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Making comparable risk estimates for railway assets of different types

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Railway managers plan interventions on infrastructures to reduce risks. To plan these interventions effectively, they need comparable risk estimates for all the assets, by considering all types of failure causes and failure modes and all the costs and effects on stakeholders due to these failures. However, existing risk models have been developed for specific asset types and specific failure scenarios, and they result in a wide range of qualitative and quantitative results that are not compatible. Hence, often managers cannot use the results of these models directly in an aggregated assessment to prioritise risk-reducing interventions across a network effectively. This paper presents a methodology for using results from existing models in a systematic way to produce comparable risk estimates for different asset types. Although the methodology is based on simple standard tools, it is the first time that they have been brought together in a way that will help infrastructure managers make consistent risk estimates by systematically determining scenarios related to asset failures and estimating their effects on the railway service in comparable units. The usefulness of the methodology is demonstrated by using it to produce comparable risk estimates for the track, switches and bridges of a part of an Irish network.

Notation

Acc	accidents
a	asset
B	bridge
C	consequence expressed in cost
D	duration
Dam	damages
Del	delays
E	effect on service
e	asset extent
g	asset type and subtype
H	hazard event
I	infrastructure event
Int	corrective intervention
L	load event
N	network use event
P	probability
R	risk
S	switch
Sc	scenario
So	societal event
T	track section
u_D	unit cost per minute of delay

Introduction

Railways form an integral component of transportation systems, and therefore, the effects of railway failures and, consequently, the risks related to these failures are often significant. Railway managers can execute interventions to reduce the risks related to failures. However, as the available resources for the execution of interventions are restricted, railway managers must decide which interventions should be executed to minimise these risks

optimally. Making this decision requires estimating the risks related to each part of the railway with and without the execution of interventions and comparing the risk reduction that can be achieved from one intervention with the risk reduction that can be accomplished by each of the other possible interventions on all the different parts of the railway. This process, therefore, requires comparable risk estimates across the different parts of the railway.

According to ISO 31000 on risk management, risk is expressed in terms of four elements, (*a*) potential sources (i.e. elements that have the potential to increase the risk), (*b*) events (i.e. occurrence or change of a particular set of circumstances), (*c*) the effects of events (i.e. consequences of the events) and (*d*) their probability of occurring (i.e. the chance of something happening) (ISO, 2018). To estimate the risks related to railway failures, railway managers must, therefore, consider the hazards that may lead to asset failures, the asset failures, the effects of asset failures and their probability of occurring. It is important to note that the effects of asset failures are the costs and all the effects of providing inadequate railway service for each stakeholder (Papathanasiou *et al.*, 2020) – for example, costs due to restoration, delays and accidents.

Despite the increasing amount of research, in recent years, focused on examining these four elements to estimate the risks related to railway failures, in most cases, the results cannot be used directly in intervention planning. Most of the existing models were developed to estimate the risks related to specific failure scenarios – for example, combination of a specific hazard leading to an asset failure, a specific failure mode and a specific cost or effect due to the asset failure. Hence, there is not a single model that can be used to estimate the risks related to all failure scenarios and for different asset types. Additionally, existing models produce incompatible results that

cannot be directly aggregated in risk estimates of complete failure scenarios. For example, some produce qualitative risk estimates, such as low, medium and high risk. Others produce quantitative estimates of the probability of an asset failure to occur multiplied by one effect type – for example, the probability of a rail break to occur and the expected number of derailments (Zhao *et al.*, 2006a). Although useful for their specific purposes, these models cannot necessarily be used directly to decide which risk-reducing interventions must be executed and when leaving managers to put them aside and make decisions based on expert judgement. At best, this leads to less than sufficient investment of resources on interventions. At worst, it leads to the risks related to some assets being inadvertently neglected and failures occurring when they could have been avoided.

Although the results of the existing models cannot be directly used in intervention planning, because they are incompatible, it is possible to utilise these models by systematically linking the specific hazards leading to failures, failure modes and effects due to failures they consider. A methodology is required to analyse and incorporate systematically the existing models to produce comparable risk estimates for all assets in a network to achieve this. This paper presents such a methodology that fills this research gap by enabling comparable risk estimates for all assets in a railway network. This methodology provides (a) a way to determine scenarios related to infrastructure failures systematically by connecting the asset failures to the ability of the network to provide service and (b) a way to quantify systematically the direct and indirect effects of infrastructure failures on corrective intervention costs and railway service. This methodology can produce comparable risk estimates for all types of asset failures due to various hazards that have divergent effects by allowing the integration of results produced by existing models to estimate the probability and effects of the examined scenarios. To demonstrate the use of the methodology, the risks of a railway network similar to one in Dublin, Ireland, consisting of three types of railway infrastructure assets – namely, track sections, switches and bridges – are estimated. The railway network is assumed susceptible to traffic loads, flood and extreme ambient temperatures. The risk estimates are made using a prototype software tool that allows (a) the use of

the results from different models with different sophistication levels, from expert opinion to detailed physical models, and (b) updating the values as improved models are available.

The remainder of this paper is divided as follows. The section headed ‘Background’ contains background information on the definitions used in this work, the requirements of the risk assessment methodology for managing railway infrastructure and the position of this research position within the current literature. The section headed ‘Methodology’ contains an overview of the proposed risk assessment methodology. The section headed ‘Description of the case study’ includes a description of the railway network used to demonstrate the usefulness of the methodology. The sections headed ‘Scenarios’, ‘Effects on service’ and ‘Risk estimates’ explain how the methodology was implemented for the scenarios and the effects on stakeholders to produce the comparable risk estimates. The methodology and the case study are discussed in the section headed ‘Discussion’, and the conclusions are given in the section headed ‘Conclusions’.

Background

Explanation of the terms ‘risk’, ‘railway service’, ‘system’ and ‘asset’

Central to this work are the terms ‘risk’, ‘railway service’, ‘system’ and ‘asset’. As these are widely used in railway management with different meanings, the explanation of these terms for this work is given in Table 1.

