (even though the splice rectified the previous degradation or behaviour) because the wire is still not in a new condition and the presence of splices in the wire run can adversely affect the behaviour of the overall catenary system. The mean time spent in each condition band each year was then calculated.

Figure 5-13 shows the change in the condition of the contact wire in the first wire run of OLE in the access area studied. It is seen that as the contact wire ages, more sections become degraded or contain a splice. In year 70, the contact wire is renewed, resulting in no splices or degraded sections anywhere along its length. From these results, year 70 seems to be a suitable year for renewal because at this time there is approximately only a 20% chance of the wire containing no degraded sections and the probability of the wire being in a very poor condition, with 4 or more degraded conditions, is over 10% and will continue to increase.

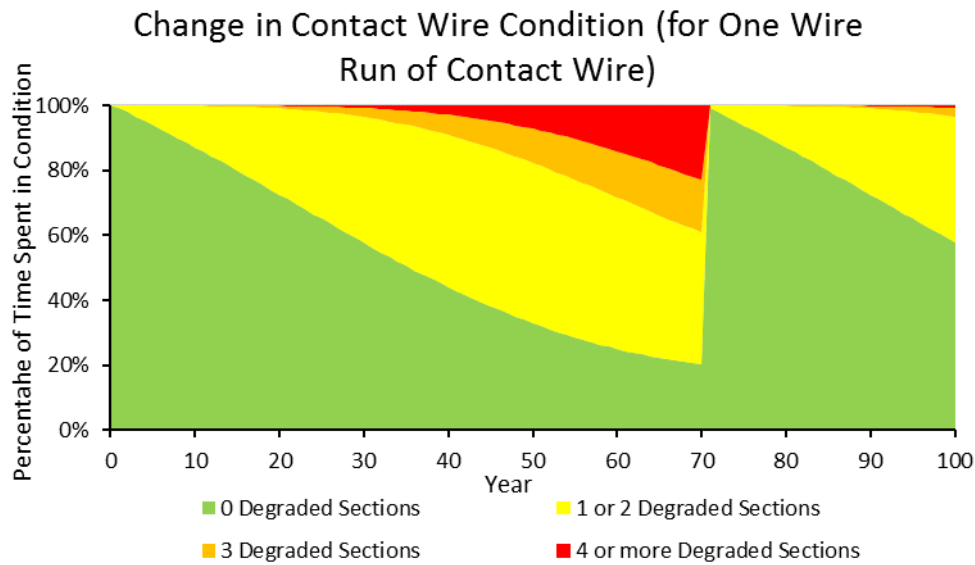


Figure 5-13 Change in Contact Wire Condition Over Time for One Wire Run of Contact Wire

In addition to the condition of the components, the mean age of the different components in the wire run can also be calculated. The mean age of different components, of a certain component type, can be used as a proxy for the condition of a component type in the area studied. Estimating the expected mean age of components in the future can also be useful when considering upgrades. Since the maintenance action considered for insulators is replacement, the mean age of insulators in the total area studied was calculated. Figure 5-14 shows the change in the mean age of insulators in the access area studied. At first the mean age increases linearly with the study time but then after approximately 20 years, as insulators are more likely to be maintained (and therefore replaced) the mean age increases disproportionately relative to the study time. After 100 years, the mean age of the insulators is approximately 58 years.

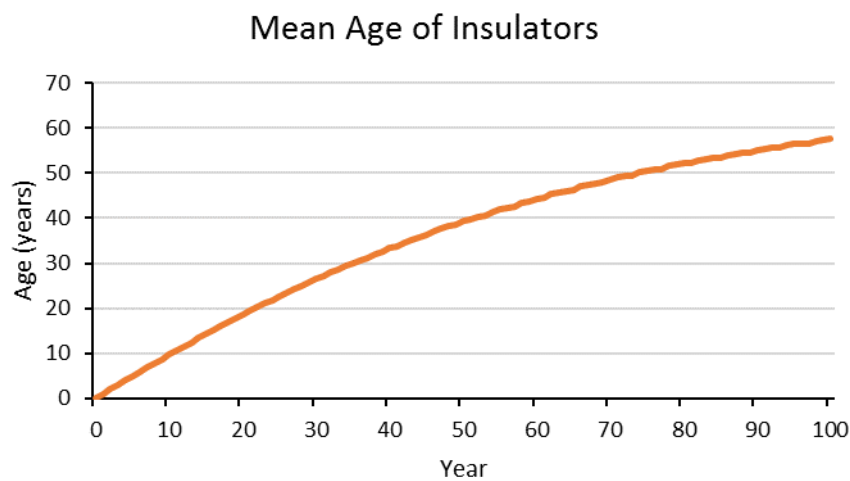


Figure 5-14 Mean Age of Insulators Over Time

Since the maintenance actions of the other components does not involve a replacement, the mean age of the components increases directly proportionally to the study time, meaning no calculation is required in the model. However, the mean time since the last maintenance of the component can be calculated for the different component types. For instance, the mean time since the registration equipment was last maintained can be calculated.

5.3.6 System Level Outputs and Life Cycle Cost Analysis

System level outputs are obtained to express the total maintenance cost, total failure cost, total number of failures and the overall total system cost over the 100-year period analysed for the access area studied. These outputs are very useful for life cycle cost analysis, as they give a simple overview of the overall performance of the system and the expected costs for a given maintenance strategy.

Yearly Total Maintenance and Failure Costs

The maintenance costs (including renewal and isolation costs) and failure costs are added together to obtain the overall total system cost. This combination is done in the model during each simulation to allow the full range of statistics (such as the median and interquartile range) to be calculated for the total maintenance cost, total failure cost and overall total system cost. It is beneficial for decision makers to understand how the expected costs are likely to vary over the system's life cycle. Different asset management strategies can be devised and tested in the model, to see what effect they have on the expected costs.

Figure 5-15 shows the mean total maintenance cost (excluding the large cost of renewing the catenary and contact wires after 70 years) and the mean total failure cost in each year. The total system yearly cost is also plotted on the line above. In each year the mean failure cost is significantly greater than the mean maintenance cost. This is due to the large costs incurred as a result of fines relating to the disruption to the timetabled service during a failure event. The yearly maintenance and failure costs increase with time, as the components age, resulting in their conditions becoming degraded, so they are more likely to be maintained or fail. In year 71 the renewal of the contact and catenary wires takes place (along with opportunistic maintenance), which improves the condition of the system, resulting in fewer failures and a lower failure cost in the following years. Note that the fluctuations in the failure cost are due to the occurrence of the high level intrusive inspection. During the years when a high level inspection takes place, the failure costs are lower because component defects are more likely to be identified and maintained before a failure occurs. During these years the maintenance cost also peaks, because the high level inspection and additional maintenance is undertaken.

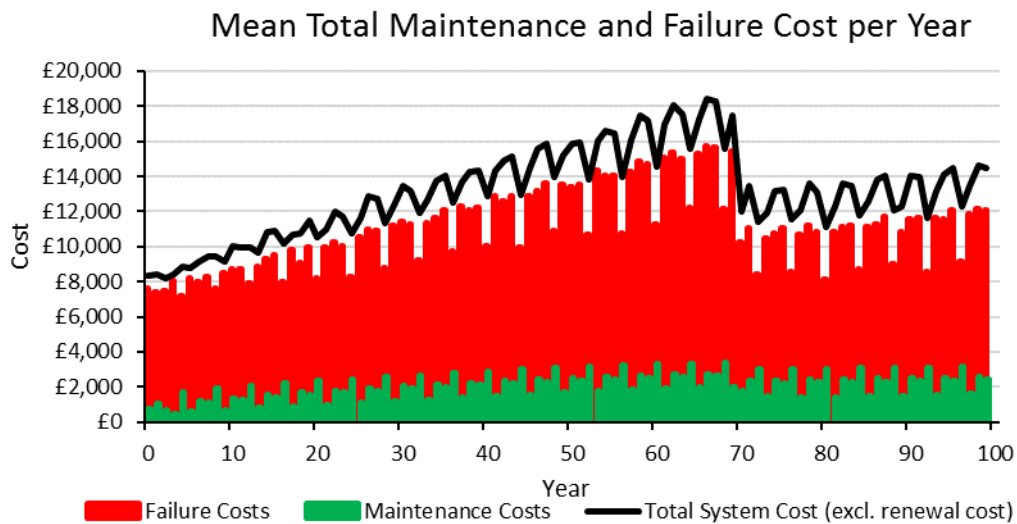


Figure 5-15 Mean Yearly Total Maintenance and Failure Costs

Yearly Number of System Failures

The total number of failures per year of the OLE system in the access area studied are recorded throughout the simulations so that the full range of statistics is obtained. The total number of failures per year is also split into 3 separate categories according to their failure cost, using similar cost categories to those specified by Network Rail. The different categories are defined as follows: major service affecting failures (failures costing more than £240k), moderate service affecting failures (failures costing between £40k and £240k) and minor service affecting failures (failures costing less than £40k). Note that these costs have all been multiplied by a factor. Predicting how the number of system failures will change over time and understanding the severity of these different failures, in terms of the costs incurred, can be useful for evaluating the expected performance of the system in terms of its reliability.

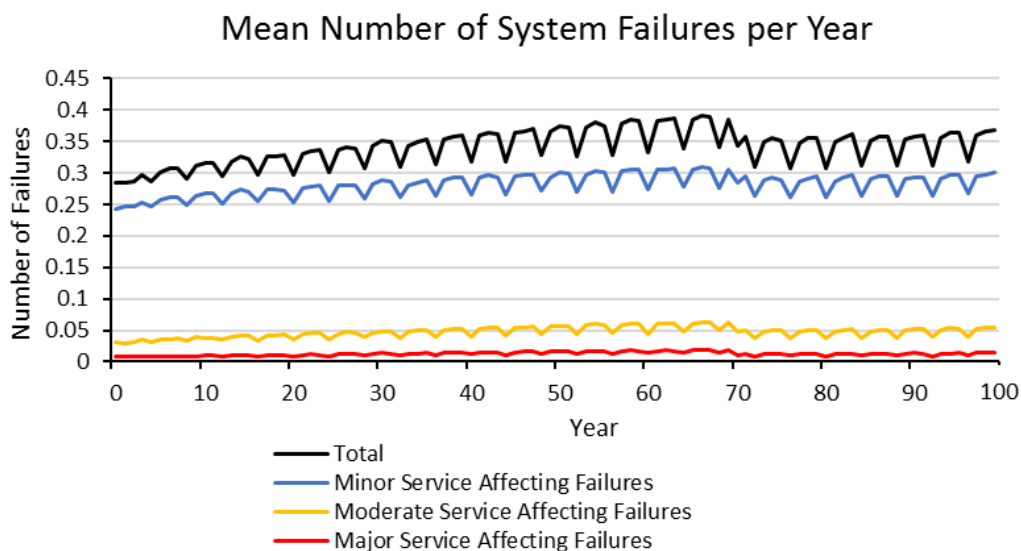


Figure 5-16 Mean Number of System Failures per Year

Figure 5-16 shows the mean total number of failures per year, split into the 3 categories according to the failure cost incurred. It can be seen that the vast majority of failures are minor service affecting failures. The number of major service affecting failures remains low and relatively constant across the entire period analysed. This is expected because these failures are generally very random and rare events. The total number of failures is seen to increase from approximately 0.28 failures per year initially, to 0.38 failures per year at year 70. After the renewal in year 71, the number of failures per year lowers to between 0.3 and 0.35 failure per year and increases only slightly until year 100. Note, as described previously, during the years where a high level intrusive inspection takes place at the start, the failure rate is lower because component defects are more likely to be revealed and maintained at the start of these years, thus lowering the number of failures.

Cumulative Total System Cost

The overall cumulative total system cost for a given year is comprised of the cumulative maintenance costs (including isolation and renewal costs) and cumulative failure costs. This is the main output that is studied during the life cycle cost analysis of a system. The full range of statistics, such as the mean, median and standard deviation of the cumulative cost, are calculated for each year over the 100-year period analysed. This section presents those statistics and gives a detailed overview of the results for the cumulative cost for 100 years, i.e. the total cost for the entire 100-year period analysed. Because 100 years is the typical timeframe that Network Rail considers during its whole life cost analysis, if the initial installation costs were added to the cumulative cost obtained in this study, then the overall whole life cost of the system can be calculated. Note that Network Rail commonly applies discounting to the future costs (as described earlier in section 3.2.5 in the literature review). The results obtained can easily be multiplied by the discounting rates if required. This section will now proceed to present the outputs associated with the cumulative total system cost.

Figure 5-17 shows various statistics describing the yearly cumulative total system cost, i.e. the total cost of the system up to and including a given year. The statistics express the expected overall cost of the system up to each of the years. The interquartile range gives an insight into the expected range of costs and shows the associated uncertainty. Due to the failure cost distributions (that the failure costs were calculated from) being predominantly lognormally distributed, in some simulations the failure costs incurred were very large which results in the mean total cost being positively skewed. As a result, the mean cost is greater than the median cost throughout the 100-year period. Note that the large increase in year 71 is due to the renewal of the catenary and contact wires.

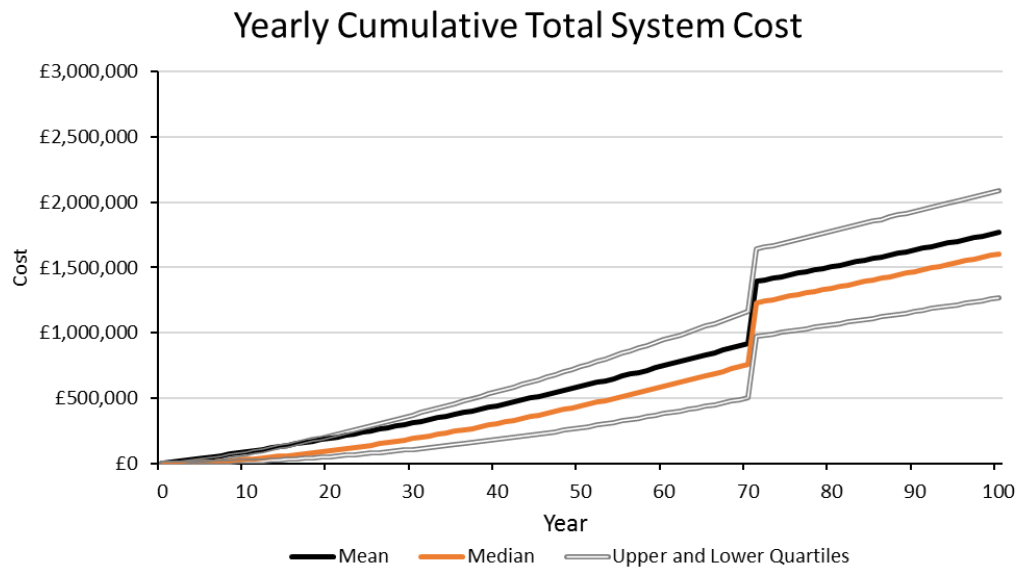


Figure 5-17 Yearly Cumulative Total System Cost

Table 5-3 lists the values obtained for the cumulative cost statistics for 100 years. Results for the total cost and the maintenance and failure costs (that constitute the total cost) are provided. Note how the standard deviation and interquartile range are the same for the total cost and the failure cost, because the corresponding values of these statistics for the maintenance cost is very low. This suggests the uncertainty of the total cost is predominantly due to uncertainty of the expected failure costs.

Table 5-3 Cumulative Cost Statistics for 100 Years

	Total Cost	Maintenance Cost (including renewals)	Failure Cost
Mean	£1.770 M	£0.670 M	£1.100 M
Median	£1.606 M	£0.670 M	£0.935 M
Maximum	£7.110 M	£0.715 M	£6.447 M
Minimum	£0.704 M	£0.628 M	£0.039 M
Standard Deviation	£0.689 M	£0.011 M	£0.689 M
Upper Quartile	£2.090 M	£0.678 M	£1.419 M
Lower Quartile	£1.271 M	£0.663 M	£0.600 M
Interquartile Range	£0.819 M	£0.014 M	£0.819 M

To make better informed asset management decisions, it is important that the complete range of results is understood so that the uncertainties are accounted for. Asset management decisions may be based on results such as the total system cost up to a certain year, whilst also accounting for their uncertainty. The cumulative maintenance cost, failure cost and total cost for each year for each simulation were recorded to allow histograms, which express the number of simulations that contain

costs within certain ranges, to be plotted. Examples of these histograms are shown below for the cumulative costs for 100 years.

Figure 5-18 shows the cumulative total maintenance cost of all the components in the access area over the 100-year period. The chart clearly shows that the total expected maintenance costs are normally distributed and the mean and standard deviation shown in Table 5-3 accurately describe the expected cost and uncertainty. Figure 5-19 shows the cumulative total failure cost of all the components in the access area over the 100-year period. Because the failure costs incurred for the different components are mainly lognormally distributed, the total failure cost is similarly distributed. There is a large range of costs for the simulations and a small probability of very large costs being incurred. Figure 5-19 shows that for approximately 55% of the simulations undertaken the total failure cost incurred was less than £1.05 million, which suggests that the total failure costs are more likely to be lower than the mean value of £1.1 million obtained. Figure 5-20 shows the histogram for the cumulative total cost over a 100-year period, which consists of both the maintenance costs and the failure costs. Since the failure costs make up the majority of the total costs, the spread of the total costs is a similar shape to that of the failure costs. There is a large range of costs and a 2% chance of the total cost being greater than £3.6 million, however approximately 50% of the simulations had a total cost between £1.05 million and £1.8 million. Producing such histograms allows the results for different asset management strategies or system specifications to be compared, taking into account the uncertainties of the outputs.

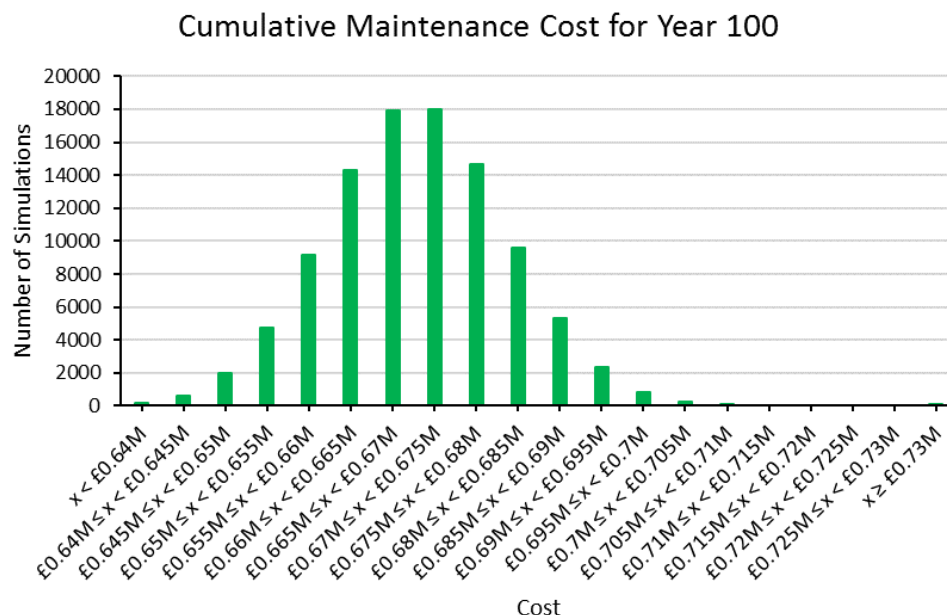


Figure 5-18 Cumulative Maintenance Cost for Year 100

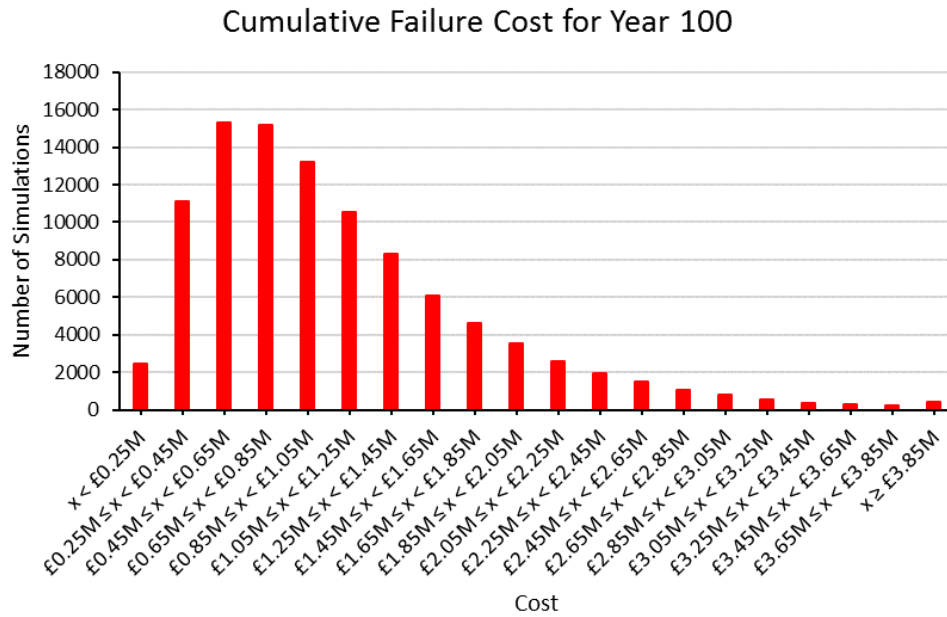


Figure 5-19 Cumulative Failure Cost for Year 100

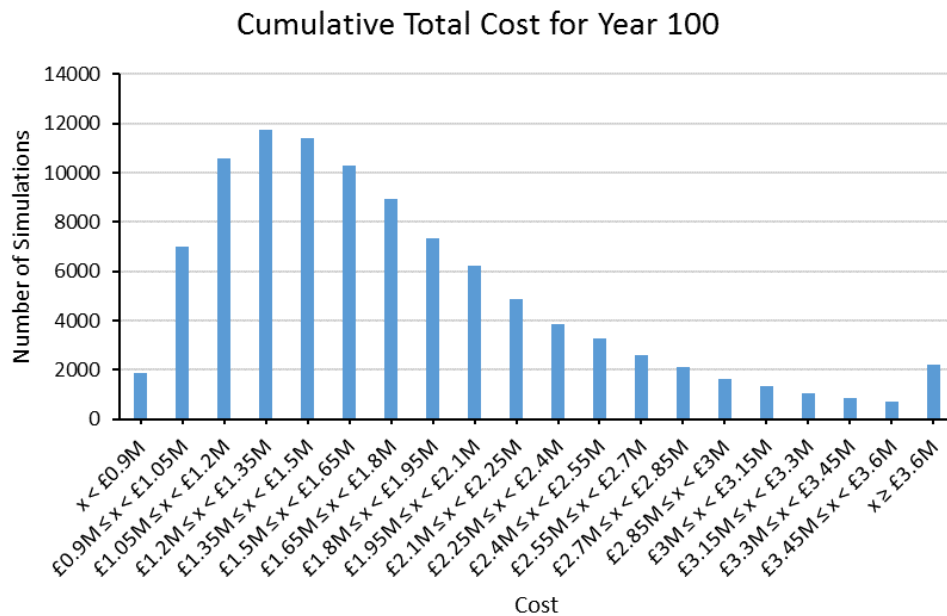


Figure 5-20 Cumulative Total Cost for Year 100

5.3.7 Sensitivity Analysis of Model Parameters

The parameters of the distributions for the times to reach component degradation and failure states can affect the model's outputs. Therefore, in this study, a simple sensitivity analysis has been undertaken to understand how a variation in the parameters of a distribution influences the outputs of the model. Particular focus can then be applied to the processes modelled by the distributions that were found to have the largest influence on the model's outputs. For instance, further data collection and data analysis can be undertaken for the component types and processes associated with the

distributions found to have the largest influence on the outputs. This will help to increase the certainty in the values for the distribution parameters and improve the accuracy of the outputs obtained.

A simple one-at-a-time sensitivity analysis has been undertaken, whereby one input parameter is varied by a fixed amount and the outputs of the model are obtained before returning this parameter to its baseline value and varying another parameter. This process is repeated for each parameter studied in the sensitivity analysis. Hamby (1994) reviewed the different techniques that can be used for parameter sensitivity analysis, and described the methodology of one-at-a-time sensitivity analysis. Other methods, such as factorial design can be used to consider different combinations of variations of the different parameters. Such methods would, therefore, allow the full uncertainty associated with each component type in the whole system model to be considered at the same time. However, since there are many processes considered in the Petri net model, such an approach would result in an excessive number of combinations of parameters to consider. Therefore, a one-at-a-time sensitivity analysis is used in this thesis.

The sensitivity analysis presented focuses on varying the parameters associated with the mean time to reach a degraded condition, for each component type, and the mean time to failure and mean failure cost of the contact wire. The failure of the contact wire was chosen for analysis because this component was found to have the largest number of failures and failure cost out of all the OLE components studied in detail, as described earlier in section 5.3.4. The outputs that are studied in the sensitivity analysis are the total system cost and the total number of failures over the 100-year period analysed. The total system cost is chosen because it is the main output used to evaluate the asset management and life cycle cost of the OLE. The total number of failures is chosen because it provides an insight into the reliability of the system. Note that other parameters and more outputs can be considered in the sensitivity analysis, but the main objective of this section is to show how a sensitivity analysis can be undertaken using the model that has been developed. Therefore, a more simple and concise analysis is undertaken.

Each parameter considered, such as the mean time to degradation, is varied by an increase and decrease of both 10% and 20%. For the distributions that are represented by a Weibull distribution, the shape parameter (β) is fixed to be constant, therefore, varying the mean time to degradation or failure by a given amount results in the characteristic life, i.e. the scale parameter (η) changing by an equal amount. For example, in the case of insulators, the baseline parameters for the Weibull distribution describing the times to degradation are $\beta=1.3$, $\eta=32850$ days, therefore a variation of -10% results in the scale parameter decreasing such that the updated parameters are $\beta=1.3$, $\eta=32850 \times 0.9$

= 29565 days. A maximum variation of 20% is considered because values greater than this will result in an unrealistic value for the mean time to degradation or failure.

Variation of Component Degradation Distribution Parameters

In this study the mean time to degradation was varied for each component by a fixed amount. In the model, this involved changing the parameters for the distributions describing the time to move from the good/working condition to the degraded condition for each component type.

Table 5-4 shows the mean total system cost for the change in mean time to degradation for each component type studied. Note that the baseline total cost, where all the parameters are at their default values described earlier in Table 5-3 for the example analysis, the mean total system cost over the 100-year period analysed was £1.77 million. A graphical comparison is used to clearly communicate the influence that a change in the mean time to degradation of the different components has on the outputs of the model. Figure 5-21 shows the percentage change of the mean total system cost, relative to the baseline value (£1.77 million), and Figure 5-22 shows the percentage change of the mean total number of system failures, relative to the baseline value (34.1 failures).

Table 5-4 Mean Total System Cost for Variations in the Mean Time to Degradation of Each Component Type

Component	Mean Total System Cost			
	Change in Mean Time to Degradation			
	-20%	-10%	10%	20%
Catenary Wire	£1.83M	£1.79M	£1.75M	£1.74M
Contact Wire	£1.81M	£1.79M	£1.76M	£1.75M
Droppers	£1.79M	£1.78M	£1.76M	£1.76M
Insulators	£1.81M	£1.79M	£1.75M	£1.74M
Registration Equipment	£1.81M	£1.79M	£1.75M	£1.74M
Return Conductor	£1.78M	£1.78M	£1.77M	£1.76M
Structures	£1.78M	£1.78M	£1.77M	£1.76M
Adjustments to Wire Run	£1.77M	£1.77M	£1.77M	£1.76M

For all the components, an increase in the mean time to degradation results in a decrease in the total cost and the total number of system failures (with the exception of structures, which are not modelled to fail, therefore, they do not change the number of failures). This trend is expected because slower component degradation means that the components are less likely to require maintenance, which has an associated cost. Additionally, slower degradation means the components are less likely to be in a degraded condition, where their failure rate increases. Therefore, the number of failures is also reduced, albeit by a small amount for many of the components.

A 20% decrease in the mean time to degradation of the catenary wire is seen to result in the largest increase in the total system cost ($\approx 3.3\%$). The corresponding increase in the number of system failures ($\approx 1.1\%$) is not as great. This is because the failure cost of the catenary wire is quite large, meaning that even a small increase in the number of catenary wire failures significantly increases the failure cost. This is similar for the contact wire, where a 20% decrease in the mean time to degradation does not influence the number of system failures significantly ($\approx 0.9\%$), but a more pronounced influence is shown for the total cost ($\approx 2.4\%$). In comparison, a decrease in the mean time to degradation of the insulators and droppers results in a larger number of system failures, but the influence on the total cost is less pronounced because the failure cost associated with these components is not as large.

The results also suggest that the increase in the outputs (the total system cost or number of system failures) relative to their baseline value, due to the decrease in the mean time to degradation, is greater than the corresponding decrease in the outputs, due to the increase in the mean time to degradation. This is because increasing the mean time to degradation will only decrease the failure rate to a certain extent, since failures can still occur when a component is in a good condition and is not degraded. The results suggest that the failure rate and failure cost of the components play a key role in the total cost, which is expected because the majority of the costs are due to component failures, as described earlier in Section 5.3.6. Variation of the contact wire failure rate and cost is described in the next part of this section.

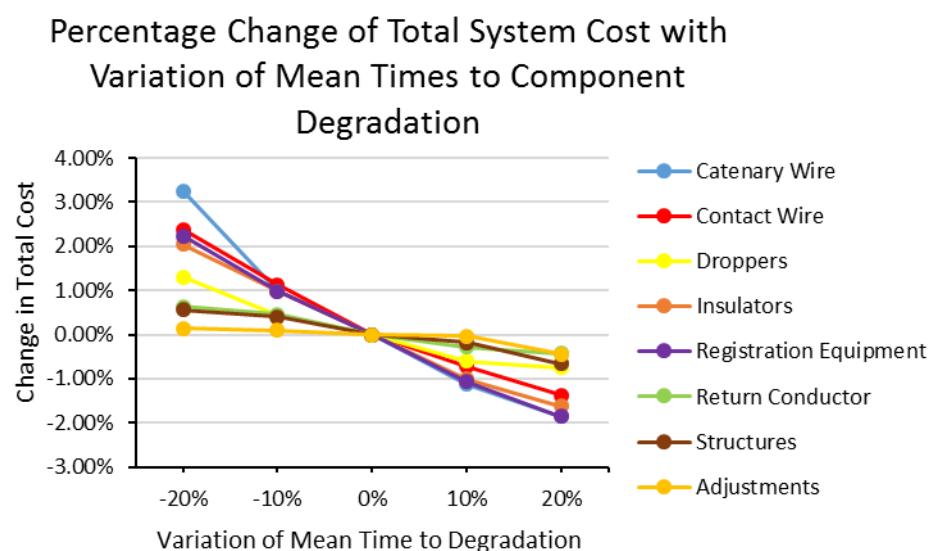


Figure 5-21 Percentage Change of Total System Cost with Variation of Mean Time to Component Degradation for Each Component

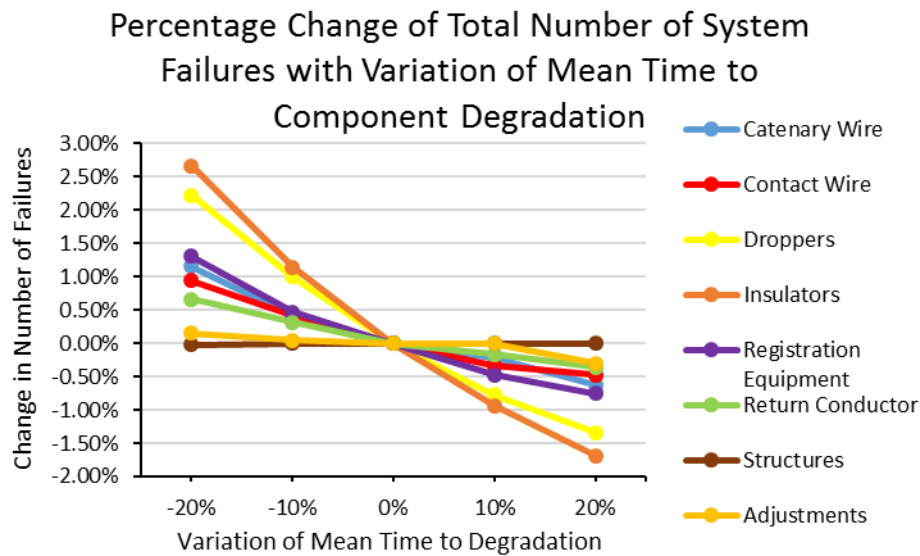


Figure 5-22 Percentage Change of Total Number of System Failures with Variation of Mean Time to Component Degradation for Each Component

Variation of Distribution Parameters Associated with the Failure of the Contact Wire

In this study, a sensitivity analysis of the parameters in the distributions associated with the failure rate and failure cost of the contact wire was undertaken. The mean time to failure from a good condition (which is predominantly due to random failures, such as a defective pantograph damaging the wire), the mean time to failure from a degraded condition, and the mean failure cost were varied by fixed amounts. Figure 5-23 shows the influence that the variation of the parameters studied has on the total system cost and Figure 5-24 shows their influence on the total number of system failures over the 100-year period analysed.

An increase in the mean time to failure, from a good condition or a degraded condition, results in a decrease in the total cost of the system. This is expected, as a reduced failure rate results in less failure costs. Interestingly, the percentage change in total cost is approximately twice as large as the percentage change in the total number of system failures, due to variation of the mean times to failure for the contact wire. This is attributable to how the contact wire's failure rate is relatively low compared to the system failure rate, because the number of failures caused by external influences is far greater than the number of failures by OLE components, as shown previously in Figure 5-11. However, the cost incurred due to the failure of the contact wire can be very large, therefore, an increase in the failure rate of the component results in a large increase in the total cost of the system. An increase in the mean failure cost results in an increase in the total cost, therefore, in Figure 5-23, the gradient of the mean failure cost series is positive whereas the gradients are negative for the series that represent the mean time to failure from good and degraded conditions. A decrease in the mean failure cost has a similar influence to percentage change of the total cost as an increase in the mean

time to failure from a good condition. Note that variation of the failure cost has no influence on the number of system failures, therefore, the gradient of this series is equal to zero in Figure 5-24. Any slight variations from a 0% change in the total number of failures with variation of the failure cost is due to the convergence of the number of failures not being quite identical for the different runs of the model.

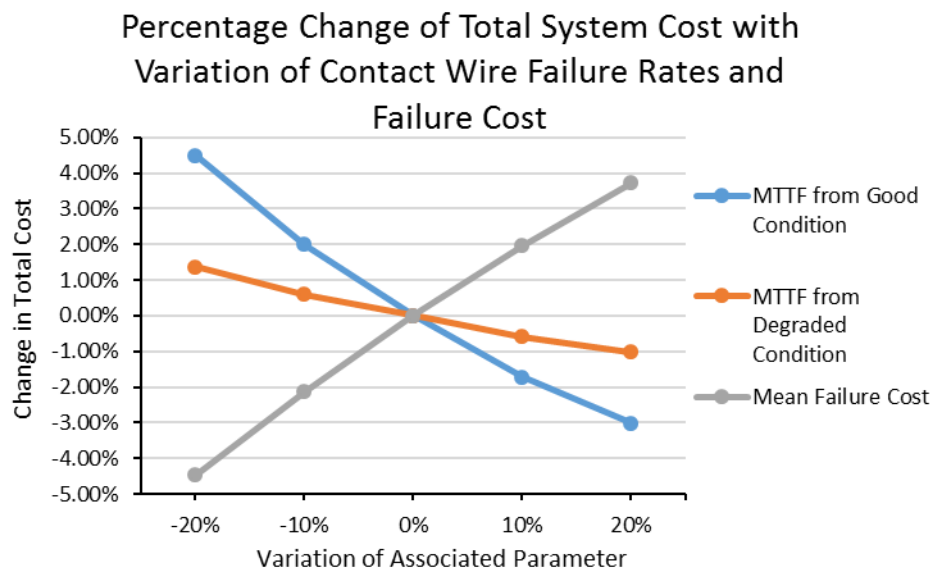


Figure 5-23 Percentage Change of Total System Cost with Variation of Contact Wire Failure Rates and Failure Cost

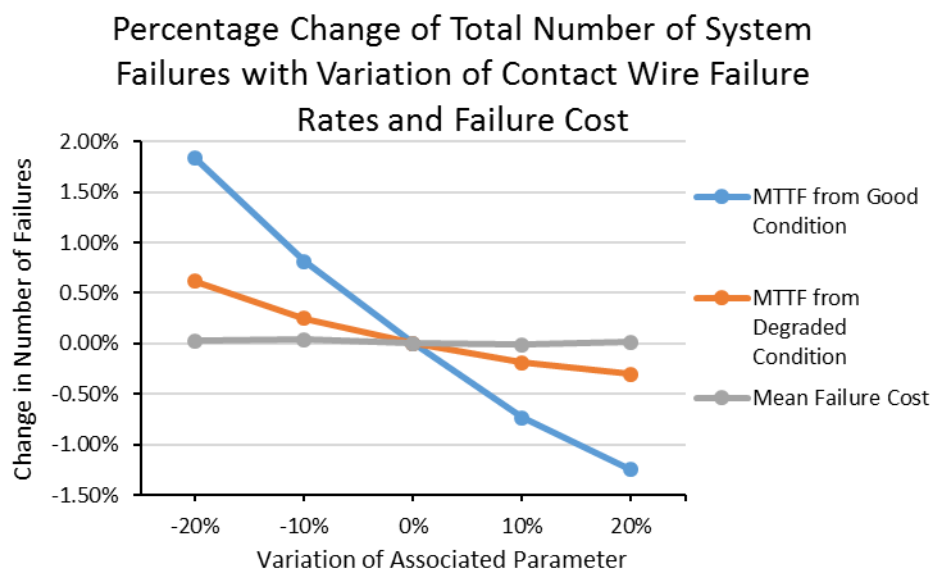


Figure 5-24 Percentage Change of Total Number of System Failures with Variation of Contact Wire Failure Rates and Failure Cost

In summary, this section has shown how a sensitivity analysis can be undertaken using the model. The results show that the parameters associated with the failure rate and failure cost of the components with large failure costs, such as the contact wire, have the greatest influence on the total system cost,

particularly the mean time to failure of the contact wire from a good condition. This suggests that attention should be applied to fully understanding the occurrence and cost of the different component failures, especially the occurrence of failures when the components are in a good condition.

5.4 Summary

This chapter has described how the model can be used by asset managers as a tool to evaluate the performance and life cycle cost of the OLE components. Additionally, a comparison between different asset management intervention strategies can be made through the analysis of the outputs obtained using the model. An example analysis, which studied all the OLE components in a single access area containing 2 wire runs, was presented. The numerous outputs that were obtained express the expected future performance of the components and the system as a whole, in terms of the number of maintenances and failures, and the expected costs associated with the maintenance and failures of the components and the system as whole over a 100-year period.

The model is capable of calculating the same outputs that Network Rail's current life cycle cost model calculates in order to evaluate the future expected costs of the OLE. Figure 5-25 shows a comparison between the outputs obtained by Network Rail's model and the model developed in this thesis for the mean number of failures per year for the catenary wire. The chart shows how the number of failures are similar for each model which suggests that the developed model calculates acceptable results. The small differences between the values for the different models can be explained by the way the models work and the processes that they consider. For example, the Network Rail model shows the number of failures per year as being constant and then increasing in steps after a certain number of years (where it is assumed the component condition will have deteriorated and the failure rate is increased). In comparison, the model developed in this thesis shows a more gradual increase in the number of failures with various fluctuations due to the inspection frequency (as discussed earlier in section 5.3.4). Therefore, for the section of OLE analysed, the model developed in this thesis calculates a more realistic change in the yearly number of failures for the catenary wire over the 100-year period analysed as there are no sudden step increases in the failure rate. Overall, the total number of catenary wire failures over the analysed 100-year period were similar for the different models with the Network Rail model predicting approximately 2.5% more catenary wire failures to occur.

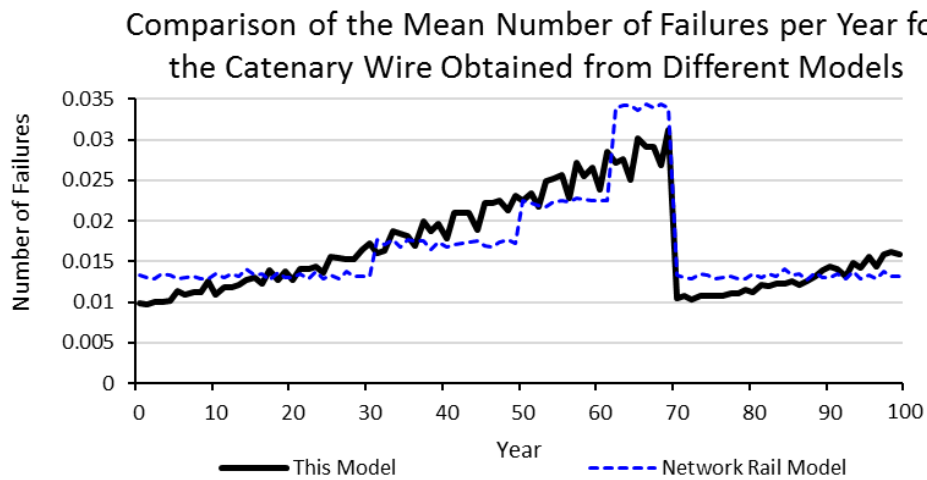


Figure 5-25 Comparison Between this Model and the Network Rail Model for the Results Showing the Mean Number of Catenary Wire Failures per Year

The model developed in this thesis also calculates additional outputs associated with the number of maintenance visits and the components' condition. A detailed range of statistics that help quantify the uncertainty associated with the system's behaviour are obtained, for example the maximum and minimum, standard deviation and interquartile range for the different outputs, at numerous granularities, are also calculated. This allows the evaluated life cycle cost and the asset management intervention strategies to be analysed in detail. An explanation of how the outputs obtained represent the different processes modelled was provided, in terms of the change in values over the life cycle of the system, e.g. the change in the number of failures per year for the different component types.

The large variety of outputs, at a number of levels of granularity, that this model is capable of calculating are more comprehensive and detailed than the outputs obtained in other asset management or life cycle models described in literature, particularly for OLE models. This thesis, therefore, contributes to the current literature in the subject area by providing a detailed description of the variety of statistics that can be calculated using asset management and life cycle cost analysis models. The outputs obtained also demonstrate the applicability of Petri nets as an appropriate method for modelling the asset management and life cycle cost of engineering systems.

A simple sensitivity analysis was undertaken, where the influence that the various input parameters of the model, associated with component degradation and failure processes, has on the total system cost and the number of failures over the 100-year period modelled was analysed. The parameters associated with the failure cost and failure rate of the components were found to have the largest influence on the outputs considered. This suggests that particular attention should be paid to finding accurate estimates for the parameters of the distributions describing the time to failure and the failure cost for the different components, in order to improve the accuracy of the model.

Chapter 6 Optimising OLE Asset Management Strategies

It is beneficial to asset managers and other decision makers to be able to find the most suitable values of the input variables, that the asset manager has control of, in the asset management model with respect to the desired objectives. In the case of the asset management of the OLE, Network Rail's primary objective is to ensure that the required outputs of the line (such as the line speed and capacity) can be achieved at the lowest whole life cost. In this study, an optimisation method is used in conjunction with the High Level Petri net model in order to find the optimum values for the input variables associated with the asset management of the OLE, for instance the inspection frequency and the maximum times that component maintenance must be completed by.

This chapter firstly provides a brief overview of different optimisation methods. The different objectives and variables associated with optimising OLE asset management strategies are then outlined, followed by a description of the application of the Genetic Algorithm, which is the optimisation method used in this study. Finally, the results that have been obtained are presented along with a discussion of their significance.

6.1 Overview of Optimisation Methods

Optimisation involves finding the inputs or characteristics of a process that maximise or minimise its outcome. For instance, a process could be described by a mathematical function and one could use an optimisation method to find the values for the input parameters that result in the minimum value of the function. Note that there may be multiple optimal solutions to a problem. The process to be optimised is commonly referred to as the objective function and its outcome is referred to as the fitness or cost (particularly if the optimisation is related to monetary costs). Optimisation problems can be multi-objective, where a number of objective functions, that may conflict, are optimised simultaneously. An example of a multi-objective optimisation problem could be to find the optimum inspection intervals for a component with respect to minimising the whole life cost and maximising the average condition of the component. In order to achieve improved average component conditions, more maintenance actions would have to be undertaken which would increase the whole life cost. Therefore, a set of optimum results are obtained which represent a trade-off between the two objectives: the whole life cost and average condition of the system.

There are many different optimisation methods that can be used to find the optimum solutions. This section proceeds to describe some of the main methods found in the literature and their applicability

for optimising the Petri net model. Further information about these methods can be obtained in Chong & Zak (2013), where a detailed introduction to the subject area is provided.

A simple optimisation method is to carry out an exhaustive search where the optimal solution is found by evaluating the objective function repeatedly for all the different possible input variables (Haupt and Haupt, 2004). The number of different combinations of inputs to consider, and therefore the number of times the objective function must be evaluated, can be considerable when there is a large, multi-dimensional search space, as described in Equation 6-1.

$$V = \prod_{i=1}^{N_{Var}} Q_i \quad \text{Equation 6-1}$$

Where V is the number of different input variable combinations, N_{Var} is the number of different input variables and Q_i is the number of different values that variable i can attain.

Whilst this method will find the optimum solutions in the search space, evaluating the objective function for complex processes many times can be extremely time consuming. This method is not practical for optimising the Petri net model that has been developed in this study, because the model itself takes over one minute to compute. Therefore, the search space does not need to be excessively large before the overall time to complete the optimisation becomes unfeasible.

Other optimisation methods aim to find the optimum solution without having to evaluate all the possibilities in the search area. For example, analytical methods involve finding the stationary points of the objective function by calculating the first derivative of the objective function and finding the values for the input variables, where the first derivative is equal to zero. The value of the second derivative will be positive if the stationary point refers to a minimum, or negative if it refers to a maximum. Since it is unknown whether the stationary points found refer to a local maximum or minimum, in order to find the best solution one must find all the different stationary points in the search area. Analytical methods can find the maximum and minimum efficiently but require the derivative of the objective function to be found, which can also be a time consuming process, or even impossible, for some problems. As a result, methods that require derivative information are not applicable for optimising the Petri net model and are not considered in this study.

Haupt and Haupt (2004) state that the largest group of optimisation methods are based on line search approaches. These methods use an iterative approach to minimise the objective function. If one wishes to maximise the objective function, then the output of the function is simply changed to be negative, to allow optimisation methods that minimise this modified function to return the solution for the maximum of the initial function. Line search methods generally work by varying the input

variables in a certain direction and by a certain amount and then evaluating the objective function. The next value the input variable will take is based on the previous evaluated value of the objective function. This is repeated for one of the input variables, until the minimum value of the objective function is found. This is done for each of the input variables sequentially and the entire process continues until the objective function is minimised. Some of these methods rely on only evaluating the objective function, such as the golden section method, whereas other approaches use root finding methods, such as Newton's method, which requires derivative information about the objective function, to make a more efficient decision on the direction and the amount to vary a variable. Line search methods can be susceptible to being stuck in a local minimum and the methods that do not use derivative information can take a long time to complete.

Global search algorithms are optimisation methods that involve exploring the entire search area and use only the values of the objective function (no derivatives are required). They are applicable to optimising the High Level Petri net model developed in this study and they are not as susceptible to becoming stuck in a local minimum as line search methods. The genetic algorithm (GA), developed by Holland (1975), is a global search algorithm that has proven to be useful for optimising Petri net models in previous research. For example, Le (2014) used a multi-objective GA in conjunction with a Petri net model to find the optimum asset management strategies for a railway bridge by seeking the strategies that provide the lowest whole life cost and the best average condition of the assets considered. In addition, a GA was used by Min et al. (2012) to find the optimum maintenance strategies for the OLE using a stochastic reliability model (as described earlier in the literature review in section 3.3.3.2). The optimisation involved choosing the different types of maintenance action to undertake during each fixed interval preventative maintenance visit. The maintenance actions considered were do nothing, repair or replace. A multi objective optimisation was used, where the total cost was minimised and the average reliability maximised over the period modelled.

The GA is based on the principles of genetics and natural selection, where a population, which consists of different candidate solutions for the possible combinations of input variables, evolves to become a fitter population containing better solutions. Each generation should evolve to contain fitter individuals until the population contains an individual (or multiple individuals) that represents the optimum solution. The GA does not require the derivative of the objective function and it can be used to optimise complex problems, containing many input variables that may be discrete or continuous. A set of optimum solutions can be found, which is a particularly useful feature for multi-objective optimisation. The GA can be implemented to run in parallel, thus allowing faster computation. It is also a very flexible method that can optimise many different types of problem. Due to the advantages listed above, the GA has been chosen to be used in conjunction with the High Level Petri net model.

The various inputs that asset managers or decision makers have control of, such as the component maintenance times, can be optimised with respect to their desired objectives, primarily reducing the whole life cost of the system. A more detailed description of how the GA is used in this study is given in section 6.3.

6.2 Optimisation of OLE Asset Management

In the case of optimising the asset management strategy of the OLE, in order to obtain a suitable set of input variables that are optimised, one must consider the different processes that asset managers can influence to improve the performance of the system. Additionally, appropriate indicators that can be used to measure the performance of the system must be selected to represent the objective functions that are maximised or minimised as part of the optimisation procedure. The High Level Petri net model that has been developed can be used to calculate the value of the objective functions that express an aspect of the performance of the system, such as the system's total cost over the period analysed. The Petri net can therefore be used as a function, which calculates the value of the objective functions based on the given input variables, in conjunction with the optimisation method, in order to find the optimum set of values for the input variables.

The main input variables, which can be chosen during the optimisation, and the performance measures for the system, which can be used as the objective functions that are maximised or minimised, are listed below:

Inputs:

- **Asset Management Intervention Strategies** (such as inspection intervals and maintenance scheduling times). This can influence the components' condition and failure rates, as well as their maintenance requirements.
- **Line Usage**. This can influence maintenance opportunities and the cost of service disruptions, as well as the components' degradation and failure rates.
- **OLE Type**. This influences the components' degradation and failure rates, as well as their maintainability.

Performance Measures (Objective Functions):

- **Component Condition**
- **Cost** (e.g. the total cost of the system or a component type over the period analysed)
- **Number of Failures** (for the system or a component type)
- **Number of Maintenance Visits Required** (for the system or a component type)

The asset management intervention strategies consist of different decisions for the different intervention actions that can be undertaken. In this study, the main intervention actions that are modelled are inspections, component maintenance actions and large scale renewals. Therefore, optimising the asset management intervention strategies will involve specifying the values associated with the timing of the inspection intervals, the timing of the renewal of the contact and catenary wires and the maximum times that maintenance must be completed by, for the various OLE component types that are studied. Note, each OLE component type is modelled to only have one maintenance action that repairs the component when it is found to be degraded, therefore, other maintenance actions cannot be specified.

Generally, railway asset managers do not have the authority to decide the usage of the line, other than in the very short term, i.e. after a failure the line may be shut temporarily or speed restrictions put in place. Therefore, the line usage is not considered in the optimisation. Whilst asset managers have some control over the different component types to install on the line, decisions are usually made prior to the line being electrified and the design used is based on the line's characteristics (mainly its speed and usage). The types of components installed on the line would not change significantly over the system's life cycle, unless design flaws are found for certain components and upgrades are scheduled to improve the performance of the system, as part of the asset management strategy.

From an asset management perspective, as discussed earlier, an interesting problem to consider is how asset managers can reduce the system's whole life cost, whilst ensuring that the line speed and timetabled service demands are met. This means the reliability of the system must be at an acceptable level throughout its entire life cycle. As a result, in this study, the primary measure of the system's performance is the total cost of the system over the period analysed. It would be possible to maximise the average condition of the components over the system's life cycle, but doing this would require frequent maintenance of the components. This would likely result in over maintaining components that are perfectly operable and the additional maintenance would result in increased cost. Furthermore, the performance of the system (in terms of reliability) may not improve significantly as a result. Since poor system reliability results in more failures of the system and the costs incurred due to failure are often large relative to maintenance costs, using the whole life cost as an objective function to be minimised should also result in the number of system failures being minimised (or not being excessive). However, applying different asset management strategies to an access area will result in a different number of maintenance visits needed to perform maintenance on the components. A given maintenance depot may not have sufficient resources, such as staff or road rail vehicles, to visit a single access area more than a certain number of times (due to the large length of railway line

they are responsible for). The total number of maintenance visits to an access area is therefore also used as an objective function to be minimised.

In summary, the input variables chosen in this study are related to the inspection frequency, the timing of the contact and catenary wire renewal and the maximum time that maintenance must be completed by for the various components. Further details of how the values of these variables are varied for optimisation is described in the following section. The system's total cost (over the 100-year period analysed) and the total number of maintenance visits are chosen as the objective functions, thus making the optimisation procedure multi-objective.

The set of solutions obtained from such an optimisation will provide a set of asset management strategies that offers the lowest total cost of the system for different numbers of maintenance visits to the access area that is studied. Decision makers can then choose the most appropriate strategy from the set of optimum strategies by considering their available resources (in terms of the number of maintenance visits that can be scheduled). The optimum solutions can also be studied in more detail by analysing the full range of statistics collected by the High Level Petri net for these solutions to allow a more detailed comparison to take place.

Individual optimisation studies can be carried out on separate component types or for separate intervention actions, e.g. only optimising the inspection interval over the system's life cycle in one study where the other intervention actions are fixed, according to Network Rail standards. This allows a detailed analysis of the best decisions for the different component types or the different intervention actions to be carried out, without any influence from other components or other intervention actions. In this study, a holistic approach, where all the intervention actions for the whole system are considered within the optimisation problem, has been undertaken to find the best overall asset management strategy.

The discounting of future costs is not considered in this optimisation as the years that the discount rates change can have a large influence on the timing of events, such as when to undertake a renewal. Therefore, it is not recommended to discount future costs when undertaking an optimisation (British Treasury, 2003).

A description of the different strategies that can be implemented for the intervention actions considered and how they can be optimised is given in the next section.

6.2.1 Optimising High Level Inspection Frequency

Recall that during a high level intrusive inspection, the condition of the components is inspected and any maintenance work that is required (or previously scheduled) is undertaken, if time allows. As a result, after a high level inspection the system should be in a better condition, which means that the probability of a failure occurring is reduced. The inspection interval for the other inspection regimes, such as the low level walking inspection or cab patrol, are not considered in the optimisation, since these regimes are relatively inexpensive and are currently undertaken frequently, without putting a strain on the available resources (because isolation of the line and the use of the road rail vehicle are not required).