Comparable asset-based risk estimates

The risk related to a railway asset is the product of the probability of the asset to fail and the costs and effects on service due to this failure. By estimating the probability of any asset failure and the extent of any effects, one can produce risk estimates related to this failure. For example, by estimating the probability of a switch to fail and the effect of this failure on additional travel time for the passengers due to the section where the switch is located being unavailable due to failure and until its restoration, the risk, R_S , related to the scenario ‘switch failure leads to x passenger

Table 1. Definition and explanations of common terms used in railway management

Term	Definition/explanation	Reference
Risk	Risk is expressed in terms of four elements, (a) potential sources, (b) events, (c) the effects of events and (d) their probability of occurring. The risk related to a failure scenario is the product of the failure probability and the effects of failure. 1. $R = P \times C$	ISO 31000 (ISO, 2018)
Railway service	The service provided when transporting passengers and goods from station A to B.	Papathanasiou <i>et al.</i> (2020)
Rail system	The system required to provide the railway service. It includes the rail infrastructure, the rolling stock and the operation.	Papathanasiou <i>et al.</i> (2020)
Railway assets	The fixed physical assets that are part of the rail infrastructure and are required to provide the railway service. They can be of different types – namely, ground area; the track and trackbed; the engineering structures; the level crossings; the track superstructure; the access ways; the installations for safety, signalling and telecommunication; the lighting installations; and the electric traction supply system.	European Community (EC, 2012)

delay minutes' can be estimated. One can also estimate the risk related to fatalities due to track buckling leading to a derailment, R_T , by estimating the probability of a railway track to buckle under a given atmospheric temperature, the probability of this failure to lead to a derailment and the expected number of fatalities due to the derailment. Therefore, by considering the different hazards, varied asset failures and many types of effects, failure scenarios are determined and the risks related to them can be estimated. However, estimating risks related to such specific failure scenarios is different from estimating the risk consistently across different asset types to produce comparable asset-based risk estimates. The risks R_S and R_T of the previous examples are not comparable because they are expressed in different units – that is, R_S is expressed in delay minutes, while R_T is expressed in the number of fatalities. They also cannot be used alone to decide if the switch or the track should be prioritised for a risk-reducing intervention, given budget limitations, because they do not consider all the possible failure scenarios and their effects.

Each railway asset is exposed to different hazards, can fail in different ways (i.e. failure modes) and these failures result in different types of direct and indirect effects (i.e. costs and effects on stakeholders). To estimate the risk related to an asset, one must, therefore, analyse large numbers of interrelated and cascading events related to this asset failure – that is, scenarios. However, in every case an asset failure is caused by hazards leading to loads and stresses applied to the asset beyond its strength limit, causing

fractures or deformations. Once an asset failure occurs, the ability of the asset to function as intended is lost, causing a loss in the ability of the network to provide adequate service to the stakeholders – that is, effects on service – and corrective interventions. When this common ground is used to determine scenarios, then the risk estimates related to these scenarios are compatible. To produce such consistent risk estimates across different assets, one must consider consistent scenarios that include asset failures, starting from a failure mode and then analysing the events that can lead to this failure – that is, causes of failure – the events that result from this failure and the effects on stakeholders due to this failure, and then one must estimate these effects in comparable units. When scenarios are determined systematically by linking hazards and the resulting loads to asset failures and then to costs and effects on service and when these effects on service are estimated in comparable units, then correlative asset-based risks estimates can be produced.

Research on asset-based risk estimates

Although there are a plethora of models both in research and in practice that analyse railway asset failures, usually, they focus on specific parts of the failure scenarios, resulting in an inconsistent determination of the probabilities of failures and/or the costs and effects of failures on the railway service.

Research on the estimation of infrastructure-related risk can be divided into six groups. Table 2 shows these groups and the discrepancy in the risk estimates between existing risk assessment

Table 2. Research focus of risk models during the past 20 years

Group	Focus	Content	Examples in literature
A	One cause of asset failures – for example, earthquake – and estimates the probability of one or several failures modes of a specific asset type to occur	Models that analyse hazard vulnerability	Pitilakis <i>et al.</i> (2006), Peterson and Church (2008), Azevedo <i>et al.</i> (2010), Corigliano <i>et al.</i> (2011), Jaedicke <i>et al.</i> (2013), Rathje <i>et al.</i> (2014), Choine <i>et al.</i> (2015), Hong <i>et al.</i> (2015), Kellermann <i>et al.</i> (2015), Zampieri <i>et al.</i> (2015), Dikanski <i>et al.</i> (2017), Macciotta <i>et al.</i> (2017), Koks <i>et al.</i> (2019)
B	One failure mode – for example, rail break – and estimates the probability of this failure mode to occur due to one or several causes	Models that analyse structural reliability	Sandström and Ekberg (2009), Kumar <i>et al.</i> (2010), Pams Capoccioni <i>et al.</i> (2015), Bai <i>et al.</i> (2015), Ghodrati <i>et al.</i> (2016), Chen <i>et al.</i> (2016), Jamshidi <i>et al.</i> (2017), Lamb <i>et al.</i> (2017), Nielsen and Li (2018), Sadler <i>et al.</i> (2018)
C	One failure mode – for example, rail break – and estimates the extent of different types of effects on service to occur due to this failure mode	Models that analyse functional reliability	Chang and Nojima (2001), Zhao <i>et al.</i> (2006b), Martinović <i>et al.</i> (2016), Takayanagi <i>et al.</i> (2019)
D	One type of effect on service – for example, accident – and estimates the extent of this effect due to the occurrence of one or several failure modes of a specific type of asset	Models that analyse functional reliability	Anderson (2005), Zhao <i>et al.</i> (2006a), Santamaria <i>et al.</i> (2009), Zhao <i>et al.</i> (2007), Liu <i>et al.</i> (2011), Hu <i>et al.</i> (2011), Jafarian and Rezvani (2012), Liu <i>et al.</i> (2012), Morales-Ivorra <i>et al.</i> (2016)
E	One type of effect on service – for example, delays – and estimates the extent of this effect due to the occurrence of several failures on different parts of the railway system, including failures that are not related to the infrastructure – for example, train failure	Models that analyse the functional reliability of railway transport	Muttram (2002), An <i>et al.</i> (2011), Miller-Hooks <i>et al.</i> (2012), Bureika <i>et al.</i> (2013), Liu <i>et al.</i> (2017), Leitner (2017), Zhao <i>et al.</i> (2017), Janić (2018), Xu <i>et al.</i> (2019)
F	One or several specific failure scenarios, including one or several failure modes, and their causes and effects on service – for example, rail breakage due to earthquake leading to fatalities – and estimates the risk related to those scenarios	Models that analyse specific failure scenarios	Saccomanno <i>et al.</i> (2004), Podofilini <i>et al.</i> (2006), Flammini <i>et al.</i> (2009), Pyrgidis <i>et al.</i> (2016), Azad <i>et al.</i> (2016), Dindar <i>et al.</i> (2016), Ferranti <i>et al.</i> (2016), Kobaszyńska-Twardowska <i>et al.</i> (2019)