As the components in the system degrade, the probability of a defect arising increases, hence high level inspections should be undertaken more regularly to identify and rectify any component defects. In this study, it is proposed that the inspection interval for the high level intrusive inspection can be optimised through varying the inspection frequency over the life cycle of the system. This is done by splitting the 100-year period considered into periods of 10 years and then seeking the optimum inspection frequency in each of these 10-year periods. Periods of 10 years are considered because over this time span the typical yearly maintenance requirements and failure rate of the components will be similar. After 10 years, the components will have degraded to an extent that will change the maintenance requirements of the system. Additionally, Network Rail often specifies its key organisation aims and objectives in planned control periods which are 5 years in length, therefore, a 10-year period that the inspection frequency is varied can neatly coincide with 2 control periods.

Considering different inspection intervals that can change over the system's life cycle is a radical change to the current regime implemented. The optimal results obtained will make an interesting comparison to the current regime implemented by Network Rail (which were used in the model for the results shown in Chapter 5). To limit the search area, and make the results more appropriate or plausible, the range of possible inspection intervals is determined by a set of discrete values. The different values considered for the inspection intervals are: 1 year, 1.5 years, 2 years, 2.5 years, 3 years, 4 years and 5 years. If discrete values were not used, and instead the inspection interval could be anything between 0 and 5 years, then the set of optimum values obtained might be inappropriate (e.g. 237 days), which is not practical for specifying an inspection regime. Furthermore, through limiting the search area, the optimisation process will be faster. Note that 5 years is the maximum inspection interval considered in this study, because 4 years is the current interval used by Network Rail (for high category lines), therefore, the maximum interval should not excessively exceed this.

6.2.2 Optimising Component Maintenance Scheduling Times

The optimisation of maintenance focuses on specifying the maximum times that maintenance must be completed by for a component type. For simplicity, the maximum time that maintenance must be completed by is referred to as the maintenance scheduling time. In this study, the maintenance scheduling times for components that are in a degraded condition are optimised. The maintenance scheduling times when a component is in the severely degraded condition are not changed, since this maintenance is normally undertaken relatively urgently, e.g. within 7 days for an insulator. The maintenance scheduling times, for maintenance from the degraded condition, are considered for all the component types, apart from structures, because these components are dealt with separately (by the civil engineering team) and their maintenance is not grouped to occur at the same time as the other OLE components.

The different times considered are the following discrete values: 7 days, 14 days, 28 days, 90 days, 180 days, 365 days, 550 days, 730 days, 1095 days and 1460 days. These values were chosen to represent similar times that Network Rail currently schedules maintenance by for the various components. Note that the decision not to perform maintenance on a component when it is found in a degraded state, and instead wait to maintain it once it enters the severely degraded state, can also be considered. Also, note that the opportunistic maintenance is still assumed to occur for the different components in the access area. However, if the maximum maintenance time for a component type is only seven days, then there is less chance of it being opportunistically maintained with the other components.

6.2.3 Optimising the Timing of the Renewal of Catenary and Contact Wires

Additionally, the timing of the renewal of the contact and catenary wires is optimised by selecting the best year to carry out this work. The years to consider are every year from year 50 to year 99. 50 years is chosen as the starting interval because, under normal operating circumstances, they would not be renewed before 50 years. 99 years is chosen as the final interval in order to force the renewal of the components to take place during the 100-year period analysed. Furthermore, it is unlikely that Network Rail would allow the components to age to that extent.

6.3 Optimisation Procedure

As described earlier, the High Level Petri net model is used as a function to evaluate the two objective functions, i.e. the total cost and the number of maintenance visits, which are minimised. The same access area of OLE that was studied in the example study shown previously in section 5.3 is used for

optimisation. The GA chooses the input variables (which refer to different asset management intervention strategies) for each candidate solution and calculates the fitness of each solution based on the values of the objective functions (calculated using the Petri net model).

The different intervention actions are dependent on each other, i.e. changes to one intervention action can directly influence the suitability of other interventions actions. For instance, if the high level intrusive inspections are performed less frequently, then the components may not be maintained as often (due to less opportunistic maintenance occurring during the high level inspection). Therefore, the number of component failures may increase (due to an increased number of failures of degraded components that require maintenance) unless the component maintenance times are also adjusted. Similarly, if the inspection frequency is to be varied over the life cycle of the system, if the year that the catenary and contact wires are renewed is changed, then the inspection frequency will also have to change for the years following the renewal because the system's overall condition will have improved, which will alter its maintenance requirements.

Since the different intervention actions are dependent on each other, in this study all the intervention actions that are applicable for optimisation are considered in the same optimisation procedure. However, if only a minor change is desired, for instance if the asset manager wishes to keep the frequency of the high level inspections the same as the current standards state, then only certain intervention actions (e.g. the component maintenance times) can be considered in the optimisation.

In this section, an overview of the terminology associated with the GA and a description of the different stages of the algorithm is given. The implementation of the GA in this research, along with its use in conjunction with the Petri net model, is then described in detail. The GA implemented in this study is based on the NGSA-II GA described by Deb et. al (2002), which has been widely cited as an effective GA method that can be applied to a wide-range of problems.

6.3.1 Genetic Algorithm Description

6.3.1.1 Genetic Algorithm Terminology

Terminology synonymous with genetics and natural selection is used to describe some of the main features in the GA, since it is based on the process of evolution. A '*chromosome*' refers to a set of input variables that the objective function takes. Each of these different variables can be referred to as a '*gene*', which can take different values, expressed as '*alleles*' for the different genes. The different input variables are encoded to create a chromosome. This process is sometimes carried out using a binary string to represent a chromosome, from which the different values for the input variables can be decoded. Similarly, the chromosome can be represented by an array containing the values of the

different input variables. The output value of the objective function is referred to as the '*fitness*'. A single candidate solution is referred to as an '*individual*' and a group of individuals (i.e. a series of different possible solutions) is referred to as the '*population*'. Each individual contains a chromosome and a fitness value which is found by evaluating the objective function using the input variables listed in the individual's chromosome. All these terms are used in the following description of the GA method.

6.3.1.2 Genetic Algorithm Method

As shown in Figure 6-1, the first stage of the GA involves defining the objective function and the different input and output variables. Like other optimisation methods, the GA is commonly implemented to minimise the objective function. For maximisation problems, the output of the objective function can be made to be negative and then the normal GA procedure is followed. An initial population is created; this consists of a number of individuals, each with chromosomes that are encoded with values for the input variables. The initial population can be generated purely randomly or contain individuals with a chromosome encoded with best estimates for the input variables.

Next, for each individual in a population, the chromosome is decoded to obtain the different input variables for the objective function. Then, the fitness value for each individual is calculated by evaluating the objective function for the corresponding input variables. Note, for multi-objective optimisation there are numerous objective functions and fitness values.

The selection process takes place once the fitness value has been obtained for each member of the current population. This process intends to mimic natural selection, whereby the '*fittest*' individuals, providing the best current solutions for the problem, have a greater chance of being chosen to mate and pass on their genes to future generations. Individuals are selected from the population to mate (as part of the crossover process) and the offspring created represent the individuals in the next generation. In most GAs each generation has the same size population.

After the selection process has found all the individuals to be paired for mating, the crossover process takes place. This process aims to mimic the mating procedure, where individuals mate to produce offspring that shares their traits. The offspring produced inherit a combination of the genes from both their parents and represent new candidate solutions for the problem.

For each individual in the next generation, the variables that constitute their chromosome are subject to the possibility of mutation. The chance of a mutation occurring is based on a small probability, determined by the mutation rate. When the mutation of a variable occurs, its value will change to another random value. This process is intended to mimic how a gene can be mutated and it is used to

increase the search area, which can be very useful in preventing the algorithm from converging to a local minimum.

After the mutation process, the new population of individuals for the next generation is ready to be evaluated and the GA process is repeated from the stage where the variables are decoded from the individuals' chromosomes. This entire process is then repeated to model how continual generations live and procreate, and the overall fitness of the population should increase. Just after a new population has been created, i.e. after the mutation stage, a convergence check of the previous population can be made. There are numerous ways of checking for convergence, for example the GA should have converged when each individual's fitness is a similar value and the mean fitness of the population, or the fitness of the best individual solution, has not changed for several generations. Similarly, the GA can be chosen to run for a fixed number of generations and then the different generations of populations can be compared afterwards to check for convergence, as demonstrated in this study. Figure 6-1 depicts the overall GA process.

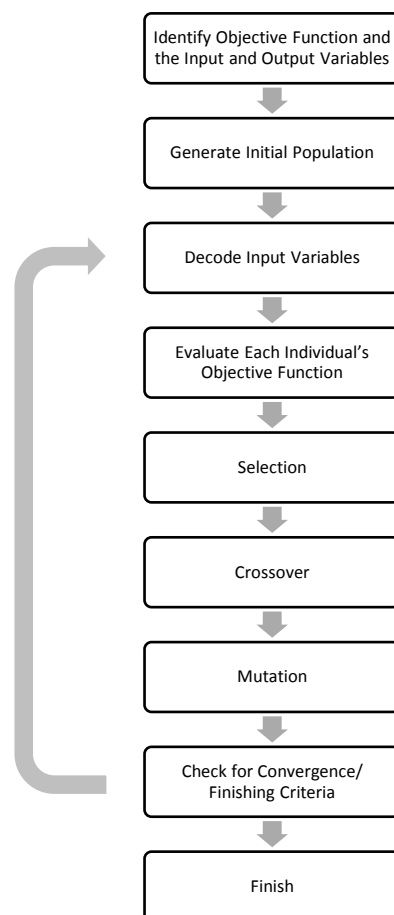


Figure 6-1 Overview of the Genetic Algorithm Process

The GA implemented in this thesis was coded in C++ to closely resemble the NSGA-II algorithm described by Deb et. al (2002). The code was verified by outputting the information for each individual

in the current population, for each generation studied, and ensuring that the right individuals were present and checking that the genes were altered correctly according to the selection, crossover and mutation processes. To validate that the code can produce correct results, a simple mathematical function, involving the sum of input parameters, was minimised using the GA code to ensure it found the correct solution. Repeatability of the optimisation procedure undertaken using the model was tested using different initial populations and population sizes and the results obtained were similar.

6.3.2 Application of the Genetic Algorithm in Conjunction with the Petri Net Model

In this study, the high level intrusive inspection frequencies, timing of the renewal of the contact and catenary wires and the maintenance scheduling times for the different components are optimised at the same time. The optimum values are found with respect to minimising both the total cost and the number of maintenance visits. A detailed description of how the GA procedure was implemented now follows.

6.3.2.1 Objective Functions and Input Variables

The objective functions considered are the total cost and number of maintenance visits for the 100-year period studied. The Petri net model developed is used to calculate the values of the objective functions by running the model, using the asset management strategies described by the set of input variables that constitute an individual's chromosome, until the total cost and the number of maintenance visits have converged. The values of the two objective functions refer to the fitness values for a candidate solution.

The input variables, which represent the different genes that make up an individual's chromosome, are the frequency of the high level intrusive inspections, the timing of the renewal of the catenary and contact wires and the maintenance scheduling times for the different components, that refer to the maximum times that maintenance must be completed by for the different OLE component types when they are found to be in a degraded condition. A different input variable exists for each intervention action that is optimised and the value of the variable describes the strategy associated with the intervention action that refers to a time (such as the inspection frequency or maintenance time for a component). The set of values, which the different input variables (or genes) can have, are listed in Table 6-1.

The high level inspection frequency is to be varied over 10, 10-year periods that constitute the 100-year period of the system that is modelled. Therefore, each individual's chromosome contains 10

genes that refer to the inspection frequency in one of the 10-year periods. A set of discrete values for the inspection frequencies are considered, these values are listed in the first row of Table 6-1.

An individual's chromosome also contains a gene that refers to the timing of the renewal of the catenary and contact wires. Additionally, the chromosome also contains 7 genes that refer to the maintenance times of the catenary wire, contact wire, droppers, insulators, registration equipment, adjustments to a wire run and the return conductor. The set of discrete values for the input variables (or genes) that represent the strategy for each intervention action are also listed in Table 6-1. Note, that for the catenary wire, insulators and return conductor, a maintenance scheduling time of 36500 days is included to consider the option where maintenance is chosen to occur only when the component is in a severely degraded condition. Because 36500 days is equal to 100 years, in the 100-year period modelled the maintenance would never occur. For the other components a severely degraded condition is not modelled, therefore, maintenance must occur from the degraded condition.

Table 6-1 Different Sets of Values Considered for Each Intervention Action Optimised

Intervention Action Optimised	Set of Values (units in days)	Position in Chromosome
Inspection Frequencies for the 10, 10-Year Periods	365, 550, 730, 913, 1095, 1460, 1825	0 to 9
Renewal of the Contact and Catenary Wires	50, 51, ... 99 years (converted to days in the model)	10
Catenary Wire Maintenance Time	7, 14, 28, 180, 365, 550, 730, 1095, 1460, 36500	11
Contact Wire Maintenance Time	7, 14, 28, 180, 365, 550, 730, 1095, 1460	12
Dropper Maintenance Time	7, 14, 28, 180, 365, 550, 730, 1095, 1460	13
Insulator Maintenance Time	7, 14, 28, 180, 365, 550, 730, 1095, 1460, 36500	14
Registration Equipment Maintenance Time	7, 14, 28, 180, 365, 550, 730, 1095, 1460	15
Return Conductor Maintenance Time	7, 14, 28, 180, 365, 550, 730, 1095, 1460, 36500	16
Adjustment of Components in Wire Run Maintenance Time	7, 14, 28, 180, 365, 550, 730, 1095, 1460	17

6.3.2.2 Variable Encoding

The different input variables are combined to create a vector that represents an individual's chromosome. In this study, each individual's chromosome contains 18 genes (ten referring to the inspection interval frequencies, one referring to the renewal frequency and seven referring to the component maintenance times). The vector of input variables, that represents an individual's chromosome, is an input parameter to the Petri net and the relevant transitions obtain their firing

times based on these input variables. An individual's chromosome therefore refers to the overall asset management strategy that is evaluated, when the model is run for a candidate solution. Figure 6-2 shows an example vector of the input variables (i.e. a chromosome). The position of each variable in this vector, which is the same as the ordering in the individual's chromosome, determines the gene it represents. The intervention action represented by each gene and its corresponding position in an individual's chromosome were listed previously in Table 6-1. For example, element 12 in the vector has a value of 180 days and refers to the maintenance scheduling time for the contact wire.

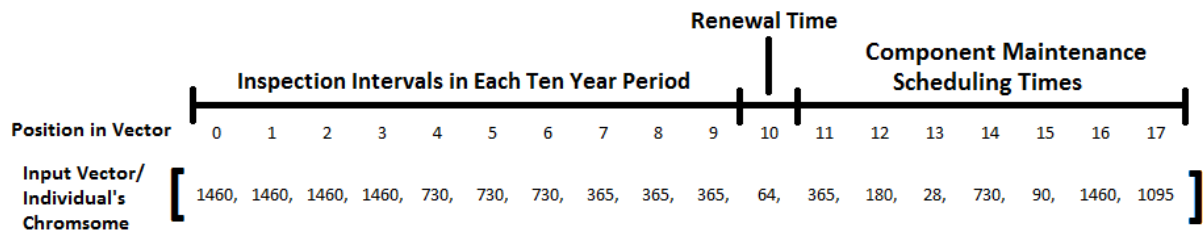


Figure 6-2 Example of Input Vector or Values of an Individual's Chromosome

6.3.2.3 Initial Population and Decoding of Input Variables

An initial population of individuals is created. Each individual represents a candidate solution and contains a set of required input variables (genes), which constitute its chromosome. The objective functions are evaluated for each individual (which is done using the Petri net model) in order to determine their fitness values. A population size of 100 was used and the initial population was created by randomly generating the input variables that constitute each individual's chromosome (where the range of values that the variables can assume is fixed and was listed in Table 6-1). A population size of 100 was used because large populations result in running the model an excessive number of times but too small a population can result in less variance in the current genes contained within the individuals. A population size between 100 to 200 has been shown to be effective in other studies (Min et al., 2012), (Deb et al., 2002).

As mentioned earlier, each individual's chromosome is passed into the Petri net model as a vector of input variables. The Petri net model represents a function that has an individual's chromosome as an input parameter and from this it calculates the fitness values (the total cost and the number of maintenance visits over the 100-year period studied). This Petri net model function first decodes the input variables in the chromosome and assigns the associated transitions with their firing times based on these input variables.

As shown previously in Figure 6-2, the first 10 variables in an individual's chromosome represent the inspection frequencies for 10, 10-year periods in the 100-year period modelled. In the Petri net model,

when an individual is evaluated, the input variables are decoded and the future dates of each inspection are calculated before the model is evaluated. The transitions that fire when the high level inspection is scheduled to occur obtain their firing time by considering the current time and calculating when the next high level inspection is scheduled to take place. Note that where the inspection interval changes for different 10-year periods, e.g. after the first 10-year period, unless the previous inspection scheduled finished at exactly 10 years, then the first inspection date in the next period (e.g. 10 to 20 years) will be equal to the date of the last inspection plus the previous period's inspection interval. For instance, if the inspection interval for the period 0 to 10 years was 3 years, there would be an inspection scheduled in year 3, year 6, year 9 and then year 12. Afterwards, the inspection interval for the period 10 to 20 years is applied, which could be every 2 years, meaning an inspection would be scheduled in year 14, year 16, year 18 and year 20.

For the variables that refer to maintenance scheduling times, each variable is assigned as the firing time for the transition that represents the corresponding maintenance action. For example, for the maintenance of the catenary wire (from a degraded state) transition T4 (shown earlier in Figure 4-10 on page 133) is assigned the firing time from element number 11 in the vector of input variables. For the renewal time, since the input variables gives the time in years, the value is multiplied by 365 to give the time in days. This time is then assigned to transition T49 (shown earlier in Figure 4-11 on page 137), which is a transition in the large scale renewals subnet that schedules the renewal of the catenary and contact wires.

The Petri net model is run for each individual to evaluate the objective functions and obtain the fitness values. Since each individual's solution is independent of the other individuals in the population, each individual was evaluated in parallel (at the same time) to reduce the run time.

6.3.2.4 Selection

After evaluating each individual in the current population, the selection process takes place. The selection process involves choosing different individuals to become parents that are paired for mating. The algorithm aims to select the individuals that represent the best solutions, i.e. the fittest individuals, with a higher probability, thus replicating the survival of the fittest phenomenon. To do this, the individuals in the population are ranked based on the values of the objective functions, i.e. their fitness values. For a single objective GA this is simple, however, in a multi-objective GA, the ranking process is more complicated since the objective functions may conflict.

This research also uses elitism, which involves ensuring that the 'fittest' 50 individuals (i.e. the individuals with the best solutions and therefore the best ranks), out of the population of 100, are

automatically selected to be in the next generation. Zitzler et al. (2000) showed that elitism can improve the speed of the GA, as well as prevent some of the best solutions from being forgotten in future generations of the population. 50 elites are chosen to ensure that a large variety of the best solutions currently found remain in future generations. The parents of the offspring that make up the remaining 50 individuals required in the next generation are selected from the 50 elite individuals using tournament selection, where the individuals with a better rank (i.e. the fitter individuals) have a higher probability of being selected.

Firstly, the ranking process is explained, followed by a description of how the individuals are selected to become parents based on their assigned ranks using tournament selection.

Ranking Process

The individuals are ranked according to how many other individual's solutions (fitness values) dominate their solution. An individual's solution dominates another solution if all of its fitness values represent a better answer to the corresponding objective function. Let $F1_A$ and $F1_B$ be the first fitness values of individuals A and B respectively, and $F2_A$ and $F2_B$ be the second fitness values of individuals A and B respectively. Individual A is dominated by individual B, if $F1_B < F1_A$ and $F2_B \leq F1_A$, or $F1_B \leq F1_A$ and $F2_B < F2_A$. The number of individuals dominating each individual is calculated for each individual in the population. The number of solutions that dominate an individual's solution is used to rank the overall fitness of each individual. The set of individuals that are non-dominated are Pareto optimal solutions and the boundary that they form is referred to as the Pareto front. Figure 6-3 shows the fitness values for a set of individuals' solutions. Each rank is listed next to it and those shown in red represent the non-dominated solutions that therefore have a ranking of zero. For example, the solutions with rankings of 2 and 5 are dominated by the other solutions (as shown by the number of solutions inside the rectangles created by their co-ordinates). Note, in this study, if a solution costs over £2 million, its Pareto rank is increased by 100, so that excessively expensive solutions are not favoured if they have a low number of maintenance visits.

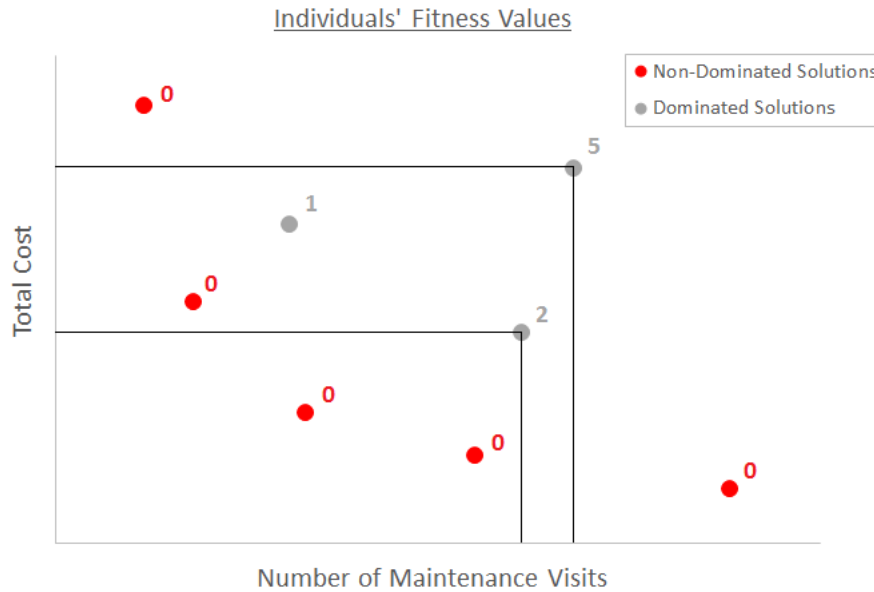


Figure 6-3 Example of Pareto Ranking

However, further complexities arise when attempting to select from solutions that have the same Pareto rank. A simple way of doing this is to choose the individuals based on the best value for the primary fitness value, i.e. the solutions with the lowest total cost. This research uses the same non-dominated sorting process used in the NSGA-II GA described by Deb et. al (2002), which distinguishes between solutions in the same Pareto rank according to their crowding-distance. The crowding-distance refers to how close an individual's solution is to neighbouring solutions in the same Pareto rank, where a smaller crowding-distance means a solution is closer to neighbouring solutions. In order to try to maintain the diversity in the set of individuals that are selected, the individuals with solutions that have a larger crowding-distance are selected in favour of other individuals in the same Pareto rank.

Figure 6-4, graphically shows how the crowding-distance relates to a set of solutions. For each fitness value, the difference between the fitness values of the neighbouring solutions that have the same Pareto ranking, relative to the solution being evaluated, is calculated and divided by the range between the minimum and maximum value for the fitness value in order to normalise it. The values obtained for each fitness value are added together to obtain the individual's crowding-distance. Note that the individuals with a solution at the extremities of the Pareto front (i.e. at the maximum and minimum values for the different fitness values) are assigned an infinite crowding-distance since they do not have neighbouring solutions on both sides. Equation 6-2 defines the calculation of an individual's crowding-distance using the symbols referred to in Figure 6-4.

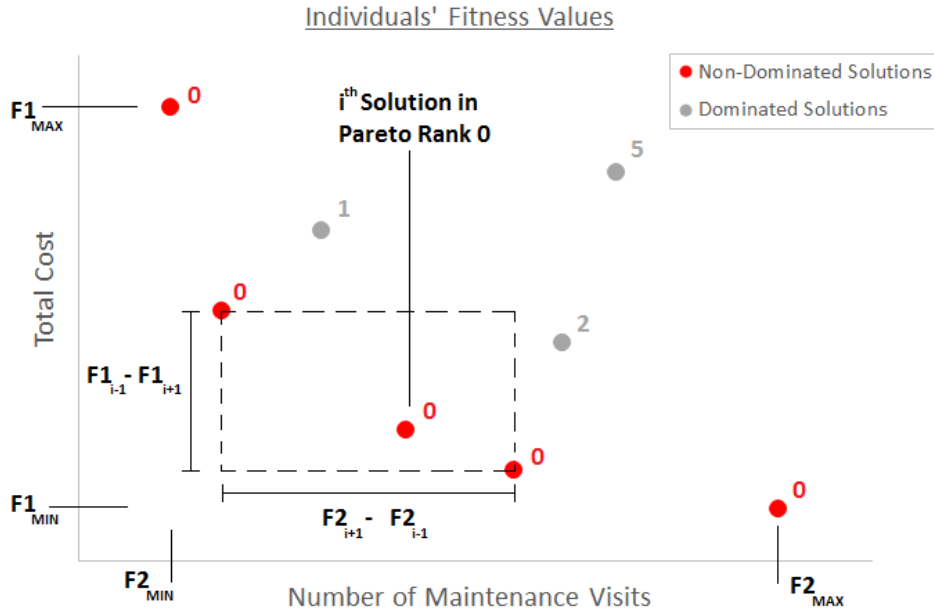


Figure 6-4 Example of Crowding Distance Calculation

$$CD_i = \frac{F1_{i-1} - F1_{i+1}}{F1_{MAX} - F1_{MIN}} + \frac{F2_{i+1} - F2_{i-1}}{F2_{MAX} - F2_{Min}} \quad \text{Equation 6-2}$$

Where CD is the crowding distance, i refers to the i^{th} individual in a set of individuals in the same Pareto rank that are sorted according to their primary fitness values (the total cost), and $F1$ and $F2$ are the values of the primary and secondary fitness values, i.e. the total cost and the number of maintenance visits.

After finding the Pareto ranks of each of the individuals, the 50 best-ranking individuals are selected as elites to exist in the next generation. Where two or more individuals are in the same Pareto rank, then they are ranked, relative to each other, according to their crowding-distance, with a large crowding-distance leading to a better rank. These individuals represent a mating pool, where they can be selected to become parents. This process therefore closely resembles the survival of the fittest phenomenon, whereby only the fittest individuals are able to survive and procreate.

Tournament Selection

A selection process, known as tournament selection, is used to select individuals, from the 50 elite individuals, to form parents that will mate (during the crossover process). Each set of parents will produce 2 offspring, therefore, the number of individuals to select is equal to the size of the population needed to be replenished in the next generation- which is equal to 50 (or 25 pairs). Note that because the fitter individuals are more likely to be chosen they may be a parent for multiple sets of offspring.

Tournament selection works by randomly choosing a small group of individuals (in this research 5 individuals are chosen at a time). The fittest individual from this group, based on its rank, is then selected. However, if the same individual is chosen to mate with itself, then it is discarded and the process is repeated. This entire process is repeated until the number of required pairs of parents (25) have been selected. The number of individuals to compare with one another, which is known as the tournament size, influences the likelihood of the fittest individuals being selected. Too large a tournament size and only the very fittest individuals in the mating pool will ever be selected to become parents, whereas too small a tournament size will result in individuals being chosen more randomly rather than based on their fitness. The tournament size of 5 is used to achieve a balance whereby the fittest individuals are more likely to be chosen, but the very fittest individuals are unlikely to dominate all the available parent positions.

6.3.2.5 Crossover

Each pair of individuals that was selected to be parents is then subject to the crossover process in order to obtain the offspring that represent new individuals to be evaluated. The crossover process involves choosing a crossover point for the parents' chromosomes. The first parent gives the variables to the left of the crossover point in their chromosome to the first child and the second parent gives the variables left of the crossover point in their chromosome to the second child. Similarly, the first parent then gives the variables right of the crossover point to the second child and the second parent gives the variables to the right of the crossover point to the first child. Each child, therefore, contains portions of each of the parent's chromosomes, as shown in Figure 6-5. Note that multiple crossover points can be considered where the chromosomes are split into more portions that are shared between the offspring, but this study uses a single crossover point that is chosen at random for each set of parents.

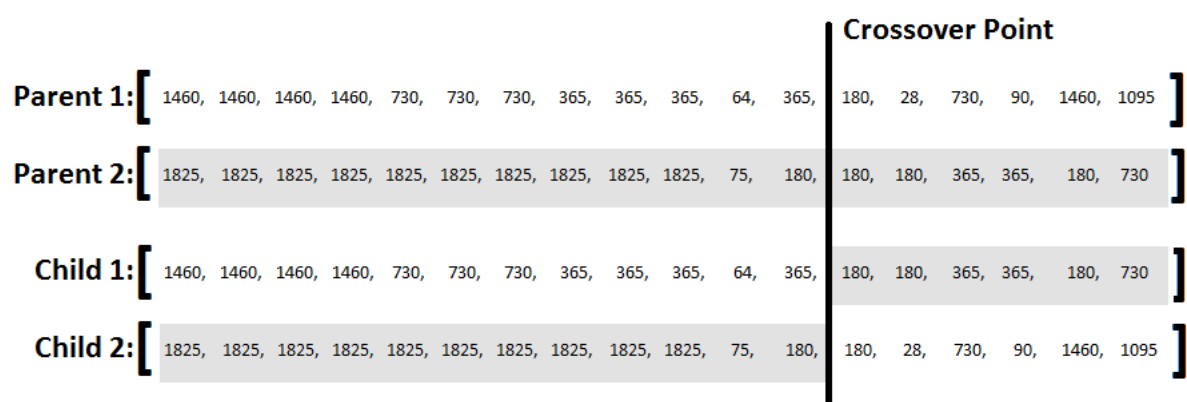


Figure 6-5 Example of the Crossover Process

The crossover process is repeated for each pair of parents that were selected. After all of the offspring are generated, the next generation of the population will be the same size, i.e. it will consist of 100 individuals (50 elite individuals from the previous generation and 50 offspring).

6.3.2.6 Mutation

Before starting the next generation, each gene within an individual's chromosome has a chance of being mutated. A mutation of one gene results in its value changing to a completely different value, by randomly choosing a value from the range of values that are applicable for the input variable that the gene represents (as listed previously in Table 6-1). The probability of a gene being mutated is equal to the mutation rate. The appropriate mutation rate is problem specific. Too high a mutation rate may result in the GA failing to converge, as an excessive number of mutations results in the next generation being comprised of individuals with random values for each variable, rather than individuals who have inherited the favourable traits of their parents. However, too low a mutation rate may result in the GA becoming stuck in a local minimum, with little opportunity to increase the search area for the values of the variables encoded in the chromosomes of the current population's individuals- i.e. alleles (certain values for a particular gene) that are not present in the population are unlikely to be introduced although the true optimum solution may require them. In this study a mutation rate of 0.01 (i.e. 1 in 100 genes will mutate each generation) was chosen because this is listed as a safe value to use for most optimisation problems in the literature. However, the 50 elite individuals that represent the fittest individuals found are not subject to mutation to ensure that the best candidate solutions currently found remain unchanged.

6.3.2.7 Continuation and Convergence

The overall process described is repeated for each successive generation. After an entire population has been evaluated, each individual's chromosome and fitness values are recorded. The Petri net model is run to evaluate the objective functions until their values (the total cost and the number of maintenance visits) have converged, so that the change in their mean value is less than 0.1% with additional simulations. Each individual's solution in the population is evaluated in parallel. To save time, before evaluating an individual's solution, its chromosome is checked against previously evaluated individuals (in previous generations). If the chromosomes are identical, i.e. they represent the same solution with the same input variables, the individual is given the fitness values of the previously evaluated individual and the objective functions do not need to be evaluated (so the Petri net does not need to compute the results for this individual). As the GA converges, more of the same

individuals, representing good solutions, begin to regularly occur in the population (as both elites and even as offspring).

The algorithm will have converged when there is a well-defined Pareto front, where most of the individuals in the population are Pareto optimal solutions, and there has been little change in the fittest individuals that exist in the population for several generations. In this study the GA was set to run for 200 generations and an acceptable convergence occurred when the majority of the individuals in the final generations were Pareto optimal. The full list of GA parameters used is given below in Table 6-2.

Table 6-2 Genetic Algorithm Parameters Used

GA Parameter	Value
Number of Genes/ Variables	18
Population Size	100
Number of Parents	50
Tournament Size	5
Mutation Rate	0.01
Number of Generations	200

6.3.3 Optimisation Results

This section presents the results of the GA. Firstly, the fitness of various generations are shown to illustrate how the algorithm proceeded to find fitter individuals. The set of optimum solutions are then shown and 3 solutions are presented in detail and compared to the current Network Rail policy. This is done by performing further analysis, which used the Petri net model that has been developed to obtain the full range of asset management statistics for the strategy specified by each solution.

The fitness of the individuals in each generation has been analysed to see how the GA progressed to continually find better solutions with future generations. Figure 6-6 shows various generations of individuals as the population becomes fitter in subsequent generations. The individuals in the initial population (generation 1) have a large range of fitness values (the total cost and the number of maintenance visits) for the different individuals. It can be seen that by generation 50, a more defined Pareto front has developed and the population has become fitter with respect to the minimisation of both the total cost and the number of maintenance visits and the range of fitness values that the individuals contain is decreased. By generation 200 the majority of the individuals in the population are Pareto optimal, where they are not dominated by any other solution, and there are further minimisations of the total cost and the number of maintenance visits in comparison to the individuals in generation 50.

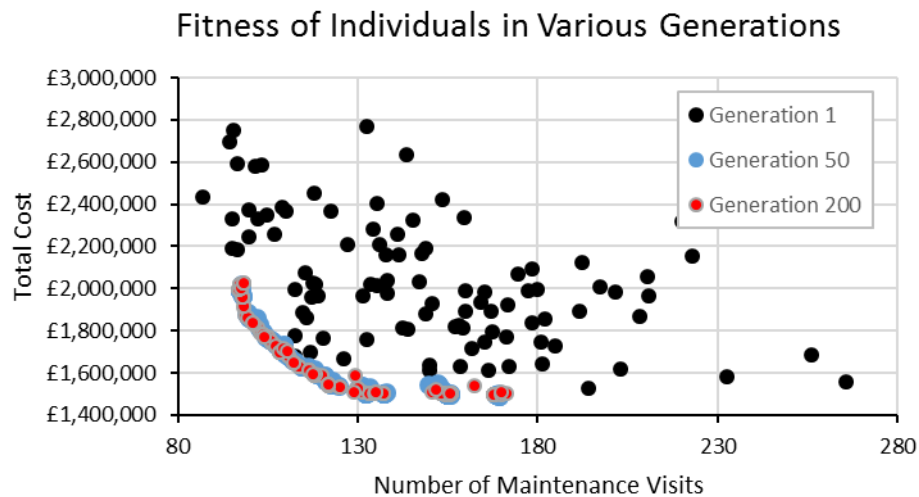


Figure 6-6 Fitness of Individuals in Various Generations

Figure 6-7 shows the fitness values for every individual that was evaluated during the study. In total there were 2224 unique individuals evaluated. This chart therefore shows the full range of values that can exist for the total cost and the number of maintenance visits for the different asset management strategies tested. The majority of the solutions evaluated exist close to the Pareto front due to the convergence of the GA. Many of the outlying solutions also occurred in the first few generations. Note that the ranking process was undertaken, such that the individuals with a total cost over £2 million had their Pareto rank increased, so that excessively expensive solutions are less likely to be selected and pass on their genes to future generations. Consequently, there were not many individuals evaluated with a total cost significantly greater than £2 million.

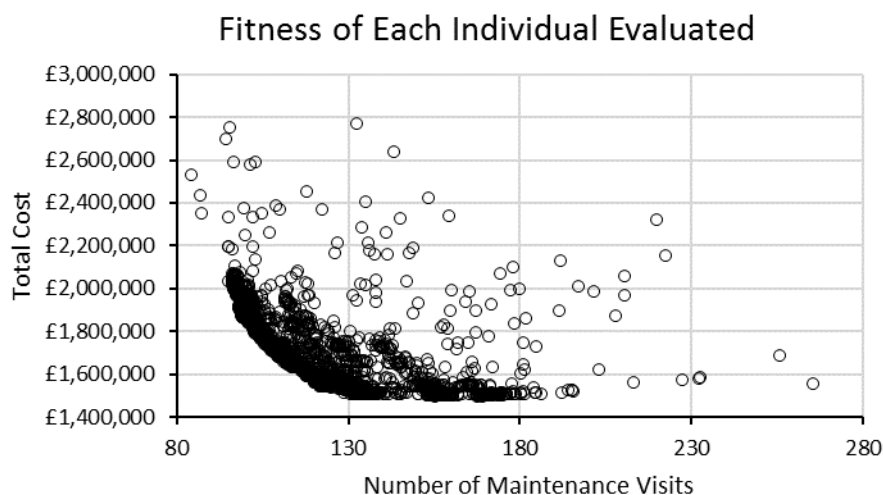


Figure 6-7 Fitness of Each Individual Evaluated During the Study

6.3.3.1 Optimum Solutions Obtained and Comparison with Current Asset Management Strategy

Figure 6-8 shows the Pareto optimal solutions, for each unique individual solution that was evaluated for the 200 generations studied. These solutions are used to represent the overall optimum solutions, rather than the Pareto optimum solutions in the final population, because they represent a more complete Pareto front, whereas in the final population some of the solutions are repeated. Out of the 2224 unique individual solutions evaluated, 88 of them were Pareto optimal. The data points highlighted in green represent the solutions that have been selected for further examination and the red point represents the current maintenance strategy implemented by Network Rail. A description of the main features of the optimal solutions in the Pareto front is given next before defining the solutions that were chosen and presenting the results of further analysis of the strategies they specify.

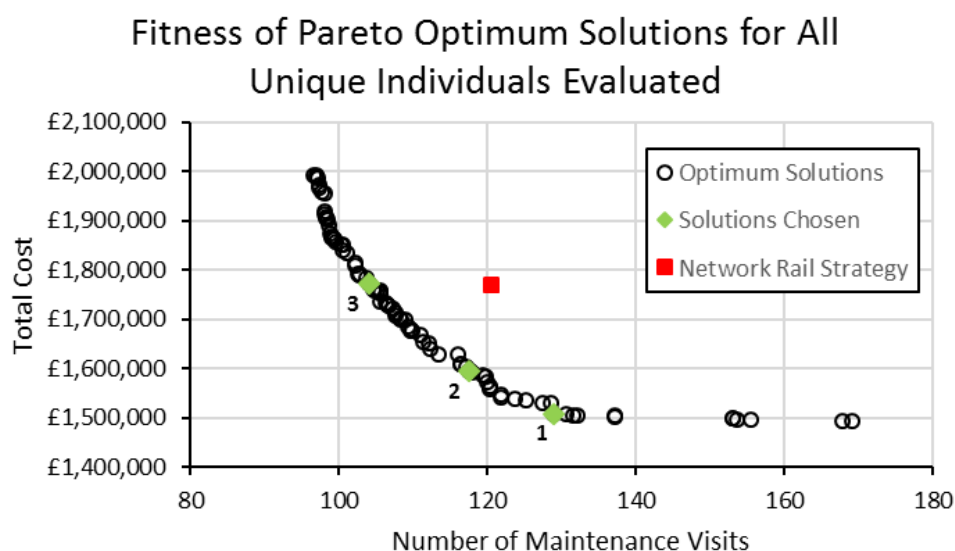


Figure 6-8 Fitness of Pareto Optimum Solutions for All Unique Individuals Evaluated

The overall Pareto front shows how the total cost increases as the number of maintenance visits decreases. This is expected, because undertaking less maintenance will result in an increased number of component failures, which often result in large costs being incurred that far outweigh the savings made by reducing maintenance visits. Note that a lower number of maintenance visits can result in a lower total cost in comparison to the non-Pareto optimal solutions, as it is likely that in some of these non-optimum solutions the components are maintained too frequently. If the components are maintained too frequently, the chance of other components also requiring maintenance that can take place at the same time is reduced. Therefore, the optimal maintenance scheduling times for a component should result in the component being maintained before the likelihood of its failure

becomes excessive. However, maintenance should not be scheduled too soon otherwise maintenance of other components is less likely to be undertaken at the same time opportunistically, which results in a greater required number of maintenance visits to the area. The Pareto optimal solutions suggest that strategies that result in more than 170 maintenance visits per year are no longer optimal (since they are dominated by the Pareto optimal solutions). However, the Pareto front shows that there is little reduction in the total cost for more than 130 maintenance visits. From this, one can infer that in the solutions where more than 130 maintenance visits are undertaken, the increased maintenance activity does not result in a substantial enough of a decrease in the number of component failures to result in a significantly lower total cost. At the other end of the Pareto front, the solutions were only able to be Pareto optimal if they have a total cost of less than £2million (to ensure that excessively expensive solutions are not considered). The Pareto front shows that for the solutions that contain fewer than 100 maintenance visits there is a significant increase in the total cost with a further reduction in the number of maintenance visits. This is expected, because if the component maintenance scheduling times are too long, the probability of component failure will increase.

As described earlier, the resources available to the maintenance engineering teams (such as the number of staff and access to the road rail vehicle) means that there is a limit to the number of maintenance visits that can feasibly take place for an access area. In the previous chapter, the model was used to calculate the performance of the system using Network Rail's current maintenance strategy, where the expected total cost and the number of maintenance visits were calculated to be approximately £1.77 million and 120 respectively. The Pareto optimal solutions that result in less than 130 maintenance visits are applicable for consideration, as this is not significantly greater than that of the current policy. Therefore, the strategies stipulated should be possible for the maintenance engineers to implement without the need for more resources (i.e. more staff). Since the total cost using Network Rail's current policy is £1.77 million, the Pareto optimal solutions with a total cost greater than this do not warrant further analysis.

Solutions Chosen

The maintenance strategies contained within the three solutions that were chosen for examination in further detail are listed below in Table 6-3 and Table 6-4 and the reasons for their selection are then described.

Table 6-3 Inspection Intervals for the Optimum Solutions Selected Compared to the Network Rail Strategy

Solution	Total Cost	Number of Maintenance Visits	Inspection Intervals (over ten year periods)									
			0-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-100
1	£1.51M	128.9	1825	1825	1825	1825	1460	1825	1825	1460	1825	1825
2	£1.59M	117.6	1825	1825	1825	1825	1460	1825	1825	1460	1825	1825
3	£1.77M	104.2	1460	1825	1825	1460	1460	1825	1825	1460	1460	1825
Current Strategy	£1.77M	120.5	1460	1460	1460	1460	1460	1460	1460	1460	1460	1460

Table 6-4 Renewal Time and Component Maintenance Scheduling Times for the Optimum Solutions Selected Compared to the Current Network Rail Policy

Solution	Renewal Time (Years)	Component Maintenance Scheduling Times (Days)						
		Catenary Wire	Contact Wire	Droppers	Insulators	Registration Equipment	Return Conductor	Adjustments
1	52	7	7	28	365	365	365	365
2	52	90	7	90	365	365	365	1460
3	52	180	28	180	730	365	730	1460
Current Strategy	70	180	365	7	730	730	730	730

Solution 1 was chosen because it has one of the lowest total costs out of all the Pareto-optimal solutions, but the number of maintenance visits is significantly less than that of the small number of solutions that have a slightly lower total cost. Solution 3 was chosen because it has a similar total cost to the strategy that Network Rail currently implements, but approximately 15% fewer maintenance visits are required. Solution 2 was chosen because its fitness values are in between those of Solutions 1 and 3 and it is not much more expensive than its neighbouring solutions, which have a larger number of maintenance visits. A description of the different strategies, specified by each solution, in terms of how they influence the performance of the system is now provided.

For Solutions 1 and 2, the high level inspections occur at intervals of 5 years (1825 days) until year 40 when the interval is changed to be every 4 years (1460 days). The increased number of inspections during this period allows the degraded components, which at this stage in the system's life cycle are more prevalent due to ageing, to be maintained more frequently by the opportunistic maintenance that occurs during high level inspections. After the renewal, which is timed for 52 years for all solutions, the inspection interval then increases to 5 years again as the system is in a better condition. Between years 70 to 80, the inspection frequency is reduced to 4 years as the system ages, before increasing again to 5 years until the end of the 100-year period studied, as by this point many of the components will have been maintained previously, meaning the system's maintenance requirements are lower. For Solution 3, the inspection intervals are similar to those in Solutions 1 and 2, where the inspection interval is 5 years when the system is younger and does not require as much maintenance (apart from during the first 10-year period when the interval is 4 years). The interval then changes to 4 years during

the periods when more maintenance is required. However, for Solution 3, there are more periods where the interval is 4 years when the system has aged, i.e. between years 30 to 50 and again between years 70 and 90.

In Solution 1, which contains the strategy that results in the lowest total cost, the component maintenance scheduling times are reduced for each component type (apart from for droppers), in comparison to the times specified in the current strategy implemented by Network Rail. This will result in the number of system failures being reduced, because degraded components will be addressed sooner, therefore, they are less likely to fail due to the presence of defects or poor condition. Note that the number of failures for each of the solutions is shown in Figure 6-11 and discussed in detail later. Similarly, in Solution 2, the maintenance scheduling times are reduced, relative to the current strategy, for most of the components, apart from for the droppers and adjustments to the wire run. The maintenance scheduling time for the catenary wire is not as short as for Solution 1 (90 days compared to 7 days). As a result, the strategy represented by Solution 2 also reduces the whole life cost of the system relative to the current strategy implemented by Network Rail, due to reducing the number of failures by maintaining the more critical components sooner. The number of maintenance visits for Solution 2 is also slightly lower than that of the current strategy, despite many of the component maintenance scheduling times being reduced. This is primarily due to scheduling the maintenance work that performs adjustments to the wire run to occur later (1460 days rather than 730 days), therefore, more of these maintenance actions will occur opportunistically at the same time as other component maintenance actions and during high level inspections.

For Solution 3, the components are not maintained as quickly as in Solutions 1 and 2. The contact wire and the registration equipment have their maintenance scheduling times reduced relative to the current strategy. The maintenance scheduling times of droppers and adjustments to the wire run are increased relative to the current strategy and the other component maintenance scheduling times remain the same. However, as indicated earlier, in Solution 3 there are slightly more high level inspections occurring, where opportunistic maintenance can take place.

For all the solutions, the maintenance scheduling times for the catenary wire, contact wire, insulators, registration equipment and the return conductor have either decreased or stayed the same, relative to the current strategy implemented. This is because the failure of these components can result in extremely large costs being incurred, particularly in the case of the contact wire. Therefore, by scheduling their maintenance to occur sooner, after they are inspected to be in a degraded condition, they are less likely to fail, resulting in a reduced total cost.

For all the solutions, the renewal of the catenary and contact wires was scheduled to occur after 52 years, this is significantly earlier than the 70 year predicted service life of these components. By scheduling this renewal earlier, the components are renewed before degradation caused by ageing has become prevalent across the entire length of the wires, meaning there is less chance of the components failing due to this degradation. Note that other renewal times between 50 and 60 years do not change the total cost significantly for each solution respectively.

Note in all three solutions, the maintenance scheduling time for the droppers is increased significantly from the 7 days stipulated in the current Network Rail policy. In practice, Network Rail would probably not be confident leaving the droppers to be in a degraded condition for so long (particularly for 180 days as specified in solution 3). This is because when one dropper in a span is detached additional stress is placed upon the remaining droppers, thus increasing their chance of failure and the contact wire can drop considerably if several droppers are detached in the same span.

The model could be adapted to model how when one dropper has become detached there is an increased chance of the remaining droppers in the same span also becoming detached or failing. This could then change the results of the optimisation. However, the maintenance scheduling times stipulated for the droppers in the optimum solutions obtained in this thesis can still be considered, but the maintenance engineers would need to monitor the affected span regularly to identify any additional degraded droppers and then schedule maintenance quickly (e.g. within 2 days).

Detailed Analysis of the Solutions Chosen

The asset management strategies defined by the optimum solutions were then studied in detail by using the values that describe the strategies, i.e. the inspection and maintenance times listed in Table 6-3 and Table 6-4, as inputs to the Petri net model to calculate the full range of outputs. This allows a more detailed comparison to be made between Network Rail's current strategy and the optimum solutions chosen. The main outputs are now presented along with explanations of how the different strategies influence the values obtained.

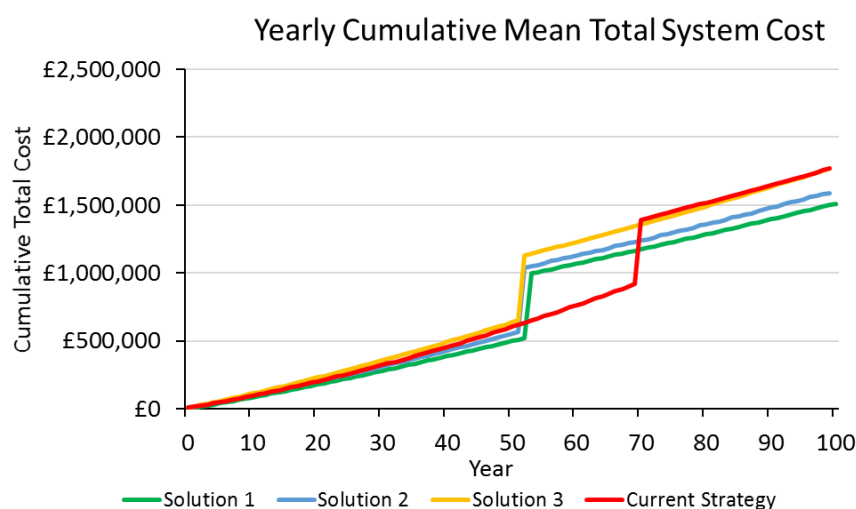


Figure 6-9 Yearly Cumulative Mean Total System Cost for the Different Solutions

Figure 6-9 shows the mean cumulative total cost over the 100-year period studied for each of the solutions. The cumulative cost of the solutions is similar during years 0 to 30. This is because when the system is younger the components are less likely to have aged and be in a degraded condition, where they are more likely to require maintenance or fail. Therefore, the different maintenance strategies for each solution do not influence the total cost as much as later in the 100-year period, when the components have aged significantly and are therefore more likely to require maintenance or fail.

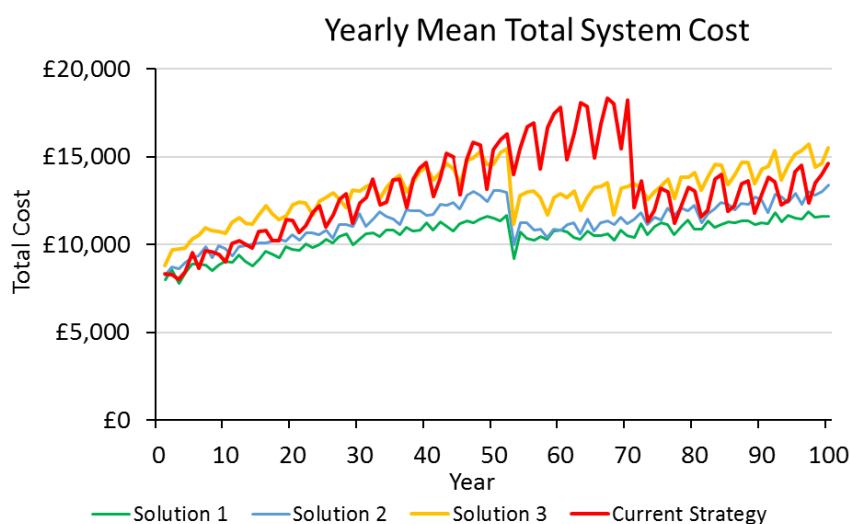


Figure 6-10 Yearly Mean Total System Cost for the Different Solutions (excluding renewal cost)

Figure 6-10 shows the yearly mean total cost for each solution (excluding the large renewal cost of the catenary and contact wires). For all the solutions, the cost increases each year as the system ages until the renewal of the catenary and contact wires, which occurs after 52 years. After the renewal, because the system's condition is improved, the yearly cost is decreased. The yearly costs for Solutions 1 and 2 are less than the current strategy implemented by Network Rail, because component maintenance

is scheduled sooner, resulting in fewer failures and a reduced cost. Note that the fluctuations in the yearly cost are caused by the occurrence of the high level inspections, where the condition of the system will be improved during the years when a high level inspection occurs, meaning the chance of failures will be reduced. More information about the number of failures is given in Figure 6-11 and Table 6-5.

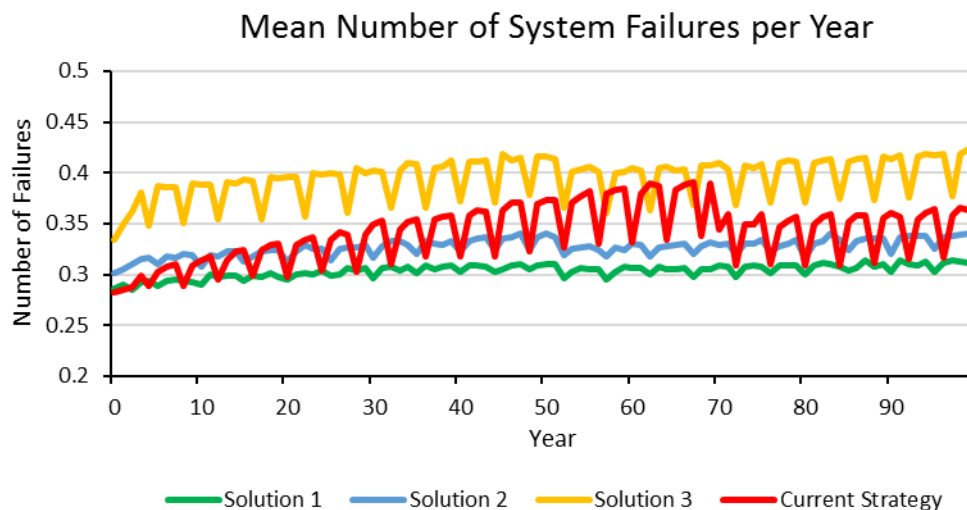


Figure 6-11 Mean Number of System Failures per Year for the Different Solutions

Figure 6-11 shows the mean number of system failures per year for each of the different solutions. For Solution 1, where the maintenance strategy involves maintaining degraded components much sooner, relative to the current policy, between approximately 0.28 and 0.32 failures occur per year. The majority of these failures are due to random processes that the maintenance strategy cannot prevent (such as bird strikes causing trips of the system or third party damage that leads to component failure). Even as the components age and degrade, the number of component failures does not increase significantly because the shorter maintenance scheduling times reduce the chance of failure due to the degraded condition of components. For Solution 2, the trend in the number of failures per year as the system ages is similar to that of Solution 1. However, because the maintenance scheduling time for some components, such as the catenary wire and the droppers, are longer, there are slightly more failures per year.