methods and tools produced for railway assets. Groups A, B, C and D examine scenarios related to infrastructure failures, focusing on either specific causes or failure models or effects. Group E focuses on the effects of failures. Therefore, these models assess effects on service regardless of their cause and the risks produced by these models that might not be related to infrastructure failures. Group F analyses complete scenarios of infrastructure failures that include specific causes and effects. The methods and tools that belong in this group often consistently determine failure scenarios and their probabilities and effects. However, these models usually focus on specific asset types and are not always capable of analysing an expanded list of hazards, failure models or effects (Wang *et al.*, 2015). Although research in all six groups contributes in different ways to estimates of risk, alone they do not ensure that a wide range of risk scenarios related to different asset types can be analysed.

Regarding the second requirement, existing risk models assess the effects of failure scenarios in different ways, resulting in incomparable risk estimates for railway assets. For example, many use risk scores (Braband, 2002; Ellis *et al.*, 2016; Feng *et al.*, 2017; Johnsen and Veen, 2013; Lloyd *et al.*, 2001; Wang *et al.*, 2018). Risk scores are useful when qualifying the risk of similar scenarios related to the same type of assets. However, it is often challenging to expand the use of a systematic scale of risk scores in a wide range of failure scenarios and asset types. The results of the models that qualify the risk using risk scores cannot be aggregated, and therefore, they do not facilitate the comparison of risks between assets or the determination of the amount of money that should be spent to reduce risk. Other models produce risk estimates that are expressed on a single type of expected effects on service – for example, delays (Azad *et al.*, 2016), number of derailed cars (Liu *et al.*, 2011), number of accidents (Schütte and Geisler, 2010) and number of fatalities (Ellis *et al.*, 2016; Macciotta *et al.*, 2017). These models, although useful in the estimation of risk related to a single effect of failures on the service, cannot incorporate multiple types of effects. Consequently, the use of these models alone might lead to neglecting essential effects of failures – for example, the cost of corrective interventions.

Few existing models express risk in monetary units enabling two direct critical comparisons, (a) between risk estimates related to different assets and (b) between risk estimates and intervention costs. To enable the planning of risk-reducing interventions, it is useful to have risk estimates and intervention costs expressed in the same units. Although the use of utility theory may be the best theoretical method to quantify both intervention costs and risks, it requires the already easily estimable unit costs of interventions to be converted into something that it is at best, not intuitive, for railway managers. Therefore, it is not suitable for infrastructure asset management. Another way to have risk estimates and preventive intervention costs expressed in the same units is to monetise the risks, to be directly comparable with intervention costs, as discussed in Adey *et al.* (2019) and Papathanasiou and

Adey (2020a). Risk estimates in monetary units are produced from models that focus on assessing the amount of money that should be spent on monitoring or executing interventions to increase safety related to single asset types – for example, track (Podofilini *et al.*, 2006), switches (Dindar *et al.*, 2016), level crossings (Pyrgidis *et al.*, 2016; Saccomanno *et al.*, 2004) and stations (Flammini *et al.*, 2009). Although the use of another standard unit instead of monetary units can be proposed, it will not take away from the argument that to be able to compare risk estimates with intervention costs effectively, they need to be expressed in the same units.

Identified research gap

Although considerable research has been conducted in recent years to improve the estimates of risk related to railway assets, there has been no research on utilising the results of these existing models to produce comparable risk estimates among different asset types due to various hazards and related to various effects that can be used to plan risk-reducing interventions.

Methodology

This methodology aims to enable railway managers to utilise the results from existing models to produce comparable risk estimates across all assets types. Hence, this risk assessment methodology provides a systematic way to

- determine scenarios (explained in the section headed ‘Systematically determining scenarios’),
- estimate the effects of scenarios in comparable units (explained in the section headed ‘Systematically estimating the effects of scenarios’).

The tasks of the methodology are presented in the section headed ‘Task’. An overview of the methodology is presented in Figure 1.

Systematically determining scenarios

The scenarios must be determined in a way that allows the integration of models that address the occurrence of different sequences of different types of events describing hazards, which may lead to asset failures, types of asset failures and types of effects of the asset failures – for example, a hazard leading to a track failure, a track failure leading to an accident and an accident leading to delays. An event can be linked to another event when cause–effect relationships govern them. When multiple events are linked in series governed by cause–effect dependencies, an event-tree structure can be created. In an event tree, every event is caused by its preceding event, except for the first event, and every event results in the following outcomes, except for the last ones. Within an event tree, scenarios can be determined by considering different sequences of events. In the middle part of Figure 2, such an example of an event tree is presented. As scenario will likely occur if the combined probability of the sequence of events within the situation will occur. This probability of a scenario to occur can be used in Equation 1 to calculate the risk related to this scenario.