For Solution 3, the failure rate is greater than the other solutions and the current strategy. This is because the maintenance times for the droppers is significantly greater than in the current strategy (180 days compared to 7 days) meaning they are more likely to fail. The maintenance scheduling times for the catenary wire, insulators and registration equipment are the same as the current strategy, so these components will fail at a similar rate to the current strategy. Although there are more failures occurring in Solution 3, the failure costs are not significantly greater than those of the current strategy,

as shown later in Table 6-7. This is because the increased failure rate witnessed is predominantly due to more failures of the droppers and the typical costs incurred due to their failure is much less than the costs incurred due to the failure of the contact wire (which has its maintenance times reduced relative to the current strategy). Note that the fluctuations in the failure rate, as seen in Figure 6-11, are attributable to the scheduling of the inspection intervals, which vary over the 100-year period for the different solutions, but stay constant (at 4 year intervals) for the current strategy. Since the maintenance scheduling times are shorter in Solutions 1 and 2, there is less fluctuation in the failure rate when the high level inspections occur. This is because maintaining component defects sooner reduces the amount of maintenance required during high level inspections and the components are less likely to be in a degraded condition where their probability of failure is increased.

Table 6-5 shows the mean total number of service affecting failures for each component type. For Solution 1, in comparison to the current strategy, the number of failures is fewer for all the components, apart from for droppers, where it increases slightly as their maintenance scheduling time is longer. Note that the number of failures caused by external influences is the same for all solutions because these are random failures that are not influenced by the degradation and maintenance of the OLE components. Solution 2 is similar to Solution 1, but there are slightly more failures occurring for the different components. Interestingly, the catenary wire actually fails slightly less frequently in Solution 3 than in the current strategy, despite having the same maintenance scheduling time. This is probably due to the maintenance of the contact wire and registration equipment being scheduled sooner than in the current strategy, meaning the catenary wire is more likely to be maintained at an earlier date opportunistically with these other components.

Table 6-5 Mean Total Number of Component Failures over the 100-Year Period Studied for Each Solution

Component	Mean Total Number of Failures Over 100 Years			
	Solution 1	Solution 2	Solution 3	Current Strategy
Catenary Wire	1.10	1.38	1.58	1.68
Contact Wire	2.91	3.03	3.06	3.38
Dropper	3.31	5.15	9.73	3.08
Insulator	1.49	1.53	3.13	3.08
Registration Equipment	0.85	0.89	0.92	1.86
Return Conductor	1.10	1.11	1.46	1.46
External Influences	19.59	19.59	19.59	19.59
Total	30.36	32.67	39.47	34.11

The full range of statistics that express the maintenance cost, failure cost and total cost for each of the solutions are shown in Table 6-6, Table 6-7 and Table 6-8 respectively. The maintenance costs for each solution are all relatively similar. Although the number of maintenance visits required, which was one of the objective functions, is significantly less for Solution 3. The failure cost of Solution 1 is the lowest and the uncertainty of the failure cost is lower for all the solutions relative to the current policy, because the standard deviation, interquartile range and maximum failure cost is lower for these solutions. This is primarily because the number of failures of the catenary and contact wires, which are more likely to result in excessive costs being incurred due to extreme events that result in a dewirement, are reduced by scheduling their maintenance sooner. Due to a reduced chance of these extreme failure costs, there is less uncertainty in the failure costs. Since the failure costs constitute the majority of the total cost of the OLE over the 100-year period studied, the total costs for the different solutions also have less uncertainty.

Table 6-6 Total Maintenance Cost Statistics for the Different Solutions

	Maintenance Cost Over 100 Years (including renewal)			
	Solution 1	Solution 2	Solution 3	Current Strategy
Mean	£0.86M	£0.84M	£0.82M	£0.86M
Median	£0.86M	£0.84M	£0.82M	£0.86M
Maximum	£0.92M	£0.89M	£0.88M	£0.92M
Min	£0.8M	£0.78M	£0.76M	£0.8M
Standard Deviation	£0.01M	£0.01M	£0.01M	£0.01M
Upper Quartile	£0.87M	£0.84M	£0.83M	£0.87M
Lower Quartile	£0.85M	£0.83M	£0.81M	£0.85M

Table 6-7 Total Failure Cost Statistics for the Different Solutions

	Failure Cost Over 100 Years			
	Solution 1	Solution 2	Solution 3	Current Strategy
Mean	£1.05M	£1.23M	£1.42M	£1.33M
Median	£0.83M	£1.03M	£1.22M	£1.12M
Maximum	£8.05M	£7.59M	£8.23M	£8.68M
Min	£0.02M	£0.07M	£0.01M	£0.05M
Standard Deviation	£0.77M	£0.79M	£0.81M	£0.87M
Upper Quartile	£1.36M	£1.57M	£1.77M	£1.72M
Lower Quartile	£0.51M	£0.68M	£0.86M	£0.71M

Table 6-8 Total Cost Statistics for the Different Solutions

	Total Cost Over 100 Years			
	Solution 1	Solution 2	Solution 3	Current Strategy
Mean	£1.91M	£2.07M	£2.24M	£2.19M
Median	£1.7M	£1.86M	£2.04M	£1.98M
Maximum	£8.93M	£8.47M	£9.06M	£9.54M
Min	£0.86M	£0.91M	£0.91M	£0.89M
Standard Deviation	£0.77M	£0.79M	£0.81M	£0.87M
Upper Quartile	£2.22M	£2.4M	£2.59M	£2.58M
Lower Quartile	£1.37M	£1.52M	£1.68M	£1.57M

6.3.3.2 Summary of Optimisation Results

The strategy represented by Solution 1 has the lowest total cost, approximately 15% less than the cost of Network Rail's current strategy. Because the number of required scheduled maintenance visits is not significantly greater, 128.9 compared to 120.5 over the 100-year period (or an average of approximately 1.3 maintenance visits per year), this solution is the most appropriate. Solution 2 reduces the total cost and the number of maintenance visits slightly relative to the current policy, but Solution 1 is more appropriate because it results in a lower total cost and the number of maintenance visits is not excessively greater, meaning Network Rail should be able to implement the strategy under the current logistical and resource constraints.

Solution 3 results in a similar total cost to the current strategy and a 15% reduction in the number of scheduled maintenance visits. However, Figure 6-11 shows that the expected number of failures in each year, over the 100-year period studied, is greater relative to the current strategy. It is likely that many of these failures will only result in minor delays, because the number of failures of the contact wire (which are more likely to result in substantial service disruption) are reduced. However, the Petri net model does not consider system downtime, so the availability of the system is not calculated. As a result, Solution 3 is not as suitable as the other solutions because implementing this strategy will result in a greater occurrence of system failures than the current strategy. Note that Solutions 2 and 3 reduce the number of required maintenance visits, which could result in the number of resources that are required (such as staff) to be decreased, which in turn could result in substantial reductions in the total cost of the system, if the cost of available resources and staff are taken into account; this is not considered in this study.

The comparison between these different solutions also demonstrates the relative effectiveness of Network Rail's current strategy. As previously mentioned, the optimum solutions suggest that the maintenance of the contact wire should be scheduled sooner to reduce the number of failures. This would reduce the total cost of the system and the uncertainty associated with the cost, because the cost incurred due to the failure of the contact wire can be considerable.

The Pareto-optimal solutions show that decreasing all the components' maintenance scheduling times will only result in a lower total cost up to a certain amount. Any further decrease will not result in a significant decrease in the number of failures of the components and the components will be less likely to be opportunistically maintained at the same time meaning the maintenance costs and the number of scheduled maintenance visits required will increase.

For all the solutions studied in detail, the inspection intervals decreased until the renewal of the catenary and contact wires was scheduled, when it was then increased again. This is expected, because the components are more likely to require maintenance later in their life when they have aged. Therefore, performing the high level inspection (where components will be opportunistically maintained) more frequently in the later years means that the components' maintenance can be addressed more effectively, by maintaining numerous degraded components during the same high level inspection, thus reducing the number of overall maintenance visits required. Because the component maintenance actions are generally scheduled sooner for each component type, relative to the current strategy, the inspection intervals are always either 4 or 5 years because any degraded components will often have already been maintained before the high level inspections take place. Therefore, with such short maintenance scheduling times, decreasing the inspection interval will simply result in an excessive number of maintenance visits.

The optimal solutions suggest that a renewal of the catenary and contact wires after 52 years is the best time. This is because a renewal at this time means that over the 100-year period studied, the contact and catenary wires will be less likely to be in a degraded condition across their entire lengths, therefore, the number of failures caused by their poor condition will be decreased. Note that if the renewal occurs at any time between 50 and 60 years (rather than exactly at 52 years), the difference in the total cost over 100 years does not change significantly. This suggests that renewing the contact and catenary wires earlier than their estimated service life (70 years) can result in a reduction in costs over the 100-year period.

In comparison to the optimum solutions found, the performance of Network Rail's current asset management strategy, with respect to the total cost and the number of maintenance visits, is suitable. Furthermore, in practice, Network Rail maintenance engineers often schedule the maintenance of

components sooner than the maximum times stated by the standards. Therefore, the different OLE components may be maintained sooner and the actual strategy implemented will be closer to the strategy specified by Solution 1. The optimum results do suggest, however, that particular priority should be applied to the catenary and contact wires, as minimising the number of failures of these components, through reducing their maintenance scheduling times when they are found to be in degraded condition, can result in a lower total cost. Similarly, it is suggested that degraded droppers can be scheduled to be maintained within 28 days, rather than 7 days, without a noticeable increase in the number of failures.

6.4 Summary

Finding the most suitable values of the variables that the asset manager has control of in the asset management model is beneficial to asset managers and can be achieved through undertaking an optimisation procedure. A discussion of the various asset management processes associated with the OLE, that are suitable for optimisation and the different performance measures that can be considered for maximisation or minimisation, as part of the optimisation procedure, are outlined. The asset management intervention actions considered in the optimisation undertaken were the high level inspection intervals, the component maintenance scheduling times and the timing of the renewal of the catenary and contact wires. These intervention actions were optimised with respect to minimising the total cost of the system and minimising the number of maintenance visits over the 100-year period modelled. The total cost was chosen, because Network Rail aim to specify asset management strategies that result in the lowest whole life cost. The number of maintenance visits was chosen because different asset management strategies may result in a large number of maintenance visits to an access area, which may not be possible due to logistical or resource constrictions.

The GA was chosen to find the optimum solutions due to its flexibility, which allows it to be used in conjunction with the Petri net model developed, and the fact that it can be used for multi-objective optimisation where a set of optimum values can be obtained. This chapter gave a thorough description of how the GA works and how it was implemented using the Petri net to calculate the values for the objective functions (the total cost and the number of maintenance visits). An optimisation of the asset management strategy was undertaken for the same access area that was studied in the example study presented in Chapter 5. Some of the optimum solutions obtained were then studied in detail and their suitability was compared to the current strategy implemented by Network Rail, by comparing various performance indicators, including the cost and the number of failures over the system's life cycle.

The optimum results that were obtained showed that reducing the component maintenance scheduling times can result in a reduced total cost of the system over the 100-year period analysed. This is because maintaining the degraded components sooner can reduce the chance of their failure. However, reducing the maintenance scheduling times too much can result in a greater total cost, because the number of failures cannot be completely eliminated, due to random component failures, and less opportunistic maintenance will take place. The solution chosen as the most suitable asset management strategy offers a 15% reduction in the total cost of the system over the 100-year period, relative to the current strategy implemented by Network Rail, but only a slight increase in the number of required scheduled maintenance visits.

Chapter 7 Conclusions

Firstly, this chapter provides a summary of the work presented in this thesis. The main conclusions are then listed, together with an appraisal of the work completed, demonstrating how the aims and objectives have been met. Next, the main ways in which this thesis contributes to research in the subject area are outlined, followed by recommendations for future work.

7.1 Summary of Work

The OLE is a critical sub-system of the 25kV AC overhead electrification system, which is the preferred method of electrification on the British railway network. The overall asset management strategy implemented by Network Rail aims to maintain the current portfolio of assets and correctly specify the assets to be installed in new systems, so that the required outputs, such as system reliability and the permissible railway line speed, can be achieved at the lowest whole life cost of the system. Since the electrified railway network is large and there are many new electrification schemes planned in the near future, substantial savings can be realised through implementing an effective asset management strategy for the OLE. Therefore, the primary aim of this research was to develop a life cycle cost model for the OLE that considers the main asset management intervention actions implemented by Network Rail, in order to calculate the expected future costs and performance of the system and allow different asset management strategies to be evaluated. Since the OLE components are subject to ageing, it is important that the whole life cycle of the system is considered in the analysis so that the future condition of the components is accounted for. In general, asset management and life cycle cost models study the degradation and failure of components, as well as the intervention actions undertaken, such as inspection and maintenance, over the whole life cycle of the system. The use of such models can allow future asset management and investment decisions to be better informed and enable asset management strategies or proposed projects to be selected, based on evidence from modelling results.

The main OLE components that were studied in detail in this thesis were the catenary wire, contact wire, droppers, insulators, registration equipment, return conductor and structures. These components were chosen since they are present in every span of the OLE and their asset management influences the whole life cost of the system, due to their maintenance requirements and reliability. The degradation and failure modes for the different components were described using a variety of sources obtained from literature, Network Rail documents and interviews with maintenance engineers. The different asset management intervention actions undertaken on the OLE by Network Rail were then outlined. Network Rail now undertakes a condition-based maintenance regime where

component maintenance is scheduled, based on the results of routine inspections that reveal the components' conditions. The maintenance scheduling time, for a component found to be degraded, is specified according to the severity of the degradation or defect. If a failure occurs, rapid response maintenance is undertaken to rectify the issue and minimise the disruption to the timetabled train service. OLE component failures can result in widespread damage and severe service disruption. It is imperative, therefore, that the likelihood of these events is minimised to preserve the availability of the system and prevent the incursion of failure costs, due to fines imposed on Network Rail for the service disruption.

An analysis of historical data that recorded OLE failures was undertaken. This analysis focused on categorising the OLE failure events according to component type. Since many of the available data records did not have sufficient information to determine the associated component type, the component failure rates could not be obtained from the analysis. However, for the records that could be accurately categorised, the effects of the failures of different component types were analysed, by considering the cost incurred due to the delay and rectification work associated with the failure. Since information about the system downtime was not accurate, the failure cost was used to describe the severity of a failure. Using the data, distributions of the failure costs were found for each component type and these distributions were later used in the model developed to enable the uncertainty associated with the cost of failure, arising due to different severities of failures, to be considered. Recommendations specifying how the current data collection process could be improved, in order to allow detailed analysis of the times to reach states of degradation and failure for the components, were also provided.

The literature review chapter introduced the area of asset management and its importance to railway infrastructure organisations, before discussing the merits of various methods that can be used for life cycle cost analysis and asset management modelling of the OLE, using references to studies presented in the literature. Currently, publications associated with the asset management and life cycle cost analysis of the OLE are scarce. The majority of studies analysing OLE components have used deterministic modelling methods to analyse the physical behaviour of the components, whilst taking into account different design and loading characteristics. In addition, some studies published used stochastic models to predict the expected number of failures and maintenance for the OLE components and calculate the life cycle cost of the system. These models considered the reliability or lifetimes of the different components probabilistically, to predict the future condition of the components when fixed time interval preventative maintenance and rapid response maintenance (after a failure) are considered. Such approaches do not consider all the processes associated with the asset management of the OLE components on the British railway network, for instance the condition-

based maintenance regime and the dependencies between different components, e.g. opportunistic maintenance.

Some studies reviewed have shown how the life cycle cost and asset management of other engineering systems, such as for railway track and wind farms, can be effectively modelled using state-based models like Petri nets and Markov models. Petri nets have been shown to be particularly suitable, since they can model both deterministic and stochastic processes and can also be used to obtain an extensive range of outputs expressing the performance of the components or the system studied (in terms of the expected number of failures and maintenance actions), as well as the system cost over its life cycle. High Level Petri nets were used in this thesis due to their ability to model more complex processes using a reduced number of places and transitions in comparison to a standard Petri net, thus making the model more intuitive and concise.

The main processes considered in the Petri net model developed in this thesis are the degradation, failure, inspection and maintenance of the components. These processes are modelled individually for each instance of each component in the section of OLE studied. Within the model, each instance of a component is represented by a unique token that also contains additional information about the component, including for instance its location, installation date and number of previous maintenance actions. The model contains places representing the condition of a component, (e.g. good/working or degraded) and the transitions move the tokens between the different places to model the processes that result in a change in condition of the components (e.g. degradation and failure).

The different states of degradation considered for a component type were chosen to replicate the different degraded conditions described in Network Rail's maintenance standards. The firing times of the transitions representing component degradation and failure are stochastically timed, where the firing time is sampled from a distribution of times to reach degradation or failure for the component. It is assumed that a component may fail from a good/working condition (due to random processes) and also from the degraded conditions, where the degradation increases the rate of failure. When a failure occurs, the cost incurred is sampled from the distribution of failure costs for the failed component (which was found through the analysis of historical failure data). The condition-based maintenance regime implemented by Network Rail is considered, where places represent the revealed degraded condition of a component (which is revealed after routine inspections) and maintenance is scheduled. When a maintenance transition is enabled, its firing time is based on the corresponding maintenance scheduling time, stated in the maintenance standards, for the associated component defect. Opportunistic maintenance is also considered in the model, whereby components requiring

maintenance in the same access area can be maintained during the same maintenance visit at an earlier date.

A whole system model was developed, where the Petri net is hierarchical, with a separate subnet modelling the processes considered for each of the different component types. Multiple instances of the same component type are modelled in the same subnet using individual tokens that are distinguishable. Other subnets are also used to model the renewal of the catenary and contact wires and the occurrence of external failure events, which are a service affecting failure associated with the OLE but are not caused by a component failure and do not damage the components (e.g. bird strikes or objects caught in the OLE). All the components, in a section of OLE studied, are concurrently modelled in the whole system model where the different subnets are interlinked by considering the dependencies between the different components and processes, such as implementing opportunistic maintenance.

The Petri net developed was evaluated using Monte Carlo simulation. A study period of 100-years was simulated to enable the life cycle of most of the components studied to be analysed. Various statistics were collected when the tokens enter certain places. For example, when a component is maintained, a token is fired to a place that records the number of maintenance actions and the time that maintenance occurred. The application of the model was demonstrated through an example study that considered all the OLE components in a single access area containing 2 wire runs. The model calculated an extensive range of outputs that express the expected future performance of the components and the system as a whole, e.g. the mean number of maintenances and failures for the different components and the system, and the expected costs associated with the maintenance and failures of the components and the system, over the 100-year period studied. These outputs can be used to evaluate the effectiveness of the asset management strategy studied and calculate the expected cost of the system. Various statistics that help quantify the uncertainty associated with the outputs were also obtained, such as the maximum and minimum value, standard deviation and interquartile range for the different outputs. A simple one-at-a-time sensitivity analysis was also undertaken to analyse the influence that a variation of the degradation and failure rates of the components has on the total cost of the system and the number of failures.

A complete modelling framework has been developed, where, first of all, the user selects the inputs to the model, which are associated with the components studied and the asset management strategy considered. Then the Petri net model is dynamically generated, according to the inputs, and evaluated to obtain the output results. The inputs are selected using various macros in an Excel document and the Petri net is generated and evaluated using C++ code that was developed as part of this research.

The outputs are written to csv files to allow easy analysis in Excel. The overall framework developed allows the model to be used as part of a tool for modelling the life cycle cost and asset management of the OLE.

The optimum asset management intervention strategies were found using a Genetic Algorithm in conjunction with the Petri net model developed. A multi-objective optimisation was considered, where the total cost and the number of scheduled maintenance visits were minimised, over the 100-year period studied, by finding the optimum inspection intervals, maintenance scheduling times and timing for the renewal of the catenary and contact wires. The optimum asset management intervention strategies found were then compared to the current strategy implemented by Network Rail. In comparison to the current strategy, the most suitable optimum strategy proposed by the model resulted in a similar number of maintenance visits required, but the total cost was approximately 15% less and the number of service affecting failures was also reduced.

7.2 Achievement of the Aims and Objectives

The main aim of this research was to develop a life cycle cost model for the OLE that considers the main asset management intervention actions and calculates the expected future costs of the system, so that different asset management strategies can be evaluated. This aim has been achieved by completing the objective of developing a High Level Petri net model. The methodology has allowed all the main processes that influence the life cycle cost of the system and the processes associated with the asset management actions undertaken to be modelled, such as component degradation, failure, inspection and maintenance. The model is capable of calculating numerous outputs, at different levels of granularity, associated with the life cycle cost of the different components and the system as a whole. In addition, outputs associated with the expected future performance of the system, including the number of failures and maintenance actions for the different components and the system, are also calculated. The detailed variety of outputs allows a thorough analysis of the future expected costs and performance of the system to take place, from which the asset management intervention strategy tested in the model can be evaluated. Using the model to evaluate the life cycle cost and performance of the system was another aim of the research and the example study highlighted how the outputs the model calculated can be beneficial to asset managers and other decision makers.

In addition, to meet the main aim of this research, one of the objectives was to examine historical data and other sources of information to gain a detailed understanding of the degradation and failure behaviour of the OLE components. This objective has been met by obtaining information from literature and various Network Rail sources, which is used in this thesis when describing the

component degradation and failure behaviour and the asset management intervention actions. Historical data was analysed but detailed time to event data was not available, therefore, a lifetime analysis could not be undertaken to find distributions for the times to degradation and failure events for the different components. Instead, these distributions were estimated based on the information extracted from the sources described above. However, historical data was analysed to study the effects of each component type's failure, in terms of the cost incurred, where distributions for the failure cost for each component type were found.

The final objective of this research was to find the optimum asset management intervention strategies that minimise the life cycle cost of the system. This was achieved through the use of a Genetic Algorithm that worked in conjunction with the Petri net model developed. The optimum strategy selected resulted in a 15% reduction in the total cost in comparison to the strategy currently implemented by Network Rail.

In conclusion, this thesis shows that the overall modelling framework developed, which uses the High Level Petri net method, can be used to effectively analyse the life cycle cost of the OLE and evaluate the future performance of the system and the suitability of asset management intervention strategies.

7.3 Contributions to Research

This thesis proposes a more detailed modelling approach not attempted in previous work. The methodology that has been applied, and many of the features used in the model developed, are also applicable to modelling similar processes in other engineering systems. Therefore, this section describes the main ways that this thesis contributes to research associated with the asset management and life cycle cost of the OLE and the modelling of asset management processes, primarily component degradation, failure, inspection and maintenance, using Petri nets.

Information about OLE Asset Management

This thesis has provided a detailed account of the main processes associated with the asset management and life cycle cost of the OLE. The component degradation and failure modes were explained and the asset management intervention actions that are undertaken on the British railway network were also outlined. A discussion of the degradation and failure data that is currently collected and recommendations for how the data collection process can be improved were included. A review of the associated literature that focuses on modelling the asset management of the OLE and similar systems, was also provided.

Application of Petri Nets for Modelling the Asset Management and Life Cycle Cost of the OLE

This research showed how Petri nets can be used to model the processes associated with the asset management and life cycle cost of the OLE. The methodology used High Level Petri nets to stochastically model the degradation, failure, inspection and maintenance of the main OLE components. Condition-based maintenance was considered instead of solely fixed time interval preventative maintenance, commonly considered in previous OLE studies. Furthermore, the whole system model that was developed allowed interactions between the different components studied, such as opportunistic maintenance, to be considered. This model is, therefore, far more detailed than other models focusing on the OLE presented in literature.

Application of Petri Nets for Modelling Asset Management Processes of Large Systems

As the OLE represents a large system consisting of many components that have various dependencies between them, the methodology applied in this research is applicable to modelling asset management processes for other engineering systems. In particular, this research is the first to describe a methodology that follows High Level Petri net standards for modelling the asset management processes of a large engineering system. The model developed shows how a condition-based maintenance regime and opportunistic maintenance can be modelled within the framework stipulated in the standards for High Level Petri nets. This has resulted in the model developed being easier to understand and replicate, and many parts of the Petri net can be easily extended or adapted to include additional processes or capabilities. The model developed also allows the system that is studied to change dynamically, in terms of the number of components studied, by simply changing the set of tokens that can reside in the different places.

The example study presented, for a 2-mile section of OLE, modelled many processes concurrently, due to the number of components studied. In comparison to most other Petri nets described in literature, that model the asset management of engineering systems, the Petri net evaluated in the example study is much larger, in terms of the number of concurrent processes modelled (due to the number of different tokens and transition modes). Despite this, the time taken to evaluate the model was not excessive, taking approximately 1 minute to evaluate a 100-year operating period of a 2-mile section of the OLE.

Extensive Output Results Associated with the Asset Management and Life Cycle Cost of the OLE

The main outputs that should be calculated to analyse the life cycle cost and asset management of the OLE, or for other infrastructure assets that degrade and fail and can also be maintained, were provided. These outputs are extensive and consist of multiple statistics at numerous granularities,

such as the mean yearly failure cost for a component type and the mean yearly failure cost for the overall system. For each output, statistics associated with the uncertainty of the expected values, such as the median, interquartile range and standard deviation, were also calculated. The full range of outputs obtained was more comprehensive and detailed than the outputs presented in previous studies. The use of the different outputs, with respect to evaluating the asset management and life cycle of the system, was also discussed.

Optimisation of Asset Management Strategies and Use of the Genetic Algorithm with Petri Nets

The different input variables that the OLE asset managers have control of and that are suitable for optimisation were discussed, together with the different performance indicators that were maximised or minimised as part of the optimisation procedure. This research showed how the Genetic Algorithm can be used in conjunction with a Petri net model to optimise a process. An accessible overview of how the Genetic Algorithm was implemented and used in conjunction with the Petri net model developed was also provided.

Asset Management Tool

The overall modelling framework developed can be used as an asset management tool, where the user inputs information about the components studied (such as the number of components and their degradation and failure behaviour) and the asset management intervention strategies (such as the inspection intervals and the component maintenance scheduling times) using macros in an Excel document. Based on the inputs, the Petri net model is dynamically generated and evaluated in bespoke C++ software and the outputs are written to a csv file to enable an easy analysis afterwards. This overall process is readily applicable to industry because it allows the model to be easily used to obtain the detailed set of outputs, which allows the analysis of the life cycle cost and asset management of the section of OLE studied. The outputs can also be incorporated into the asset life cycle profiles (ALP), which Network Rail have developed for their different assets. The data within different ALPs is then combined in a life cycle cost tool, which they have developed to analyse multiple assets together (such as the track, OLE and signalling assets) and large sections of the network. This therefore shows the practical use of the model in industry.

7.4 Limitations

The distributions for the time to degradation and failure events for the different components have been estimated based on information obtained from Network Rail engineers and literature. Therefore, these distributions may be inaccurate, particularly in the long term future (where there is currently

little knowledge of the components' behaviour after 60 years) and for the newer OLE systems that are scheduled to be installed (where the components' degradation mechanisms and reliability may differ).

The model assumes that all inspections reveal component defects 100% of the time when in reality this may not be the case for certain defects that are difficult to identify, such as stranding of the catenary wire. Similarly, maintenance is assumed to be perfect and return the components to the good/working condition when in reality component maintenance may be undertaken incorrectly occasionally and have to be rescheduled. System down time, which may occur after a failure event, is not considered which means system availability cannot be calculated using the model.

The model does not take into account any dependencies between different access areas, such as the resource constraints that the maintenance depot responsible for the line is subjected to (as described further below). Therefore, considering numerous access areas at the same time will give the same results as if the model was run separately for each of the different access areas. Furthermore, increasing the number of access areas considered in the model so that an entire electrified line is studied in the same analysis may result in a substantial amount of time to compute the outputs. Resource constraints are not considered in the model and it is assumed that maintenance can always take place when it is scheduled. This is a limitation because, in reality, the maintenance engineers will sometimes have to defer the maintenance of an access area a few days due to the number of available staff and equipment, such as the road rail vehicle, whilst more urgent maintenance is undertaken on another access area.