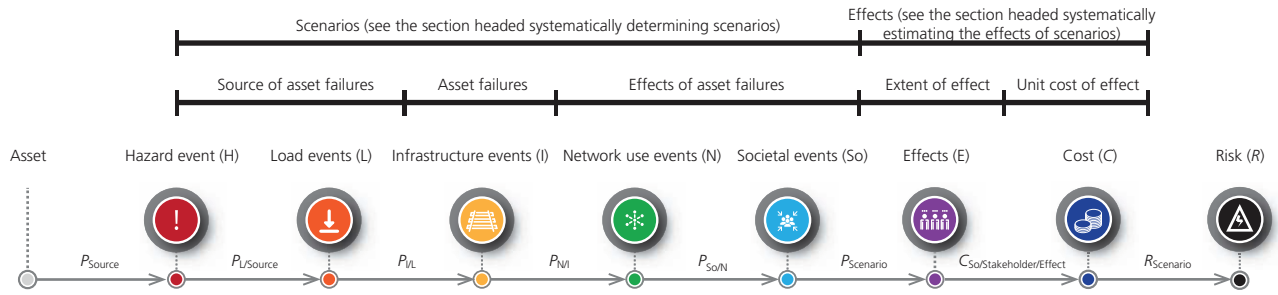


Figure 1. Overview of the methodology

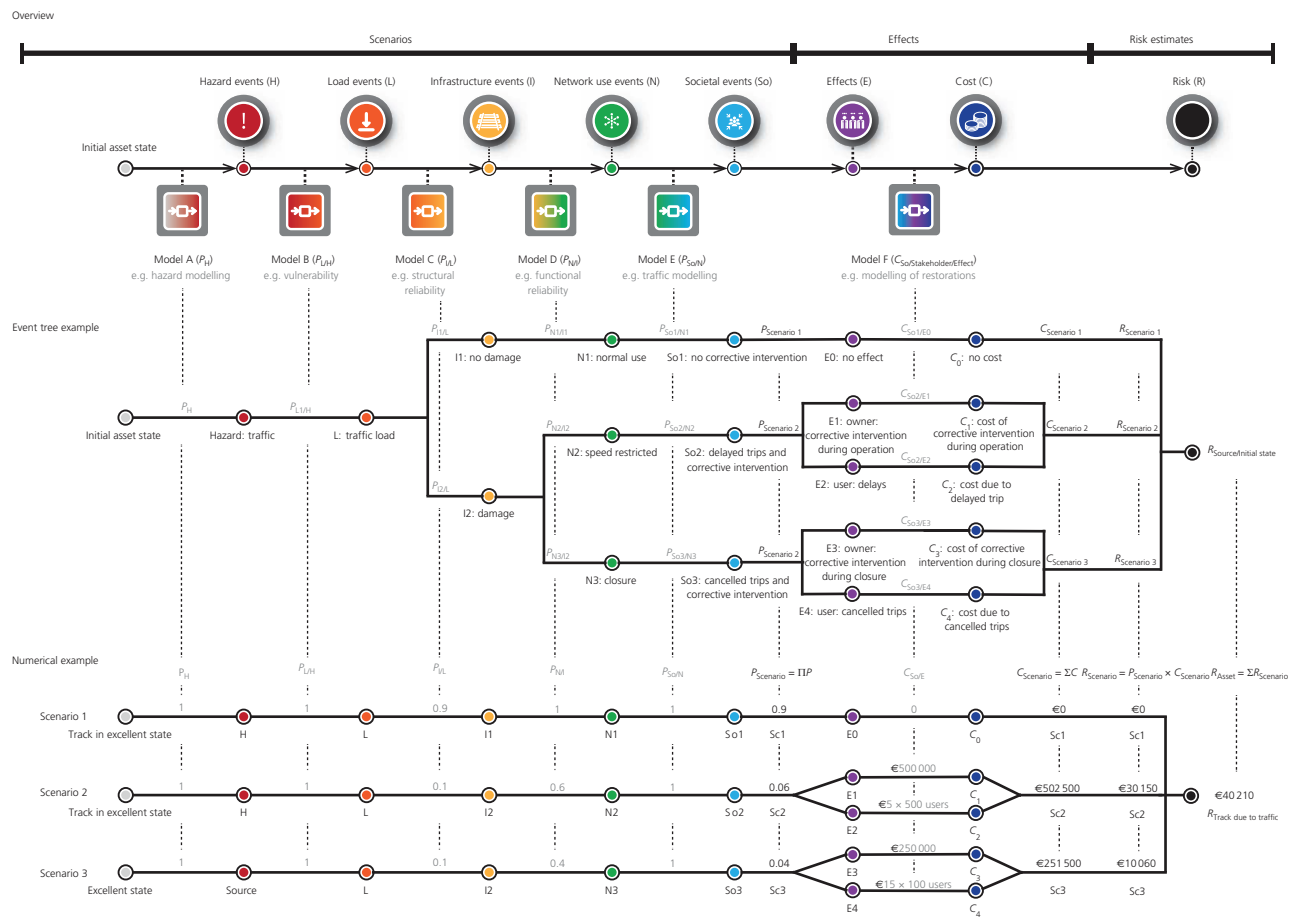


Figure 2. Overview and an example (graphical and numerical) of the methodology

Although we can consider any sequence of events in an event-tree structure, we still propose a systematic way to build these sequences of events and determine scenarios. This ensures that all relevant scenarios are determined in a compatible way. Central to the systematic determination of scenarios is the concept that an asset failure is the result of a change in the loading conditions of this asset and every asset failure can lead to changes in the railway service provided to the stakeholders, based on the way that the network is used after the failure. Therefore, it is possible

to determine a systematic way of identifying scenarios by connecting the asset failures to their causes and effects by considering a systematic sequence of events of five generic types, hazard, load, infrastructure, network use and societal events. The different types of events and the sequence created form scenarios, as shown in Figures 1 and 2. The hazard, load infrastructure, network use and societal events are illustrated with red-, orange-, yellow-, green- and light-blue-coloured circles, respectively. Each event is connected to the next in the sequence with a probability

of occurrence *P*. Similar generic types of events were proposed by Adey *et al.* (2016) and were used by Hackl *et al.* (2018) to estimate the risk due to rainfall in a part of the Swiss road network. The generic types of events, as described in Table 3, offer an orthogonal and flexible classification of the events that helps represent any scenario that begins with a hazard event that changes the loading condition of an asset, leading to changes on the infrastructure, leading to changes in the way that the network is used and finally leading to changes in the provided railway service. Hence, different models can be used in a systematic way to assess the specific relationships between the events within a scenario – for example, hazard assessment models, structural assessment models and accident assessment models, traffic models, as shown in Table 4.