The fact that the degradation of one component can influence the degradation and failure rate of other components is not fully considered in the model because it is very difficult to quantify the exact influence one component has on another (in terms of its degradation or failure rate). The model does consider the fact that when a wire run of OLE requires adjustments to alleviate poor set-up, the failure rates for the catenary wire, contact wire and droppers are increased. However, the increase in the failure rates was estimated and this feature of the model was mainly included to show how such processes can be considered within the developed framework.

7.5 Future Work

This section outlines the future work that can be undertaken to improve the model and extend its capabilities.

A detailed analysis of historical data should take place to derive the distributions for the time to reach component degradation and failure that are used in the model. This will require better data collection

processes to be put in place, or extensive analysis of paper written records and asset registers from maintenance depots, so that accurate time to event data can be obtained. Recommendations about how the data collection process can be improved and how detailed analysis can be undertaken were provided in section 2.6.3. In particular, the sensitivity analysis that was undertaken using the model showed that the failure rates of the components have a large impact on the number of failures and the total cost of the system. Therefore, particular concentration should be focused on ensuring that good quality data is collected to allow detailed analysis of the component failure rates to take place. The influence that the degradation of certain components has on the degradation and failure rate of other components should also be investigated. This would allow any relationships found between components to be modelled in the Petri net. The downtime of the system, after failure events, could also be included in the model to allow system availability to be studied. This will require data describing the downtime of the system after failure events to be analysed in order to find distributions for the length of time that the system is unavailable for, after a failure. These distributions can then be assigned to transitions that model the downtime of the system after a component failure.

In terms of further work associated with the model developed, there are several additional processes and extensions that can be considered. The size of the section of OLE studied can be expanded: from one access area to the entire length of OLE that a maintenance depot is responsible for, which is usually approximately 100 miles of OLE. The availability of maintenance resources for the maintenance depot can then be modelled and taken into consideration when scheduling maintenance. For example, a specific number of maintenance engineers can be required for maintenance to take place in an access area. If maintenance engineers are available, then maintenance can take place for an access area, otherwise, the maintenance must wait until the next date that maintenance work can be undertaken, i.e. when the system is next out-of-hours and the maintenance engineers are available. This will allow the maintenance scheduling process to be modelled more accurately. Some additional component types could be included in the model, such as neutral sections, as a longer section of electrified line will contain these components in some wire runs. Due to the very large number of components considered, the run time of the model would be significant (estimated to be approximately 10 hours for 100000 simulations for 100 years of operation for a 100 mile section of line, using the current code). As a result, improvements to the code that simulates the Petri net may need to take place to reduce the run time.

In addition to the inspection and maintenance actions modelled, other asset management intervention actions can be developed and tested within the model. For example, after a certain number of years an opportunistic renewal of all the insulators older than 50 years could be scheduled to take place. The influence that the intervention actions developed have on the cost of the system

and its performance, in terms of the number of failures and required maintenance visits, can then be analysed. Furthermore, the intervention actions developed could also be included in the optimisation procedure.

References

- Alan Baxter, 2015. Network Rail A Guide to Overhead Electrification 132787-ALB-GUN-EOH-000001. *Network Rail documentation*. Available at http://www.bathnes.gov.uk/sites/default/files/sitedocuments/Planning-and-Building-Control/Planning/nr_a_guide_to_overhead_electrification.pdf (Accessed 20 December 2016)
- Andrews, J.D. and Moss, T.R., 2002. *Reliability and Risk Assessment*. London and Bury St Edmunds, Professional Engineering Publishing Limited.
- Andrews, J. 2012. A modelling approach to railway track asset management. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, p.56-73.
- Bai, Y., Zhang, J., Liu, W. and Liu, X., 2013. Study on influence of contact wire design parameters on contact characteristics of Pantograph-Catenary. In *2013 IEEE International Conference on Intelligent Rail Transportation (ICIRT)*, IEEE, Beijing, pp. 268-273.
- Billington, J., 1991. *Extensions to coloured Petri nets and their application to protocols*. PhD Thesis, University of Cambridge.
- Billinton, R. and Allan, R., 1983. *Reliability Evaluation of Engineering Systems*. New York, Springer.
- Billinton, R. and Pan, J., 2000. Application of Monte Carlo simulation to optimal maintenance scheduling in a parallel-redundant system. *IEE Proceedings-Generation, Transmission and Distribution*, 147(5), pp.274-278.
- Bobillot, A., Massat, J.P. and Mentel, J.P., 2010. Design of Pantograph-Catenary Systems by Simulation, in *Proceedings of the Tenth International Conference on Computational Structures Technology*, Civil-Comp Press, Stirlingshire, UK.
- British Standards, 1997. BS 5760: Part 23, Guide to Life Cycle Costing.
- British Standards, 2006. BS EN 60812:2006 Analysis Techniques for System Reliability- Procedure for Failure Mode and Effects Analysis.
- British Standards, 2008. PAS 55-1:2008 Asset Management. Part 1. Specification for the optimized management of physical assets.
- British Standards, 2010. BS ISO/IEC 15909-1:2004+A1:2010 Systems and software engineering- High-level Petri nets - Part 1: Concepts, definitions and graphical notation.
- British Standards, 2012. BS EN 62551:2012 Analysis techniques for dependability. Petri net techniques
- British Transport Commission, 1956. *Modernisation of British Railways: the system of electrification for British Railways*. London, Westerham Press Limited.
- British Treasury, 2003. *The Green Book- Appraisal and Evaluation in Central Government*. Available at https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/220541/green_book_complete.pdf (Accessed 15 November 2016).
- Bucca, G. and Collina, A., 2009. A procedure for the wear prediction of collector strip and contact wire in pantograph–catenary system. *Wear*, 266(1), pp.46-59.
- Chen, S.K., Ho, T.K. and Mao, B.H., 2007. Reliability evaluations of railway power supplies by fault-tree analysis. *IET Electric Power Applications*, 1(2), pp.161-172.
- Chong, E.K. and Zak, S.H., 2013. *An introduction to optimization* (4th Edition). Wiley.

- Collina, A., Fossati, F., Papi, M. and Resta, F., 2007. Impact of overhead line irregularity on current collection and diagnostics based on the measurement of pantograph dynamics. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, 221(4), pp.547-559.
- Deb, K., Pratap, A., Agarwal, S. and Meyarivan, T.A.M.T., 2002. A fast and elitist multiobjective genetic algorithm: NSGA-II. *IEEE transactions on evolutionary computation*, 6(2), pp.182-197.
- Department for Transport, 2009. *Britain's Transport Infrastructure- Rail Electrification*. Available at <http://collections.europarchive.org/tna/20100408232230/http://www.dft.gov.uk/pgr/rail/pi/rail-electrification.pdf> (Accessed 20 November 2016).
- Dersin, P. and Valenzuela, R.C., 2012. Application of non-Markovian stochastic petri nets to the modeling of rail system maintenance and availability. In *Proceedings of the 2012 Winter Simulation Conference (WSC)*, IEEE, Berlin, pp. 1-12.
- Dufourd, C., Finkel, A. and Schnoebelen, P., 1998. Reset nets between decidability and undecidability. In *International Colloquium on Automata, Languages, and Programming*, Springer Berlin Heidelberg, Aalborg, pp. 103-115.
- Duque, O., Zorita, A.L., García-Escudero, L.A. and Fernández, M.A., 2009. Criticality determination based on failure records for decision-making in the overhead contact line system. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, 223(5), pp.485-494.
- Fay, M.P., 1999. Comparing several score tests for interval censored data. *Statistics in Medicine*, 18(3), pp.273-285.
- Fouathia, O., Maun, J.C., Labeau, P.E. and Wiot, D., 2005, June. Petri net based Monte Carlo simulation for modeling and analyzing the reliability of distribution substation facilities in Belgian power system. In *18th International Conference and Exhibition on Electricity Distribution (CIRED)*, IET, Turin, pp. 1-5.
- FourFoot, 2016. *Brighton to London Bridge driver's eye view*. YouTube Video Accessed at: <https://www.youtube.com/watch?v=KRugGYNkzCs> (Accessed 15th March 2017).
- Gentle, J.E., 2003. *Random number generation and Monte Carlo methods*. Springer Science & Business Media.
- Girault, C. and Valk, R., 2003. *Petri nets for systems engineering: a guide to modeling, verification, and applications*. Berlin, Springer Berlin Heidelberg.
- Golabi, K., Kulkarni, R.B. and Way, G.B., 1982. A statewide pavement management system. *Interfaces*, 12(6), pp.5-21
- González, F.J., Chover, J.A., Suarez, B. and Vázquez, M., 2008. Dynamic analysis using finite elements to calculate the critical wear section of the contact wire in suburban railway overhead conductor rails. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, 222(2), pp.145-157.
- Hagan, M.T., Demuth, H.B., Beale, M.H. and De Jesús, O., 1996. *Neural network design* (Vol. 20). PWS publishing company, Boston.
- Hamby, D.M., 1994. A review of techniques for parameter sensitivity analysis of environmental models. *Environmental monitoring and assessment*, 32(2), pp.135-154.

- Harell, P., Drugge, L. and Reijm, M., 2005. Study of critical sections in catenary systems during multiple pantograph operation. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, 219(4), pp.203-211.
- Haupt, R.L. and Haupt, S.E., 2004. *Practical genetic algorithms*. Hoboken, John Wiley & Sons.
- Hill, R.J., 1994. Electric railway traction. I. Electric traction and DC traction motor drives. *Power Engineering Journal*, 8(1), pp.47-56.
- Ho, T.K., Chi, Y.L., Ferreira, L., Leung, K.K. and Siu, L.K., 2006. Evaluation of maintenance schedules on railway traction power systems. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, 220(2), pp.91-102.
- Holland, J.H., 1975. *Adaptation in natural and artificial systems: an introductory analysis with applications to biology, control, and artificial intelligence*. The University of Michigan Press.
- International Standards Organisation, 2014. ISO 55000:2014 Asset management -- Overview, principles and terminology.
- International Union of Railways, 2010. *Guidelines for the Application of Asset Management in Railway Infrastructure Organisations*. Accessed at http://uic.org/IMG/pdf/2010_guidelines_for_the_application_of_asset_management.pdf (Accessed 18 November 2016).
- Institute of Asset Management, 2015. *Asset Management - an anatomy*.
- Jensen, K. and Kristensen, L.M., 2009. *Coloured Petri nets: modelling and validation of concurrent systems*. Dordrecht, Springer Science & Business Media.
- Kiessling, F., Puschmann, R., Schmieder, A. and Schneider, E., 2009. *Contact Lines for Electric Railways*. Erlangen, Publicis.
- Kirchsteiger, C., 1999. On the use of probabilistic and deterministic methods in risk analysis. *Journal of Loss Prevention in the Process Industries*, 12(5), pp.399-419.
- Klein, J.P. and Moeschberger, M.L., 2003. *Survival analysis: statistical methods for censored and truncated data*. New York, Springer-Verlag.
- Le, B., 2014. *Modelling Railway Bridge Asset Management*. PhD Thesis, University of Nottingham.
- Le, B. and Andrews, J., 2013. Modelling railway bridge asset management. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, 227(6), pp.644-656.
- Le, B. and Andrews, J., 2016. Modelling wind turbine degradation and maintenance. *Wind Energy* Volume 19 (4), pp. 571-591.
- Meier-Hirmer, C., Sourget, F., and Roussignol, M. 2006. Lifetime estimation of catenary components. In *Proceedings of the European Safety and Reliability Conference, ESREL 2006*, Estoril, Portugal, Safety and reliability for managing risk – Soares, C.G. and Zio, E. (eds); 2006 Taylor and Francis Group, London, 929-934.
- Min, L. X., Yong, W. J., Yuan, Y., & Yan, X. W. 2009. Multiobjective optimization of preventive maintenance schedule on traction power system in high-speed railway. In *Reliability and Maintainability Symposium, 2009 (RAMS 2009)*, Fort Worth, IEEE, pp.365-370.
- Network Rail, 2011. *NR/L2/ELP/21087 Specification of maintenance frequency and defect prioritisation of 25kV overhead line electrification equipment*. Internal Network Rail documentation.

- Network Rail, 2012. *Electrical Power Asset Policy*. Internal Network Rail documentation.
- Network Rail, 2014. *GW Reliability and Maintenance Re-appraisals-All Allocation Designs and Series 2 high tension-18-02-14*. Internal Network Rail documentation.
- Network Rail, 2015. *OLE High Level Inspection*. YouTube Video Accessed at <https://www.youtube.com/watch?v=ufhBHFrYq1U> (Accessed 13th January 2017).
- Office of Rail and Road, 2015. Rail infrastructure, assets and environment. Accessed at http://orr.gov.uk/__data/assets/pdf_file/0007/19537/rail-infrastructure-assets-and-environment-2014-15.pdf (Accessed 13 January 2017).
- Pack, J.R. and Altshuler, A., 1989. Fragile foundations: A report on America's public works. *Journal of Policy Analysis and Management*, 8(3), Wiley, pp.505-508.
- Petri, C. A., 1962. *Kommunikation mit automaten*. PhD Thesis, University of Bonn.
- Prescott, D. and Andrews, J., 2013. Investigating railway track asset management using a Markov analysis. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, 229(4), pp.402-416.
- Railway Safety and Standards Board, 2007. *T346: Investigating the potential for improvements in electrification systems - Summary report*.
- Railway Safety and Standards Board, 2007. *T633: Study on further electrification of Britain's railway network*.
- Remenyte-Prescott, R. and Andrews, J., 2013. Review of Infrastructure Asset Management Methods for Networked Systems. In *19th AR2TS, Advances in Risk and Reliability Technology Symposium, UK*.
- Skinner, M., Kirwan, A., & Williams, J. 2011. Challenges of developing whole life cycle cost models for Network Rail's top 30 assets. In *IET and IAM Asset Management Conference 2011, London*.
- Smith, D.J., 2011. *Reliability, Maintainability and Risk: Practical methods for engineers including reliability centred maintenance and safety-related systems*. Burlington, Elsevier.
- Tsai, Y.T., Wang, K.S. and Tsai, L.C., 2004. A study of availability-centered preventive maintenance for multi-component systems. *Reliability Engineering & System Safety*, 84(3), pp.261-270.
- Volovoi, V., 2004. Modeling of system reliability Petri nets with aging tokens. *Reliability Engineering & System Safety*, 84(2), pp.149-161.
- Wai Chung, S., 2011. *A Survey of Contact Wire Wear Parameters and the Development of a Model to Predict Wire Wear by Using the Artificial Neural Network*. PhD Thesis, City University Hong Kong.
- Zitzler, E., Deb, K. and Thiele, L., 2000. Comparison of multiobjective evolutionary algorithms: Empirical results. *Evolutionary computation*, 8(2), pp.173-195.
- Zorita, A.L., Duque, O., Fernández, M.A. and García-Escudero, L.A., 2010. Determination and optimization of the maintenance frequencies in the overhead contact line system. *Journal of Transportation Engineering*, 136(11), pp.964-972.

Appendix A Petri Net Subnets

This appendix shows the different subnets that are present in the whole system model and provides a brief description about how they represent the processes modelled. Firstly, the different data values and variables that are used in the subnets are listed and defined in Appendix A-1. The subnets that model the degradation, failure, inspection and maintenance of the main OLE components, that are studied in detail, are presented in Appendix A-2 along with the other subnets, that model large scale renewals, high level inspection scheduling and random failures caused by external influences. The whole system model, that shows how all the subnets are linked together in a hierarchical Petri net was presented in Figure 4-13 (on page 142 in Chapter 4).

Appendix A-1 Data Values and Variables Used

Table A-1 List of Data Values Used

Data Value	Description	Type	Property
ID	Component ID	integer	{0,1,...,number of instances of component type-1}
SPAN	The span of OLE the component is located in	integer	{0,1,...,number of spans-1}
WRUN	The wire run of OLE the component is located in	integer	{0,1,...,number of wire runs-1}
AREA	The access area the component is located in	integer	{0,1,... number of areas - 1}
INST_DATE	The installation date of the component	integer	Relative to the start of the simulation
LAST_MAINT_DATE	The date that maintenance was last undertaken on the component	integer	Relative to the start of the simulation
PREV_MAINT	The number of previous maintenance actions undertaken on the component	integer	$\mathbb{N}_0$ (Positive Integers including 0)
MAINT_DATE	The date maintenance of the component must be completed by	integer	Relative to the start of the simulation
MAINT_STARTED	Maintenance is currently underway	Boolean	TRUE if maintenance has started, otherwise FALSE
TIME_REMAINING	Number of time units remaining in a maintenance visit	integer	{0,1,..., number of time units in a visit}
COST	The cost associated with component failure or maintenance	integer	$\mathbb{N}$ (Positive Integers > 0)

N.B. Sets of the data values listed above are created for places in the subnets, these sets are defined in the associated appendices.

Table A-2 List of Variables Used

Variables	Data Value It Binds to
id	<i>ID</i>
s	<i>SPAN</i>
w	<i>WRUN</i>
a	<i>AREA</i>
in	<i>INST_DATE</i>
lm	<i>LAST_MAINT_DATE</i>
pm	<i>PREV_MAINT</i>
md	<i>MAINT_DATE</i>
tr	<i>TIME_REMAINING</i>
m	<i>MAINT_STARTED</i>
Variables that Do Not Bind to Data Values Directly	
sim_time = the current simulation time	
RAND = uniformly generated random number between 0 and 1	

N.B. Sets of the variables listed above are created for arcs in the subnets, these sets are defined in the associated appendices.

Appendix A-2 Subnets

Appendix A-2-1 Catenary Wire Subnet

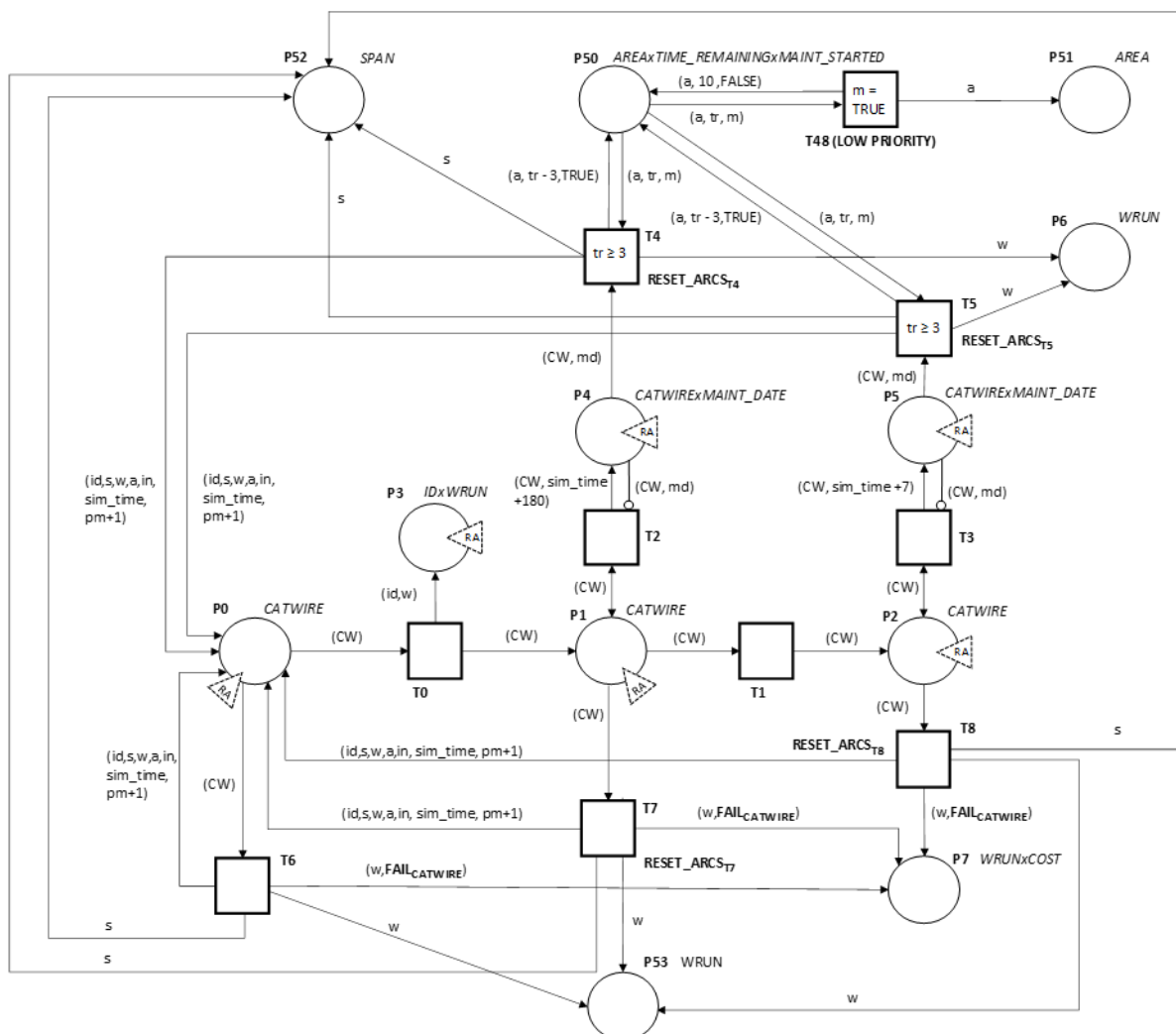


Figure A-1 Catenary Wire Subnet (Main)

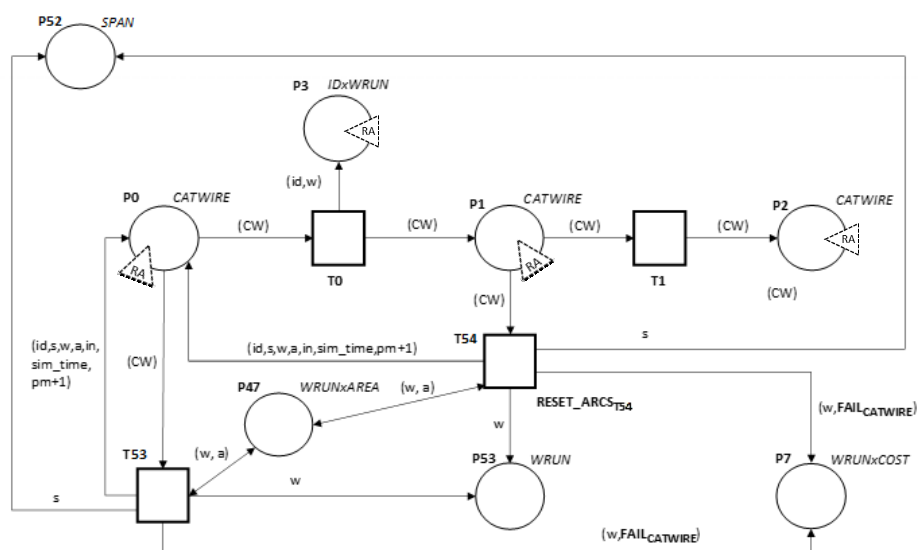


Figure A-2 Additional Transitions in Catenary Wire Subnet

Notes:

Type *CATWIRE* is the Cartesian product of data values: ID x SPAN x WRUN x AREA x INST_DATE x LAST_MAINT_DATE x PREV_MAINT. The tokens containing this set of data values represent a section of the catenary wire. Variable CW is a set of variables (id, s, w, a, in, lm, pm). The arcs containing the variable CW therefore bind to the tokens representing a section of the catenary wire.

Figure A-2 shows the additional failure transitions, that model the failure of a section of the catenary wire occurring due to poor set-up of the wire run that it is located in. This process is shown in a separate figure for clearer presentation. Place P47 is a global place, linked to other subnets, and signifies that the wire run requires adjustments to alleviate poor set-up issues (such as incorrect height and stagger of the system). This was explained in section 4.9.2 on page 129.

To keep the figures clearer, some transitions are not shown. Transition T55, which models the failure due to poor set-up of the wire run, when the section of catenary wire is in the severely degraded condition. This transition is identical to transition T54, but instead of an input arc connected to place P1, it has an input arc connected to place P2 (i.e. the place representing a severely degraded condition). Similarly, additional transitions, representing opportunistic inspection also exist. T60 and T61 mimic transition T2 and T62 and T63 mimic transition T3 in the same way that was described in section 4.12.1 on page 138.

Table A-3 Description of Places used in the Catenary Wire Subnet

Place	Description
P0	Good / Working Condition.
P1	Degraded Condition (section of catenary wire has a single strand of wire burst or minor damage).
P2	Severely Degraded Condition (section of catenary wire has multiple strands of wire burst or extensive damage).
P3	Records statistics associated with the number of degraded sections of catenary wire for a certain wire run.
P4	Revealed Degraded Condition (the maintenance engineers are aware of the degradation and maintenance is scheduled).
P5	Revealed Severely Degraded Condition (the maintenance engineers are aware of the degradation and maintenance is scheduled).
P6	Records statistics associated with the number of maintenance works undertaken on the wire run of catenary wire.
P7	Records statistics associated with the number of service affecting failures of the catenary wire and the corresponding costs incurred.
P47 (global)	The wire run of OLE requires adjustment, due to poor set-up. (Model assumes that the catenary wire can fail as a result of poor set-up of the wire run).
P50 (global)	Describes the current maintenance status of the access area.
P51 (global)	Records statistics associated with the total number of maintenance visits to an access area.
P52 (global)	The span of OLE is currently undergoing maintenance. This is an enabling place for transitions that represent opportunistic high level inspection of components located in this span.
P53 (global)	The wire run of OLE contains a failed component. This is an enabling place for transitions that represent opportunistic low level inspection of components located in this wire run.

Table A-4 Information for the Transitions in the Catenary Wire Subnet

Transition	Function/ Feature	Information (all times given in days)
T0	Firing time	If pm = 0 then Sampled from Weibull distribution: $\beta=2.5$, $\eta=43800$ Else Sampled from Weibull distribution: $\beta=1.5$, $\eta=36500$
T1	Firing Time	Sampled from Weibull distribution: $\beta=3$, $\eta=1825$
T2 & T3	Firing Time	= sim_time - date of next low level inspection (every 28 days)
T4 & T5	Firing Time	If m = 'TRUE' then Fire Time = 0 Else Fire Time = md – sim_time
T4	RESET_ARCS _{T4}	Marking = 0 for all tokens with ID = id in: P1, P2, P3 and P5
T5	RESET_ARCS _{T5}	Marking = 0 for all tokens with ID = id in: P2, P3 and P4
T6, T7, T8, T53, T54 & T55	FAIL _{CATWIRE}	= $\exp(\mu + \sigma Z)$ Samples from lognormal distribution μ and σ are location and scale parameters respectively, on the request of Network Rail the values are not shown. Z is a standard normal random number
T6	Firing Time	If pm = 0 then Sampled from exponential distribution: $\lambda=5.07E-07$ Else Sampled from exponential distribution: $\lambda=6.75E-07$
T7	Firing Time	Sampled from exponential distribution: $\lambda=2.74E-04$
T7	RESET_ARCS _{T7}	Marking = 0 for all tokens with ID = id in: P3 and P4
T8	Firing Time	Sampled from Weibull distribution: $\beta=3$, $\eta=500$
T8	RESET_ARCS _{T8}	Marking = 0 for all tokens with ID = id in: P3, P4 and P5
T48	Firing Time	= 0 (has a LOW PRIORITY, meaning it fires after every other transition that is scheduled to fire at the same time)
T53, T54 & T55	Firing Time	Sampled from exponential distribution: $\lambda=1.01E-07$
T53	RESET_ARCS _{T53}	Marking = 0 for all tokens with ID = id in: P3 and P4
T54	RESET_ARCS _{T54}	Marking = 0 for all tokens with ID = id in: P3, P4 and P5
T60, T61, T62 & T63	Firing Time	=0 (has a HIGH PRIORITY, meaning they fire before transitions with low or normal priority) N.B. transitions not shown in the figure, see notes.