Systematically estimating the effects of scenarios

Using the event-tree structure, it is possible to identify the effects resulting from the occurrence of a scenario. When the scenarios are determined as described in the section headed ‘Systematically determining scenarios’, their costs and effects incurred by the stakeholders are expressed by societal events. In other words, the societal events describe the changes in the stakeholders’ behaviour due to the changes in the service provided by the

infrastructure assets and network. The effects of the scenarios are, therefore, assessed by assessing the effects on service for each stakeholder due to the occurrence of a societal event.

Although there can be many ways to assess the effects of a scenario, the requirement here is to produce comparable risk estimates. This can be achieved if the effects on service are quantified in compatible units, and therefore, they can be compared. According to Equation 1, the unit of the risk estimates depends on the unit used to estimate the effects of the scenario. Consequently, if the effects on service related to a scenario are systematically quantified and then used to estimate risks, the risk estimates will be comparable.

In the paper by Papathanasiou *et al.* (2020), a methodology is proposed to quantify and monetise railway service effects systematically. All the stakeholders that are influenced by changes in the railway infrastructure must be first identified. Then, all the effects related to providing inadequate service for each stakeholder must be defined and quantified using monetary values. For example, suppose that the unit cost of a minute of delay per passenger for all minutes of delay is €1 and a train carrying 100 passengers is affected by 10 min of delay. In that case, the cost related to this effect on service is €1000. This

Table 3. Generic event types

Event type	Description	Examples of events to estimate the risk related to a track section due to traffic
Hazard	An event that may lead to a change in the load and stress levels applied to a railway asset	Traffic on the track – that is, the mass of the rolling stock applied on the track
Load	An event that may change the load and stress levels applied on a railway asset due to a hazard	Annual tonnage per kilometre on the track section based on the timetable
Infrastructure	An event that may change the structural or functional properties of a railway asset	Damages that partially affect the geometry or the rail condition of the track section
Network use	An event that may change the level at which the railway network is used	The operation of the track section is possible only when the speed is less than 40 km/h
Societal	An event that may change the level of the railway service provided to the stakeholders	Track section T1 is renewed, and its operation is possible only when the speed is less than 40 km/h until the renewal is complete

Table 4. Relationships between event types

Relationships between ...	Description	Sample outputs of existing models
Hazard and load event	The probability that a hazard of a particular magnitude, when occurring on the location of the asset, will lead to a specific load event – that is, load or stresses of a specific magnitude applied on the asset for a specific duration	The probability of a certain number of million gross tons to be applied on a track section over a year, given the timetable
Load and infrastructure event	The probability that a specific load event on an asset will lead to a specific infrastructure event – that is, loss of the structural or functional integrity of the asset to a specific extent	The probability of a major track failure given a specific traffic load (Jamshidi <i>et al.</i> , 2017)
Infrastructure and network use event	The probability that a specific infrastructure event on an asset will lead to a specific infrastructure event – that is, implementation of traffic restrictions of the traffic capacity of the section where the asset is located to a specific extent and for a specific duration	The probability of regular use of the section – that is, no traffic disruption – after a track failure (Zhao <i>et al.</i> , 2007)
Infrastructure and network use and societal event	The probability that a specific societal event will occur – that is, cost or effect incurred by a stakeholder – due to the occurrence of a specific infrastructure and network use event	The probability of derailment and track replacement due to a track failure (Liu <i>et al.</i> , 2011; Wang <i>et al.</i> , 2018)

approach requires examining the railway stakeholders, and the effects of changes in the provided rail service, from a higher level to a more precise indicator to allow a complete and orthogonal analysis of all the railway service effects. Using this methodology, the effects on service related to each societal event can be systematically estimated in cost, and this cost value is assigned to the scenarios. This cost can be used in Equation 1 to calculate the risk related to this scenario.

When the effects on service for each scenario and stakeholder are identified, different models can be used to estimate the specific magnitude of those effects that will occur. For example, traffic models can be used to estimate how many passengers will be affected by the closure of a section of the network. Even more advanced models – for example, the model presented by Podofilini *et al.* (2006) – that estimate the costs related to fatalities, delays and track replacement after a track failure caused an accident can be systematically utilised in the process.

For example, suppose that the risk related to two assets, asset A and asset B, is to be estimated. For both assets, three types of effects due to failure are examined, (a) the cost of corrective interventions for the manager of the assets, (b) the effects of delays to passengers due to the unavailability of the asset and (c) the effects of accidents to the passengers.

For asset A, two simple scenarios are examined, ScA.1 with $P_{ScA.1}$ equal to 0.9999 and ScA.2 with $P_{ScA.2}$ equal to 0.0001. The societal event of scenario ScA.1 is ‘no failure, no accident, no traffic disruptions and no restoration’, and that of scenario ScA.2 is ‘failure, accident, traffic disruptions and restoration’. Two scenarios are also examined for asset B, ScB.1 with $P_{ScB.1}$ equal to 0.9 and ScB.2 with $P_{ScB.2}$ equal to 0.1. The societal event of scenario ScB.1 is ‘no failure, no accident, no traffic disruptions and no restoration’, and that of scenario ScB.2 is ‘failure, no accident, traffic disruptions and restoration’. It is, therefore, considered that the failure of asset A always leads to an accident, while the failure of asset B cannot lead to an accident.

The cost of restoring asset A is €2 million. This failure leads to an accident causing an average of two fatalities and 50 injuries. When asset A fails, 1000 passengers are affected by a 10 min delay per passenger on average because the asset is unavailable and the trains are rerouted until the site is cleared and the asset is restored. The cost of restoring asset B is €10 000. The asset is unavailable until it is restored, resulting in an average 20 min delay for 100 passengers. The average economic and societal impact due to a fatality caused by a rail accident is €1 million, and that due to an injury caused by a rail accident is €0.5 million. The value of time due to train delays is €0.5 per minute of passenger delay.

Based on this information, there are no effects due to scenarios ScA.1 and ScB.1. The effects related to scenario ScA.2 are equal to €29.010 million ($2\,000\,000 + 2 \times 1\,000\,000 + 50 \times 500\,000 + 1000 \times 10 \times 0.5$). Scenario ScB.2 results in €11 000 ($10\,000 + 100 \times 20 \times 0.5$). The risk related to two assets can be calculated using Equation 1. The risk related to asset A is equal to €2901 ($0.9999 \times 0 + 0.0001 \times 29\,010\,000$), and the risk related to asset B is equal to €1100 ($0.9 \times 0 + 0.1 \times 11\,000$). Consequently, this approach allows for producing comparable risk estimates for the two assets.

Tasks

Table 5 presents the tasks of the methodology. The tasks are divided into three main parts: scenarios, effects on service and results. Figure 2 shows an overview of the methodology along with a simple graphical and numerical example of an event tree. The overview is shown in the upper frame. This illustration of the overview of the methodology is similar to the illustration presented in Figure 1. Additional to the information presented in Figure 1, the overview in Figure 2 shows the integration of models to estimate the relationships between the events and quantify the effects of the scenarios. The middle frame of Figure 2 shows an example of an event tree built according to the methodology. The models shown in the overview (upper frame in Figure 2) can estimate the probabilities and quantify the effects shown on the event tree example (middle frame in Figure 2). The bottom frame in Figure 2 shows a numerical example of the event tree shown in the middle frame. The equations used to estimate the risk are shown

Table 5. Tasks of the methodology

Parts	Tasks	Description	Example in Figure 2
Scenarios	1	Identify events	H, L, I1, I2, N1, N2, N3, So1, So2, So3
	2	Link events in cause–effect relationships	$P_H, P_{L/H}, P_{I1/L}, P_{I2/L}, P_{N1/I1}, P_{N2/I2}, P_{N3/I2}$
	3	Determine scenarios	Scenario 1
	4	Determine the initial state	Track in an excellent state
	5	Determine models to be used for each relationship between the events	Model A, model B, model C, model D, model E
Effects on service	6	Estimate the probabilities of the events	$P_{L/H} = 1, P_{N2/I2} = 0.6$
	7	Determine stakeholders	Owner, user
	8	Determine effects on service	E1, E2, E3, E4
	9	Determine models to be used for each effect	Model F
Risk estimates	10	Estimate the cost of each effect on service	$C_1 = €500\,000, C_2 = €5 \times 500 = €2500$
	11	Estimate the probabilities of each scenario	$P_{Scenario\ 1} = 0.9, P_{Scenario\ 2} = 0.06$
	12	Estimate the costs of each scenario	$C_{Scenario\ 1} = 0, C_{Scenario\ 2} = €502\,500$
	13	Estimate the risk of each scenario	$R_{Scenario\ 1} = 0, R_{Scenario\ 2} = €30\,150$
	14	Aggregate the risks per asset	$R_{Track\ due\ to\ traffic} = €40\,210$

on the top of the frame. The numbers in this frame are vertically aligned to the variables that they correspond to as directed on the event tree (middle frame). Vertical dashed lines highlight the vertical alignment of the models in the first frame; the probability variables P and cost C and risk R variables of the event tree in the middle frame; and the number corresponding to the variables in the bottom frame.

Table 5 presents the tasks in a logical sequence, showing which one takes priority. However, it is essential to note that often, when using the methodology, it is necessary to update decisions made in previous tasks. For example, according to the methodology, the events are identified before the scenarios are determined. Nevertheless, when the scenarios are determined with the predefined events and an overview of what will be modelled is clear, it is often possible to identify events that were not considered earlier in the process. Consequently, it is crucial to examine carefully at the end of each task if the decisions made sufficiently cover and reflect the scope of the analysis.

Description of the case study

The proposed methodology demonstrate the estimate risks related to the railway assets in a part of the railway network in Dublin, Ireland, shown in Figure 3. This part of the network serves only passenger trains – that is, intercity and urban commuter trains – between four stations, stations A, B, C and D, according to the network description given in the report by the National Transport Authority (NTA, 2016). The stations and their platforms are shown in Figure 3 with grey rectangular shapes. It consists of 5164 m of the track, divided into 11 track sections (based on the location of stations and signals) and 23 switches. More than three-quarters of the network length is built on 39 bridges with a total deck surface area of 16 763 m² (see the

Appendix, which also includes Table 11). Figure 3 shows this network and three types of its assets; the track sections, shown with red lines; the switches, shown with ceil circles; and the bridges, shown with vertical green lines. The track sections and bridges are further divided into subtypes, based on their structural and operational characteristics (Table 6).

Existing models that focus on the probabilities of specific events to occur were used in this case study to produce comparable risk estimates related to single-asset failures (i.e. it is assumed that only one asset can fail at a time) due to three types of hazards:

- traffic for all the 73 assets, to model failures related to traffic loads
- ambient temperature for the 11 track sections and the 23 switches, to model failures due to extreme heat – for example, track buckling
- flood for bridge B14, which crosses a river, to model the failure of the bridge due to scour.

The effects of the failures of the assets due to the hazards were quantified based on existing models.