Appendix A-2-2 Contact Wire Subnet

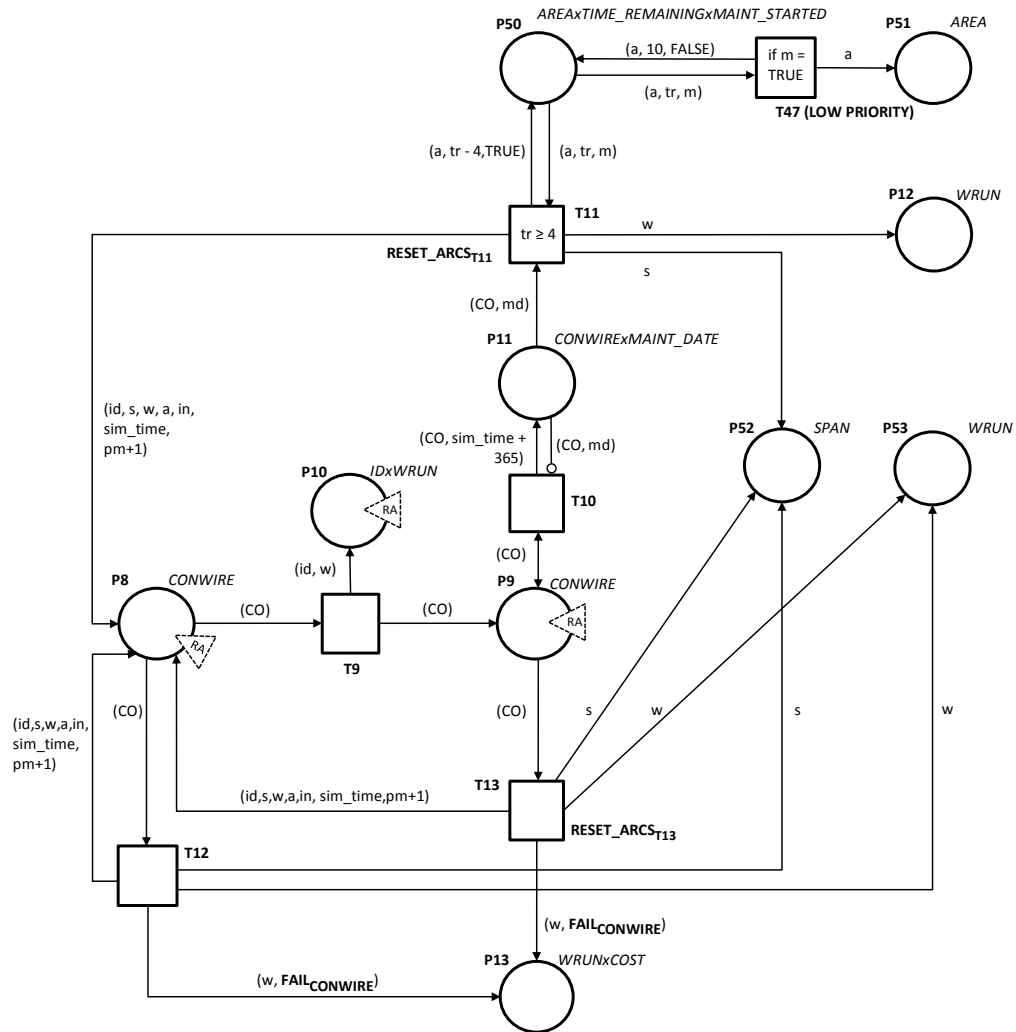


Figure A-3 Contact Wire Subnet (Main)

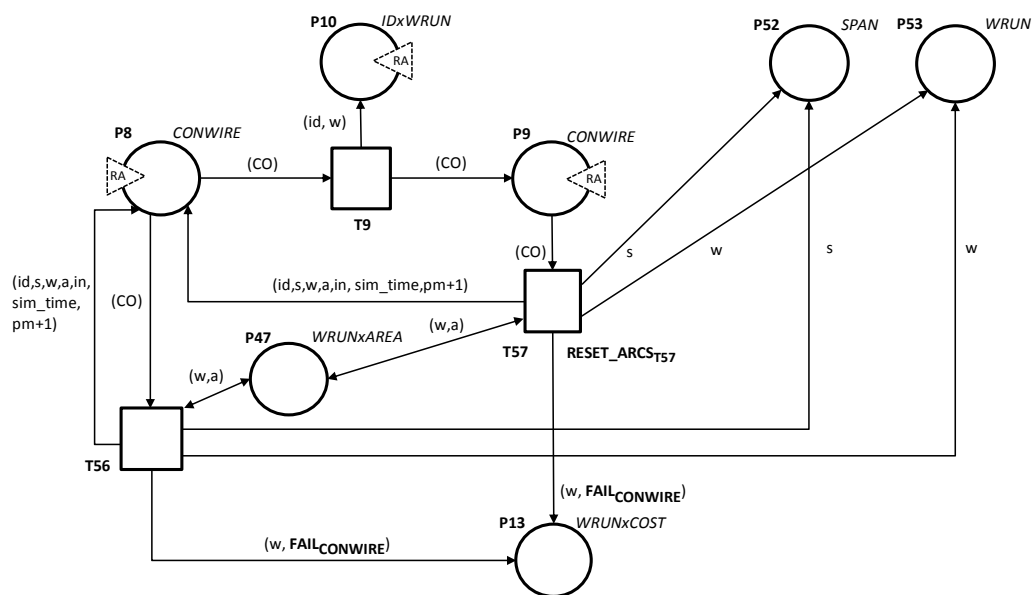


Figure A-4 Additional Transitions in Contact Wire Subnet

Notes:

Type *CONWIRE* is the Cartesian product of data values: ID x SPAN x WRUN x AREA x INST_DATE x LAST_MAINT_DATE x PREV_MAINT. The tokens containing this set of data values represent a section of the contact wire. Variable CO is a set of variables (id, s, w, a, in, lm, pm). The arcs containing the variable CO therefore bind to the tokens representing a section of the contact wire.

Figure A-4 shows the additional failure transitions, that model the failure of a section of the contact wire occurring due to poor set-up of the wire run that it is located in. This process is shown in a separate figure for clearer presentation. Place P47 is a global place, linked to other subnets, and signifies that the wire run requires adjustments to alleviate poor set-up issues (such as incorrect height and stagger of the system). This was explained in section 4.9.2 on page 129. Note that opportunistic inspection of the contact wire is not modelled because the wear of the wire is not measured during maintenance of other components.

Table A-5 Description of Places used in the Contact Wire Subnet

Place	Description
P8	Good / Working Condition.
P9	Degraded Condition (section of wire is worn or damaged).
P10	Records statistics associated with the number of degraded sections of contact wire for a certain wire run.
P11	Revealed Degraded Condition (the maintenance engineers are aware of the degradation and maintenance is scheduled).
P12	Records statistics associated with the number of maintenance works undertaken on the wire run of contact wire.
P13	Records statistics associated with the number of service affecting failures of the contact wire and the corresponding costs incurred.
P47 (global)	The wire run of OLE requires adjustment, due to poor set-up. (Model assumes that the contact wire can fail as a result of poor set-up of the wire run).
P50 (global)	Describes the current maintenance status of the access area.
P51 (global)	Records statistics associated with the total number of maintenance visits to an access area.
P52 (global)	The span of OLE is currently undergoing maintenance. This is an enabling place for transitions that represent opportunistic high level inspection of components located in this span.
P53 (global)	The wire run of OLE contains a failed component. This is an enabling place for transitions that represent opportunistic low level inspection of components located in this wire run.

Table A-6 Information for the Transitions in the Contact Wire Subnet

Transition	Function/ Feature	Information (all times given in days)
T9	Firing time	If pm = 0 then Sampled from Weibull distribution: $\beta=2.5$, $\eta=40150$ Else Sampled from Weibull distribution: $\beta=1.5$, $\eta=21900$
T10	Firing Time	= sim_time - date of next new measurement train (every 365 days)
T11	Firing Time	If m = 'TRUE' then

		Fire Time = 0 Else Fire Time = md – sim_time
T11	RESET_ARCS _{T11}	Marking = 0 for all tokens with ID = id in: P9 and P10
T12, T13, T55 & T56	FAIL _{CONWIRE}	$= \exp(\mu + \sigma Z)$ Samples from lognormal distribution μ and σ are location and scale parameters respectively, on the request of Network Rail the values are not shown. Z is a standard normal random number
T12	Firing Time	If pm = 0 then Sampled from exponential distribution: $\lambda=7.12E-06$ Else Sampled from exponential distribution: $\lambda=9.49E-06$
T13	Firing Time	Sampled from Weibull distribution: $\beta=1.5$, $\eta=1460$
T13	RESET_ARCS _{T13}	Marking = 0 for all tokens with ID = id in: P10 and P11
T48	Firing Time	= 0 (has a LOW PRIORITY, meaning it fires after every other transition that is scheduled to fire at the same time)
T56 & T57	Firing Time	Sampled from exponential distribution: $\lambda=1.42E-07$
T57	RESET_ARCS _{T57}	Marking = 0 for all tokens with ID = id in: P10 and P11

Appendix A-2-3 Dropper Subnet

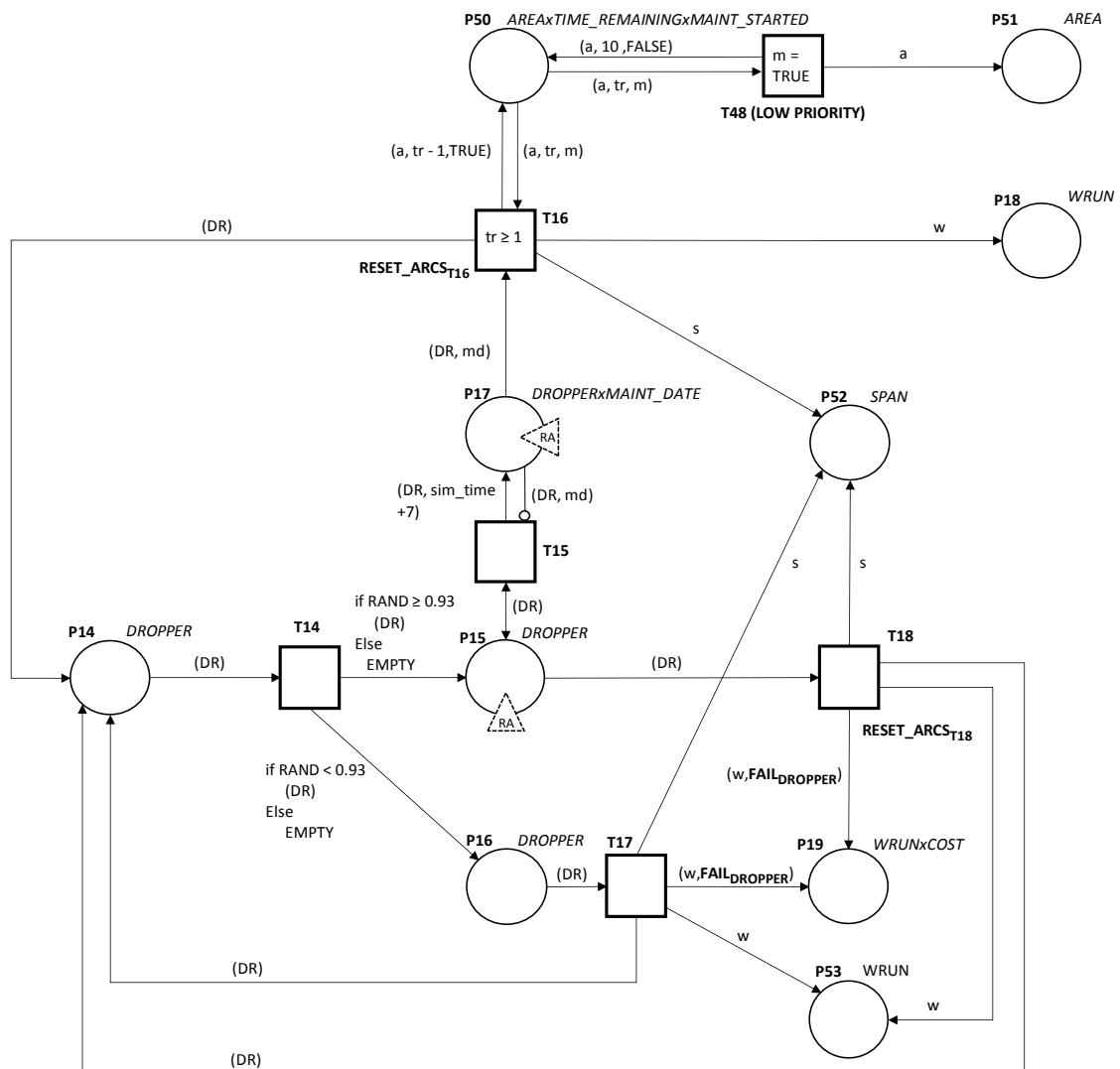


Figure A-5 Dropper Subnet

Notes:

Type *DROPPER* is the Cartesian product of data values: ID x SPAN x WRUN x AREA x INST_DATE. The tokens containing this set of data values represent a span of droppers. Variable DR is a set of variables (id, s, w, a, in). The arcs containing the variable DR therefore bind to the tokens representing a span of droppers. Transition T14 generates a random number, which is used in the arc expressions listed in its output arcs as the variable called RAND. Opportunistic inspections of droppers are not modelled because the inspection interval for droppers is assumed to be very short (every day due to train driver reports).

Table A-7 Description of Places used in the Dropper Subnet

Place	Description
P14	Good / Working Condition.
P15	Dropper failed, but clear of contact wire.
P16	Dropper failed and in danger of interfering with pantographs (or believed to be in danger).
P17	Revealed failed dropper (the maintenance engineers are aware of the issue and maintenance is scheduled, dropper is accessed to be clear of the contact wire).
P18	Records statistics associated with the number of maintenance works undertaken for droppers.
P19	Records statistics associated with the number of service affecting failures of droppers and the corresponding costs incurred.
P50 (global)	Describes the current maintenance status of the access area.
P51 (global)	Records statistics associated with the total number of maintenance visits to an access area.
P52 (global)	The span of OLE is currently undergoing maintenance. This is an enabling place for transitions that represent opportunistic high level inspection of components located in this span.
P53 (global)	The wire run of OLE contains a failed component. This is an enabling place for transitions that represent opportunistic low level inspection of components located in this wire run.

Table A-8 Information for the Transitions in the Dropper Subnet

Transition	Function/ Feature	Information (all times given in days)
T14	Firing time	Sampled from exponential distribution: $\lambda=2.26E-05$
T15	Firing Time	= 1
T16	Firing Time	If m = 'TRUE' then Fire Time = 0 Else Fire Time = md – sim_time
T16	RESET_ARCS _{T16}	Marking = 0 for all tokens with ID = id in: P15
T17 & T18	FAIL _{DROPPER}	= $\exp(\mu + \sigma Z)$ Samples from lognormal distribution μ and σ are location and scale parameters respectively, on the request of Network Rail the values are not shown. Z is a standard normal random number
T17	Firing Time	= 0
T18	Firing Time	Sampled from Weibull distribution: $\beta=2$, $\eta=365$
T13	RESET_ARCS _{T18}	Marking = 0 for all tokens with ID = id in: P17
T48	Firing Time	= 0 (has a LOW PRIORITY, meaning it fires after every other transition that is scheduled to fire at the same time)

Appendix A-2-4 Insulator Subnet

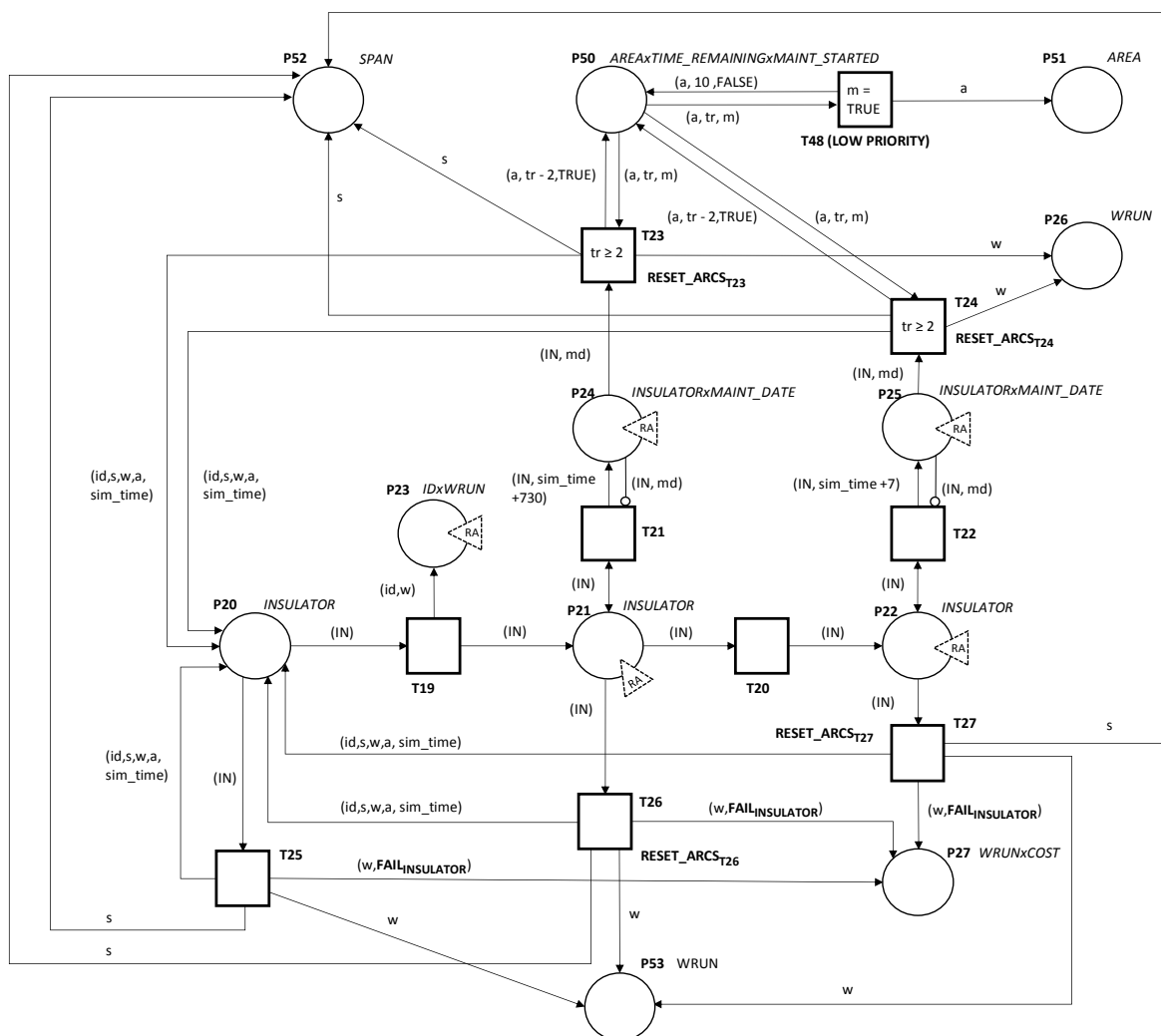


Figure A-6 Insulator Subnet

Notes:

Type *INSULATOR* is the Cartesian product of data values: ID x SPAN x WRUN x AREA x INST_DATE. The tokens containing this set of data values represent an insulator. Variable IN is a set of variables (id, s, w, a, in). The arcs containing the variable IN therefore bind to the tokens representing an insulator.

To keep the figure clearer, some transitions are not shown. Transitions representing the opportunistic inspection of insulators, during maintenance of other components and after failure events, also exist. T64 and T65 mimic transition T21 and T66 and T67 mimic transition T22 in the same way that was described in section 4.12.1 on page 138.

Table A-9 Description of Places used in the Insulator Subnet

Place	Description
P20	Good / Working Condition.
P21	Degraded Condition (insulator has <3 sheds broken or minor mechanical damage).
P22	Severely Degraded Condition (insulator has 3 or more sheds broken or major mechanical damage).

P23	Records statistics associated with the number of degraded insulators in a certain wire run.
P24	Revealed Degraded Condition (the maintenance engineers are aware of the degradation and maintenance is scheduled).
P25	Revealed Severely Degraded Condition (the maintenance engineers are aware of the degradation and maintenance is scheduled).
P26	Records statistics associated with the number of maintenance works undertaken on insulators.
P27	Records statistics associated with the number of service affecting failures of insulators and the corresponding costs incurred.
P50 (global)	Describes the current maintenance status of the access area.
P51 (global)	Records statistics associated with the total number of maintenance visits to an access area.
P52 (global)	The span of OLE is currently undergoing maintenance. This is an enabling place for transitions that represent opportunistic high level inspection of components located in this span.
P53 (global)	The wire run of OLE contains a failed component. This is an enabling place for transitions that represent opportunistic low level inspection of components located in this wire run.

Table A-10 Information for the Transitions in the Insulator Subnet

Transition	Function/ Feature	Information (all times given in days)
T19	Firing time	Sampled from Weibull distribution: $\beta=1.3$, $\eta=32850$
T20	Firing Time	Sampled from Weibull distribution: $\beta=3$, $\eta=3650$
T21 & T22	Firing Time	= sim_time - date of next cab patrol inspection (every 14 days)
T23 & T24	Firing Time	If m = 'TRUE' then Fire Time = 0 Else Fire Time = md – sim_time
T23	RESET_ARCS _{T4}	Marking = 0 for all tokens with ID = id in: P21, P22, P23 and P25
T24	RESET_ARCS _{T5}	Marking = 0 for all tokens with ID = id in: P22, P23 and P24
T25, T26 & T27	FAIL _{INSULTATOR}	= $\exp(\mu + \sigma Z)$ Samples from lognormal distribution μ and σ are location and scale parameters respectively, on the request of Network Rail the values are not shown. Z is a standard normal random number
T25	Firing Time	Sampled from exponential distribution: $\lambda=7.00E-08$
T26	Firing Time	Sampled from exponential distribution: $\lambda=5.48E-05$
T26	RESET_ARCS _{T26}	Marking = 0 for all tokens with ID = id in: P23 and P24
T27	Firing Time	Sampled from Weibull distribution: $\beta=3$, $\eta=1095$
T27	RESET_ARCS _{T27}	Marking = 0 for all tokens with ID = id in: P23, P24 and P25
T48	Firing Time	= 0 (has a LOW PRIORITY, meaning it fires after every other transition that is scheduled to fire at the same time)
T64, T65, T66 & T67	Firing Time	=0 (has a HIGH PRIORITY, meaning they fire before transitions with low or normal priority) N.B. transitions not shown in the figure, see notes.

Appendix A-2-5 Registration Equipment Subnet

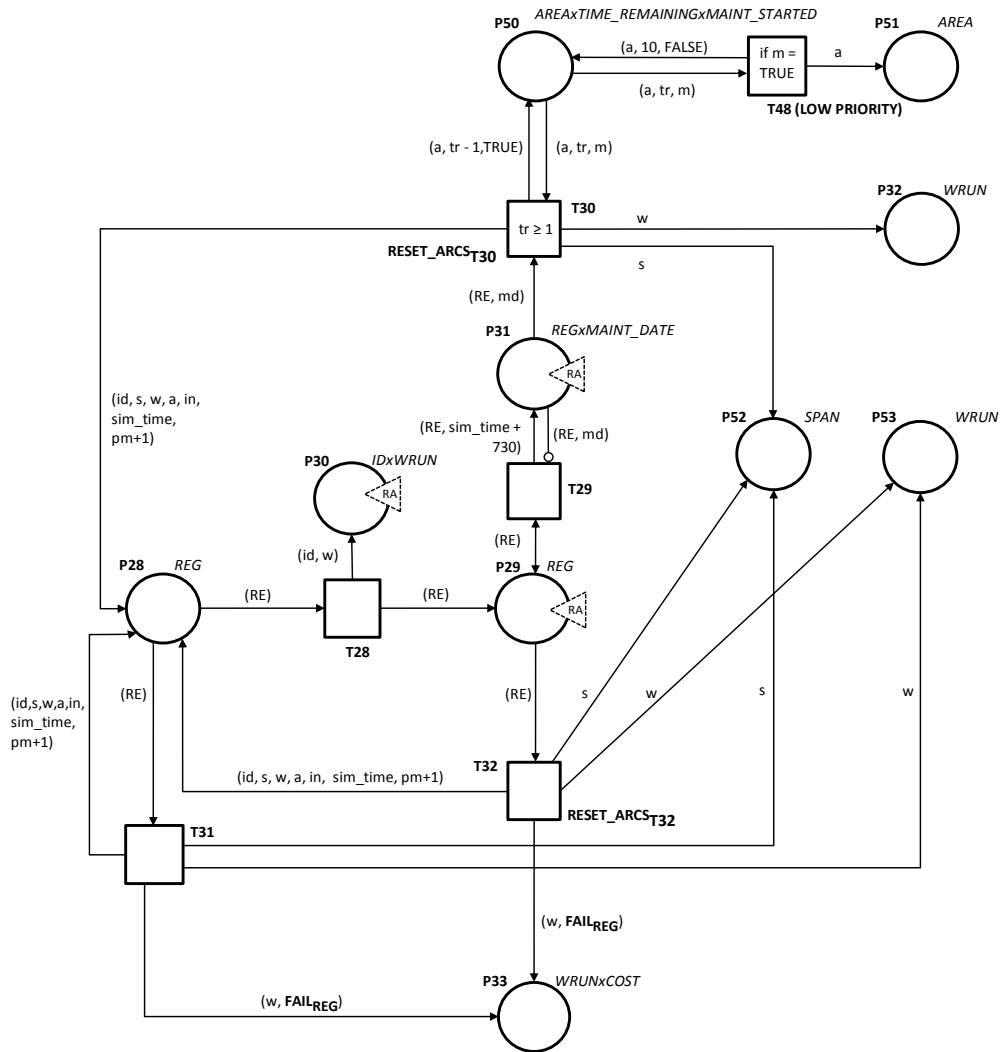


Figure A-7 Registration Equipment Subnet (Main)

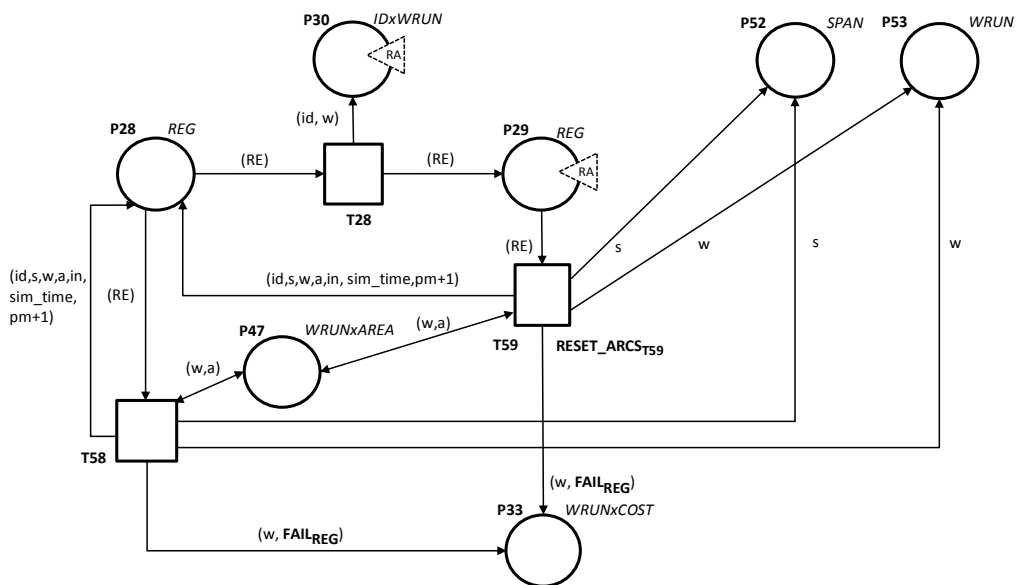


Figure A-8 Additional Transitions in Registration Equipment Subnet

Notes:

Type *REG* is the Cartesian product of data values: ID x SPAN x WRUN x AREA x INST_DATE x LAST_MAINT_DATE x PREV_MAINT. The tokens containing this set of data values represent the registration equipment. Variable RE is a set of variables (id, s, w, a, in, lm, pm). The arcs containing the variable RE therefore bind to the tokens representing the registration equipment.

To keep Figure A-7 clearer, some transitions are not shown. Transitions representing the opportunistic inspection of the registration equipment during maintenance of other components and after failure events, also exist. T68 and T69 mimic transition T29 in the same way that was described in section 4.12.1 on page 138.

Figure A-8 shows the additional failure transitions, that model the failure of the registration equipment occurring due to poor set-up of the wire run that it is located in. This process is shown in a separate figure for clearer presentation. Place P47 is a global place, linked to other subnets, and signifies that the wire run requires adjustments to alleviate poor set-up issues (such as incorrect height and stagger of the system). This was explained in section 4.9.2 on page 129.

Table A-11 Description of Places used in the Registration Equipment Subnet

Place	Description
P28	Good / Working Condition.
P29	Degraded Condition (registration equipment is damaged, seized or loose).
P30	Records statistics associated with the number of degraded registration equipment components in a wire run.
P31	Revealed Degraded Condition (the maintenance engineers are aware of the degradation and maintenance is scheduled).
P32	Records statistics associated with the number of maintenance works undertaken on the registration equipment.
P33	Records statistics associated with the number of service affecting failures of the registration equipment and the corresponding costs incurred.
P47 (global)	The wire run of OLE requires adjustment, due to poor set-up. (Model assumes that the registration equipment can fail as a result of poor set-up of the wire run).
P50 (global)	Describes the current maintenance status of the access area.
P51 (global)	Records statistics associated with the total number of maintenance visits to an access area.
P52 (global)	The span of OLE is currently undergoing maintenance. This is an enabling place for transitions that represent opportunistic high level inspection of components located in this span.
P53 (global)	The wire run of OLE contains a failed component. This is an enabling place for transitions that represent opportunistic low level inspection of components located in this wire run.

Table A-12 Information for the Transitions in the Registration Equipment Subnet

Transition	Function/ Feature	Information (all times given in days)
T28	Firing time	Sampled from Weibull distribution: $\beta=2.5$, $\eta=25550$
T29	Firing Time	= sim_time - date of next low level inspection (every 28 days)
T30	Firing Time	If m = 'TRUE' then Fire Time = 0 Else Fire Time = md – sim_time
T30	RESET_ARCS _{T30}	Marking = 0 for all tokens with ID = id in: P29 and P30
T31, T32, T58 & T59	FAIL _{REG}	= $\exp(\mu + \sigma Z)$ Samples from lognormal distribution μ and σ are location and scale parameters respectively, on the request of Network Rail the values are not shown. Z is a standard normal random number
T31	Firing Time	Sampled from exponential distribution: $\lambda=2.85E-07$
T32	Firing Time	Sampled from Weibull distribution: $\beta=2$, $\eta=3650$
T32	RESET_ARCS _{T32}	Marking = 0 for all tokens with ID = id in: P30 and P31
T48	Firing Time	= 0 (has a LOW PRIORITY, meaning it fires after every other transition that is scheduled to fire at the same time)
T58 & T59	Firing Time	Sampled from exponential distribution: $\lambda=5.70E-08$
T59	RESET_ARCS _{T59}	Marking = 0 for all tokens with ID = id in: P30 and P31
T68 & T69	Firing Time	=0 (has a HIGH PRIORITY, meaning they fire before transitions with low or normal priority) N.B. transitions not shown in the figure, see notes.

Appendix A-2-6 Return Conductor Subnet

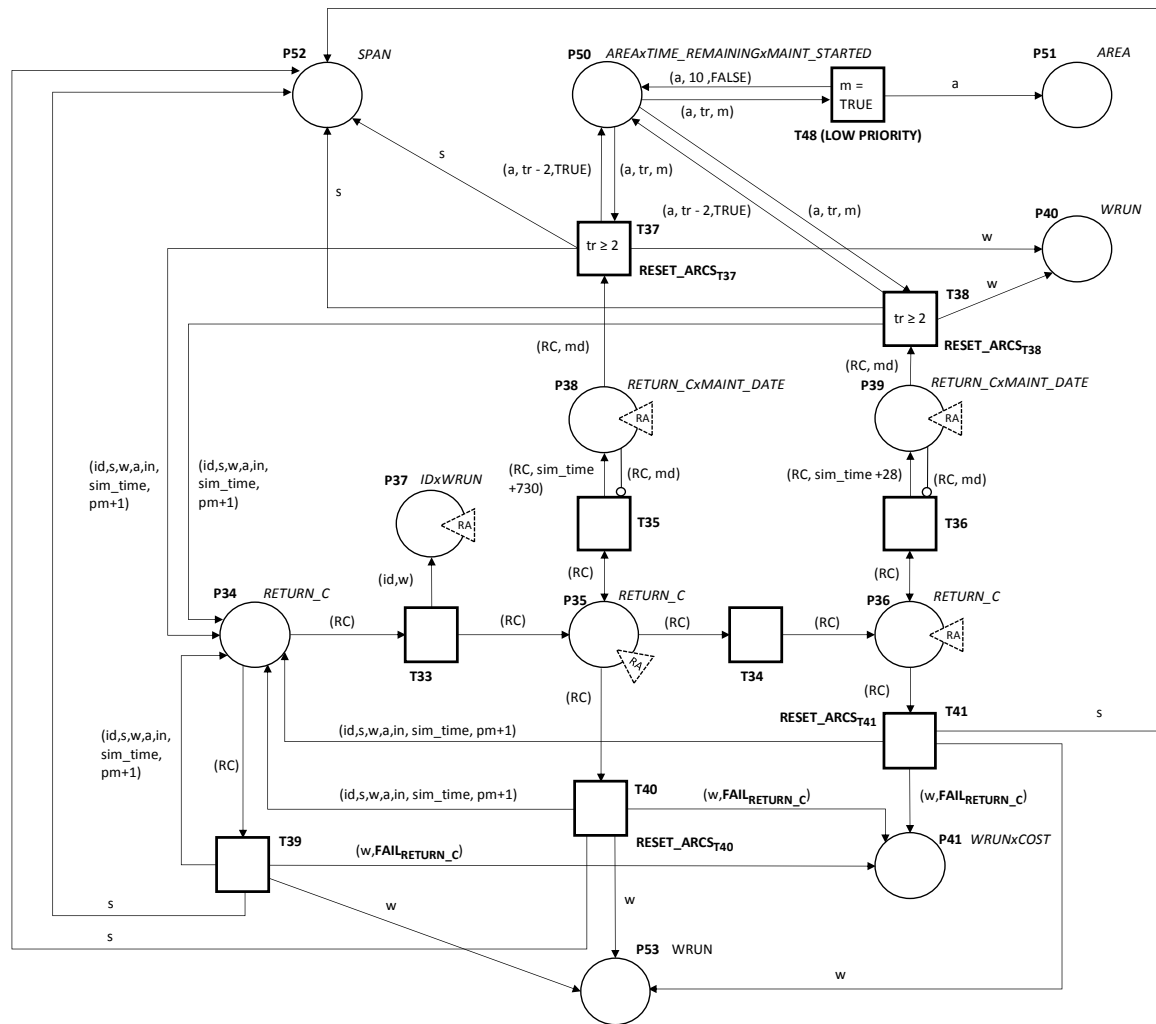


Figure A-9 Return Conductor Subnet

Notes:

Type *RETURN_C* is the Cartesian product of data values: ID x SPAN x WRUN x AREA x INST_DATE x LAST_MAINT_DATE x PREV_MAINT. The tokens containing this set of data values represent a section of the return conductor. Variable RC is a set of variables (id, s, w, a, in, lm, pm). The arcs containing the variable RC therefore bind to the tokens representing a section of the return conductor.

To keep the figure clearer, some transitions are not shown. Transitions representing the opportunistic inspection of the return conductor, during maintenance of other components and after failure events, also exist. T70 and T71 mimic transition T35 and T72 and T73 mimic transition T36 in the same way that was described in section 4.12.1 on page 138.

Table A-13 Description of Places used in the Return Conductor Subnet

Place	Description
P34	Good / Working Condition.
P35	Degraded Condition (minor damage or incorrect tension).
P36	Severely Degraded Condition (major damage or severely).

P37	Records statistics associated with the number of degraded sections of the return conductor in a certain wire run.
P38	Revealed Degraded Condition (the maintenance engineers are aware of the degradation and maintenance is scheduled).
P39	Revealed Severely Degraded Condition (the maintenance engineers are aware of the degradation and maintenance is scheduled).
P40	Records statistics associated with the number of maintenance works undertaken on the return conductor.
P41	Records statistics associated with the number of service affecting failures of the return conductor and the corresponding costs incurred.
P50 (global)	Describes the current maintenance status of the access area.
P51 (global)	Records statistics associated with the total number of maintenance visits to an access area.
P52 (global)	The span of OLE is currently undergoing maintenance. This is an enabling place for transitions that represent opportunistic high level inspection of components located in this span.
P53 (global)	The wire run of OLE contains a failed component. This is an enabling place for transitions that represent opportunistic low level inspection of components located in this wire run.

Table A-14 Information for the Transitions in the Return Conductor Subnet

Transition	Function/ Feature	Information (all times given in days)
T33	Firing time	Sampled from Weibull distribution: $\beta=1.5$, $\eta=91250$
T34	Firing Time	Sampled from Weibull distribution: $\beta=2$, $\eta=5000$
T35 & T36	Firing Time	= sim_time - date of next low level inspection (every 28 days)
T37 & T38	Firing Time	If m = 'TRUE' then Fire Time = 0 Else Fire Time = md – sim_time
T37	RESET_ARCS _{T37}	Marking = 0 for all tokens with ID = id in: P35, P36, P37 and P39
T38	RESET_ARCS _{T38}	Marking = 0 for all tokens with ID = id in: P36, P37 and P38
T39, T40 & T41	FAIL _{RETURN_c}	= $\exp(\mu + \sigma Z)$ Samples from lognormal distribution μ and σ are location and scale parameters respectively, on the request of Network Rail the values are not shown. Z is a standard normal random number
T39	Firing Time	Sampled from exponential distribution: $\lambda=4.58E-07$
T40	Firing Time	Sampled from exponential distribution: $\lambda=1.52E-04$
T40	RESET_ARCS _{T40}	Marking = 0 for all tokens with ID = id in: P38 and P38
T41	Firing Time	Sampled from Weibull distribution: $\beta=2$, $\eta=1825$
T41	RESET_ARCS _{T41}	Marking = 0 for all tokens with ID = id in: P37, P38 and P39
T48	Firing Time	= 0 (has a LOW PRIORITY, meaning it fires after every other transition that is scheduled to fire at the same time)
T70, T71, T72 & T73	Firing Time	=0 (has a HIGH PRIORITY, meaning they fire before transitions with low or normal priority) N.B. transitions not shown in the figure, see notes.

Appendix A-2-7 Structures Subnet

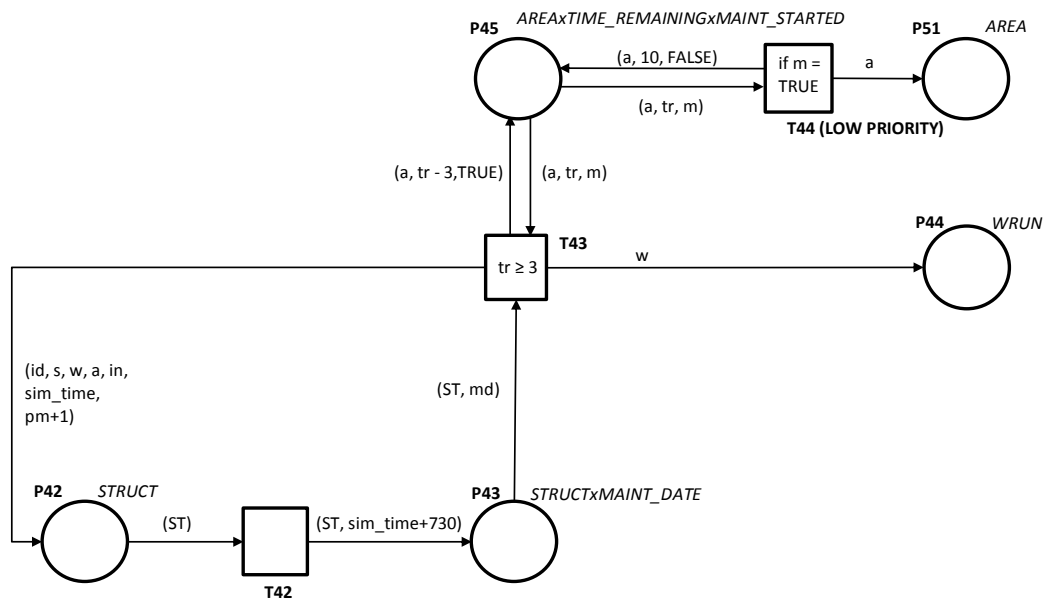


Figure A-10 Structures Subnet

Notes:

Type *STRUCT* is the Cartesian product of data values: ID x SPAN x WRUN x AREA x INST_DATE x LAST_MAINT_DATE x PREV_MAINT. The tokens containing this set of data values represent a structure. Variable ST is a set of variables (id, s, w, a, in, lm, pm). The arcs containing the variable ST therefore bind to the tokens representing a structure.

Note that inspections of the structures are not modelled because their degradation progresses slowly and they are not assumed to fail. The maintenance of structures is not grouped to occur at the same time as the other OLE components (because maintenance of structures is undertaken by the civil engineering team). However, other structures, in the same access area, are modelled to be maintained at the same time.

Table A-15 Description of Places used in the Structures Subnet

Place	Description
P42	Good / Working Condition.
P43	Degraded Condition (structure is damaged, excessive corrosion), maintenance is scheduled.
P44	Records statistics associated with the number of maintenance works undertaken on structures.
P45	Describes the current maintenance status of structures in the access area.
P51 (global)	Records statistics associated with the total number of maintenance visits to an access area.

Table A-16 Information for the Transitions in the Structures Subnet

Transition	Function/ Feature	Information (all times given in days)
T42	Firing time	If pm = 0 then Sampled from Weibull distribution: $\beta=1.5$, $\eta=54750$ Else Sampled from Weibull distribution: $\beta=1.5$, $\eta=14240$
T43	Firing Time	If m = 'TRUE' then Fire Time = 0 Else Fire Time = md – sim_time
T44	Firing Time	= 0 (has a LOW PRIORITY, meaning it fires after every other transition that is scheduled to fire at the same time)

Appendix A-2-8 Adjustments to Wire Run Subnet

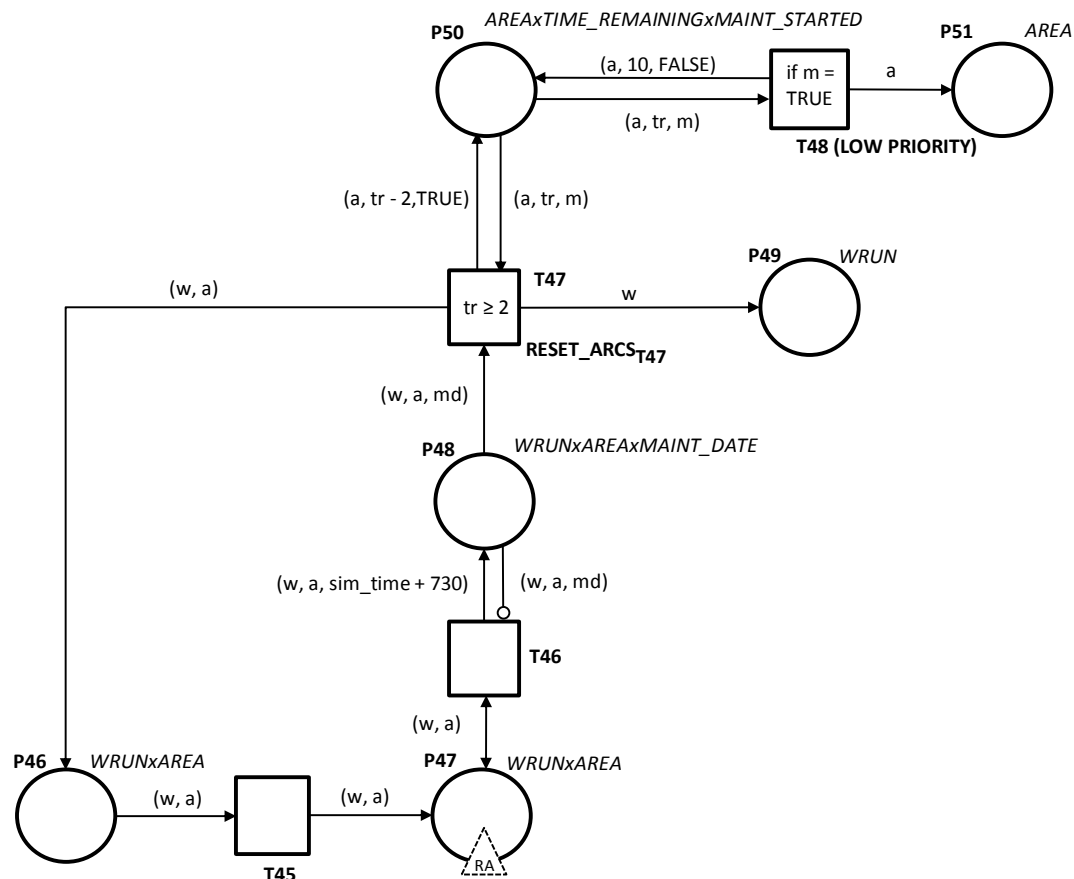


Figure A-11 Adjustments to Wire Run Subnet

Notes:

The adjustments to wire run subnet does not explicitly model any OLE components. The modelling of the adjustment of components in the wire run, mainly the registration equipment and other associated components (such as mid-point anchors and the tensioning equipment), to ensure that the height and stagger and the along track movement of the system remains tolerable, is considered at

the wire run level since the entire wire run is connected and the maintenance would commonly involve adjusting components at numerous locations of the wire run at the same time to alleviate any issues. This process is referred to as wire run adjustments. Within this subnet, tokens containing WRUN and AREA data values are used to represent the adjustments to the wire run. Place P47 represents the wire run as requiring adjustments and is an input place for various transitions in other subnets, which represent the failure of other OLE components due to the poor set-up of the wire run.

Table A-17 Description of Places used in the Adjustments to Wire Run Subnet

Place	Description
P46	No issues with set-up of wire run.
P47	Poor set-up of wire run (wire run requires adjustments).
P48	Revealed poor set-up of wire run (the maintenance engineers are aware of the issue and maintenance is scheduled).
P49	Records statistics associated with the number of maintenance works undertaken to adjust a wire run.
P50 (global)	Describes the current maintenance status of the access area.
P51 (global)	Records statistics associated with the total number of maintenance visits to an access area.

Table A-18 Information for the Transitions in the Adjustments to Wire Run Subnet

Transition	Function/ Feature	Information (all times given in days)
T45	Firing time	Sampled from exponential distribution: $\lambda=3.42E-04$
T46	Firing Time	= sim_time - date of next low level inspection (every 28 days)
T47	Firing Time	If m = 'TRUE' then Fire Time = 0 Else Fire Time = md – sim_time
T47	RESET_ARCS _{T47}	Marking = 0 for all tokens with ID = id in: P47
T48	Firing Time	= 0 (has a LOW PRIORITY, meaning it fires after every other transition that is scheduled to fire at the same time)

Appendix A-2-9 Large Scale Renewals Subnet

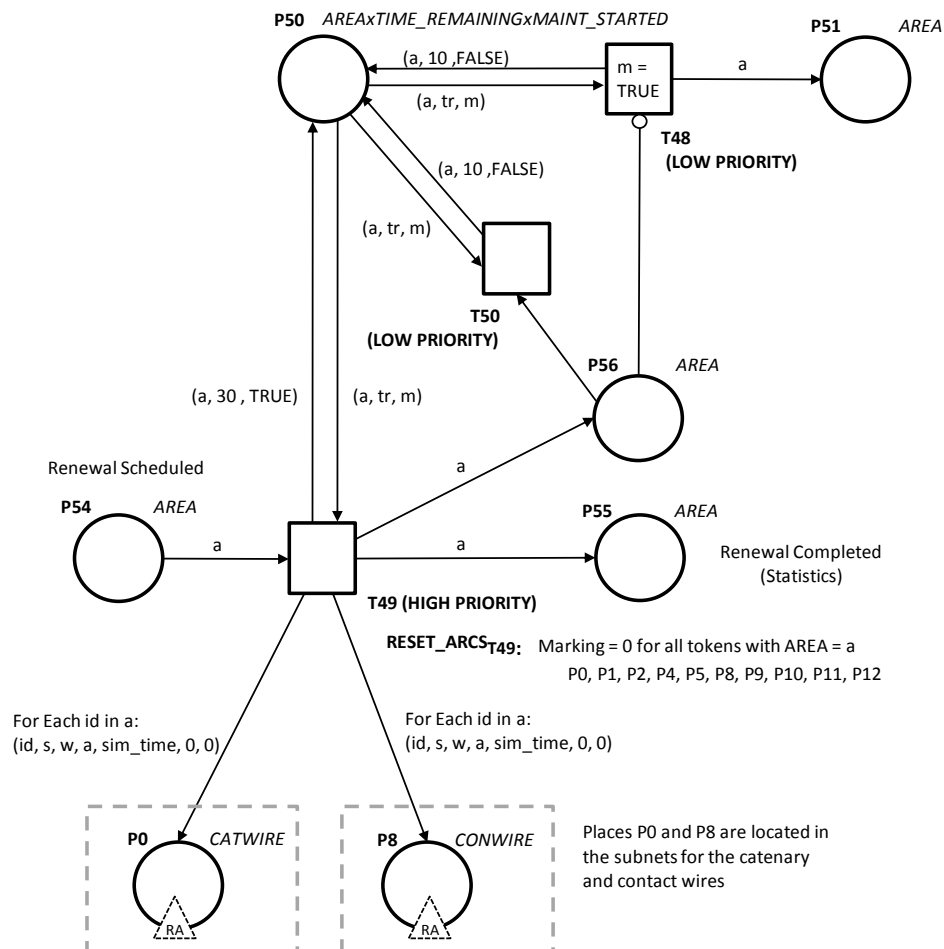


Figure A-12 Large Scale Renewals Subnet

Notes:

This subnet was fully explained in section 4.11 on page 135.

Table A-19 Description of Places used in the Large Scale Renewals Subnet

Place	Description
P0	Catenary wire working/ good condition.
P8	Contact wire working/ good condition.
P50 (global)	Describes the current maintenance status of the access area.
P51 (global)	Records statistics associated with the total number of maintenance visits to an access area.
P54	Renewal Scheduled
P55	Renewal Completed, statistics associated with the timing and cost of the renewal are recorded.
P56	Renewal Underway, marking of this place prevents the renewal being recorded as a maintenance visit.

Table A-20 Information for the Transitions in the Large Scale Renewals Subnet

Transition	Function/ Feature	Information (all times given in days)
T48	Firing Time	= 0 (has a LOW PRIORITY, meaning it fires after every other transition that is scheduled to fire at the same time)
T49	Firing Time	= 25550 (70 years)
T49	RESET_ARCS _{T49}	Marking = 0 for all tokens with AREA = a in: P0, P1, P2, P4, P5, P8, P9, P10, P11, P12 (these places are in the catenary wire and contact wire subnets).
T50	Firing Time	= 0 (has a LOW PRIORITY, meaning it fires after every other transition that is scheduled to fire at the same time)

Appendix A-2-10 High Level Intrusive Inspection Scheduling Subnet

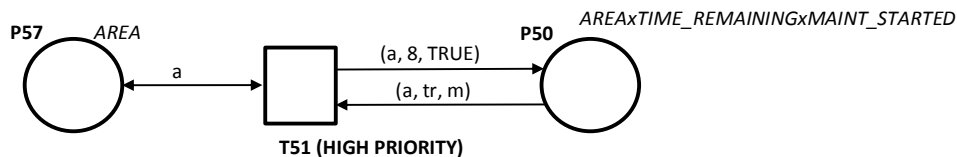


Figure A-13 High Level Intrusive Inspection Scheduling Subnet

Notes:

This subnet allows opportunistic maintenance to take place when the high level intrusive inspection is scheduled to occur for an access area. This is done by firing a token to the place describing the maintenance status of the access area, P50 (a global place), which enables the various maintenance transitions in the component subnets to fire at the same time, provided that there is enough time. In the current model, 8 time units are available to perform opportunistic maintenance of other components during a high level intrusive inspection. Therefore, 8 time units are fired, in the token containing the maintenance status, to P50. This is all done using one transition, T51, which has a firing time equal to the high level inspection interval and repeatedly fires.

Table A-21 Description of Places used in the High Level Intrusive Inspection Scheduling Subnet

Place	Description
P57	Inspection Scheduled
P50 (global)	Describes the current maintenance status of the access area.

Table A-22 Information for the Transition in the High Level Intrusive Inspection Scheduling Subnet

Transition	Function/ Feature	Information (all times given in days)
T51	Firing Time	= 730 (has a HIGH PRIORITY, meaning it fires before other transitions)

Appendix A-2-11 Failures due to External Influences Subnet

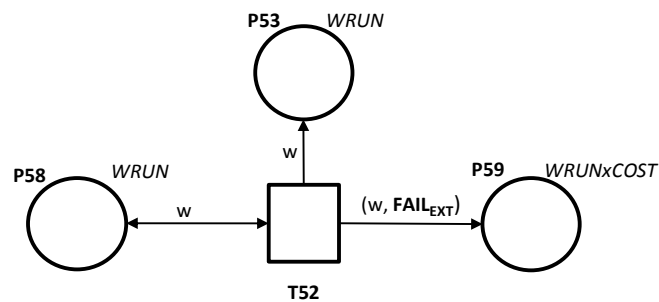


Figure A-14 Failures due to External Influences Subnet

Notes:

This subnet was fully explained in section 4.9.3 on page 131.

Table A-23 Description of Places used in the Failures due to External Influences Subnet

Place	Description
P53 (global)	Failure occurred in the wire run of OLE. This is an enabling place for transitions that represent opportunistic low level inspection of components located in this wire run.
P58	No failures due to external influences.
P59	Failure occurred. Records statistics associated with the number of service affecting failures cause by external influences of the return conductor and the corresponding costs incurred.

Table A-24 Information for the Transition in the Failures due to External Influences Subnet

Transition	Function/ Feature	Information (all times given in days)
T52	Firing Time	Sampled from exponential distribution: $\lambda=2.74\text{E-}05$