All the existing models used in the case study were developed based on either data collected for the EU project Destination Rail or data available to Irish Rail. These models are described in the reports by Allah Bukhsh *et al.* (2017), Connolly and O'Connor (2017), Barrett and Ramdas (2018) and Papathanasiou *et al.* (2018). A sample of these estimates is given in Figure 7 for track section T1. The complete data set can be found in the supplementary file of the paper by Papathanasiou and Adey (2020b). These models are meant to illustrate the estimation of the risks only for the assets of this

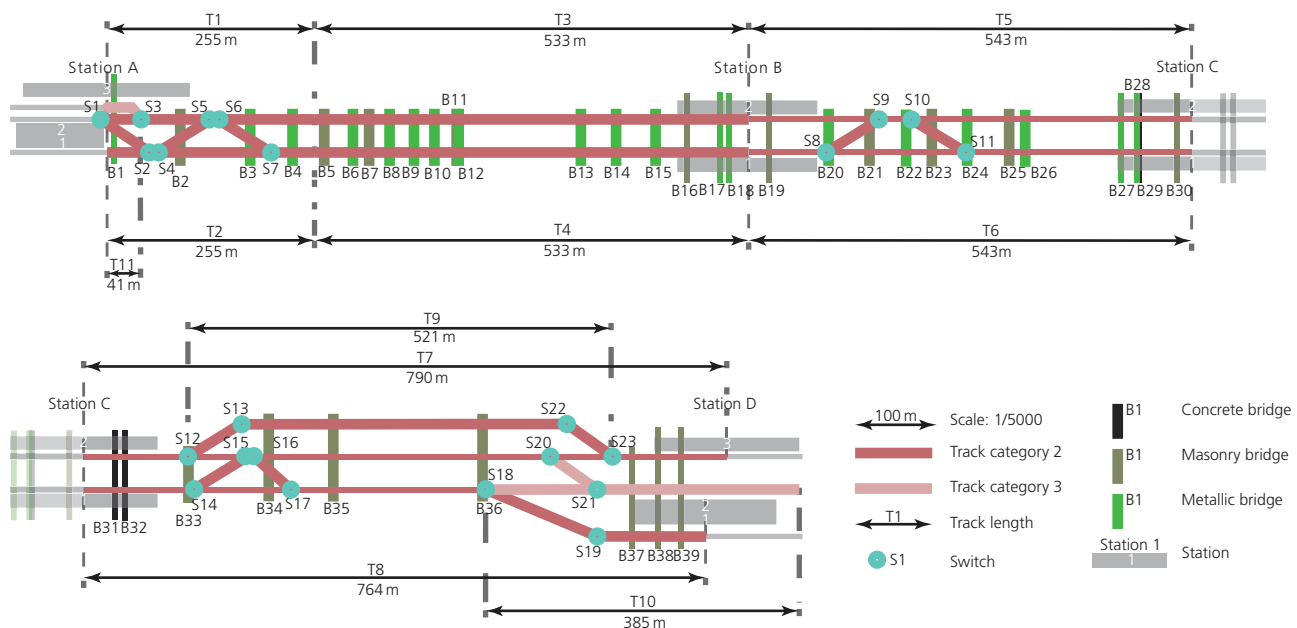


Figure 3. Assets of the case study network

Table 6. Number and extent of the assets per asset type and subtype

Asset type	Asset subtypes	Description	Number of assets	Total extent of assets	Unit of measure
Track sections	Track category 1	Track sections on lines where there is a 160 km/h maximum line speed	0	0	m of length
	Track category 2	Track sections on lines where there is between 40 and 160 km/h maximum line speed	9	4738	
	Track category 3	Track sections on lines where there is lower than 40 km/h maximum line speed	2	426	
	Total		11	5164	
Switches	—	Switch installations	23	23	Number of assets
Bridges	Concrete	Bridges whose primary construction material is concrete	3	592	m ² of deck surface area
	Masonry	Bridges whose primary construction material is masonry	17	7319	
	Metallic	Bridges whose primary construction material is metal	19	8852	
	Total		39	16 763	

network and the purposes of this work. The probabilities and costs estimated by these models might be different in other parts of the railway network in the Republic of Ireland.

It was considered that the methods and models used to estimate the probabilities and effects of failures are validated for estimating the risk of these assets due to the three hazard types – that is, traffic, ambient temperature and flood. Hence, any effect of uncertainties –

for example, in the models used to estimate the probabilities of certain damages to occur – was not considered. Information on existing models and data for estimating such values can be found in the scientific literature – for example, the work presented in Table 2.

Scenarios

The first part of the methodology is to determine the scenarios, and it consists of six tasks (Table 5). The following six subsections describe

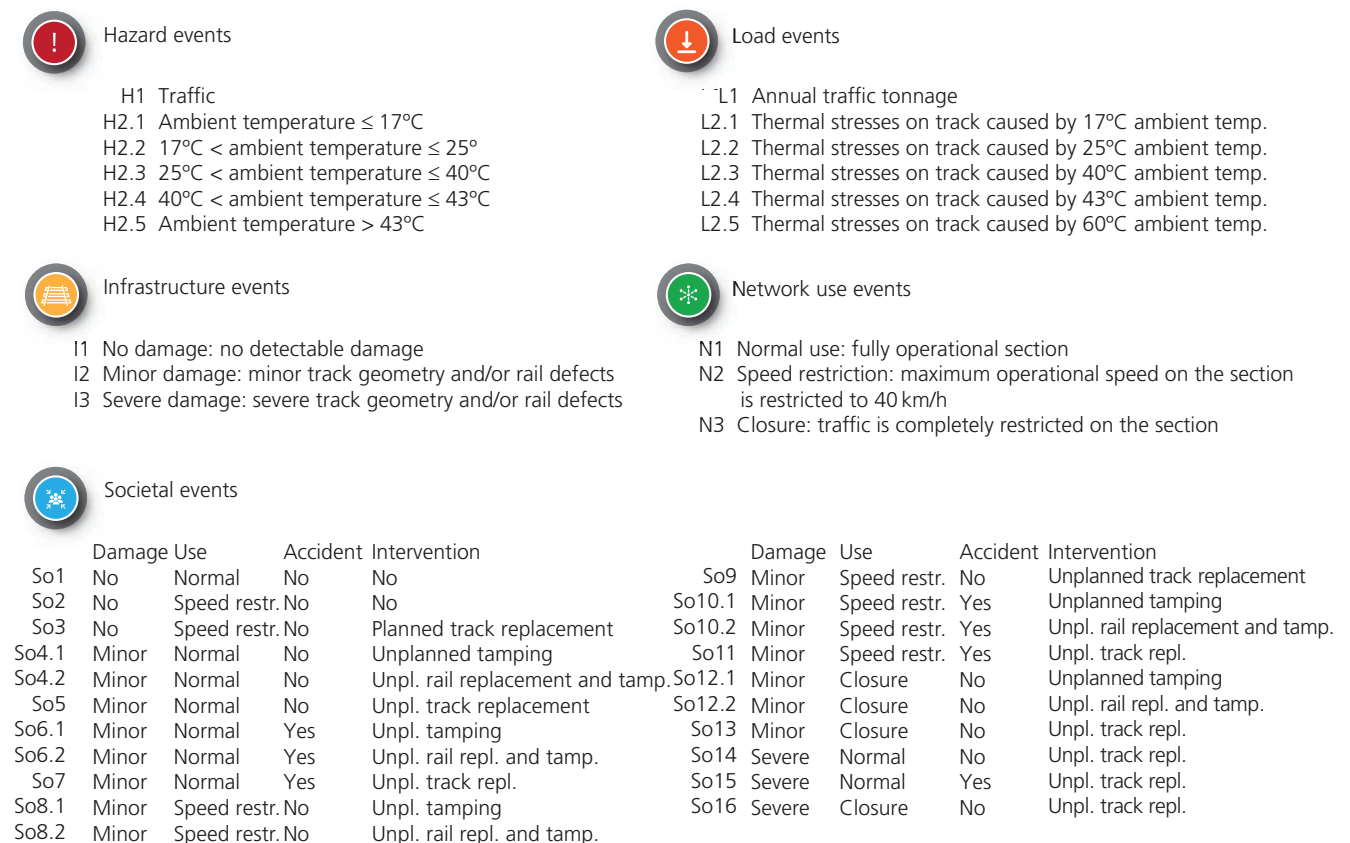


Figure 4. Events considered to estimate the risk related to track sections. repl., replacement; restr., restriction; tamp., tamping; temp., temperature; unpl., unplanned

the implementation of these six tasks for the case study described in the section headed ‘Description of the case study’.

Identify events

Figures 4 and 5 show the events that were considered for track sections and switches, respectively. The events considered for the bridges are presented in Figure 6.

To determine the societal events, the changes in railway service provided to the stakeholders must be considered. The occurrence of infrastructure and network use events affects the railway service provided to the stakeholders. However, accidents following infrastructure events and the restoration type also affect the railway service provided due to a failure. Four factors were used to determine the societal events: (a) the occurrence of damages, (b) the use of the asset after the damage, (c) the occurrence of an accident due to the damage and (d) the extent of the possible corrective intervention to restore the damage. The first two factors are directly related to the definition of infrastructure and network use events, respectively, that precede the societal events of the scenario.

Link events in cause–effect relationships

The events were linked to cause–effect relationships creating event trees. For the track sections, two hazards were considered, traffic and ambient temperature. Traffic has also been considered a hazard that might lead to bridge failures. Additionally, for bridge B14, damages due to flooding were examined. For each hazard type, a different

event tree was developed. As an example, the event tree considered for the track sections for failures due to traffic is presented in Figure 7.

For all the event trees, the following assumptions were made to determine the links between the events and examine only sensible and realistic scenarios.

- If the infrastructure event is no damage – that is, no noticeable damages on the asset due to the load events – it was not linked to a societal event that considers the occurrence accidents. Hence, only the accidents occurring due to damages on the assets were examined.
- Minor or severe damage as an infrastructure event must be linked to a corrective intervention. Minor damage as an infrastructure event can lead to either a minor or a major corrective intervention, while severe damage can be linked only to a major corrective intervention. These assumptions ensure that every damage will be sufficiently repaired and, therefore, the service will be completely restored.
- Maximum speed restriction or closure as a network use event must be linked to a corrective intervention. This assumption ensures that every traffic restriction will be lifted and, therefore, the service will be restored.
- No damage as an infrastructure event can be linked to a major corrective intervention – that is, replacing an asset. These links were necessary to model the situation when a speed restriction is implemented on a section because an asset is in the lowest acceptable state and thus severely deteriorated but does not have



Hazard events

- H1 Traffic
- H2.1 Ambient temperature ≤ 20°C
- H2.2 20°C < ambient temperature ≤ 30°C
- H2.3 30°C < ambient temperature ≤ 43°C
- H2.4 Ambient temperature > 43°C



Load events

- L1 Annual traffic tonnage
- L2.1 Neglectable thermal stresses
- L2.2 Moderate thermal stresses in switch elements
- L2.3 High thermal stresses in switch elements
- L2.4 Thermal stresses beyond the designed level in switch elements



Infrastructure events

- I1 No damage: no detectable damage
- I2 Minor damage: defects that partially affect the switch operation
- I3 Severe damage: inability of switch to guide the wheels



Network use events

- N1 Normal use: fully operational switch
- N2 Speed restriction: switch only with train speeds below 40 km/h
- N3 Closure: non-operational switch



Societal events

	Damage	Use	Accident	Intervention		Damage	Use	Accident	Intervention
So1	No	Normal	No	No	So9	Minor	Speed restr.	No	Unplanned switch replacement
So2	No	Speed restr.	No	No	So10	Minor	Speed restr.	Yes	Unplanned grinding or welding
So3	No	Speed restr.	No	Planned switch replacement	So11	Minor	Speed restr.	Yes	Unpl. switch repl.
So4	Minor	Normal	No	Unplanned grinding or welding	So12	Minor	Closure	No	Unpl. grinding or welding
So5	Minor	Normal	No	Unpl. switch replacement	So13	Minor	Closure	No	Unpl. switch repl.
So6	Minor	Normal	Yes	Unpl. grinding or welding	So14	Severe	Normal	No	Unpl. switch repl.
So7	Minor	Normal	Yes	Unpl. switch repl.	So15	Severe	Normal	Yes	Unpl. switch repl.
So8	Minor	Speed restr.	No	Unpl. grinding or welding	So16	Severe	Closure	No	Unpl. switch repl.

Figure 5. Events considered to estimate the risk related to switches. repl., replacement; restr., restriction; unpl., unplanned

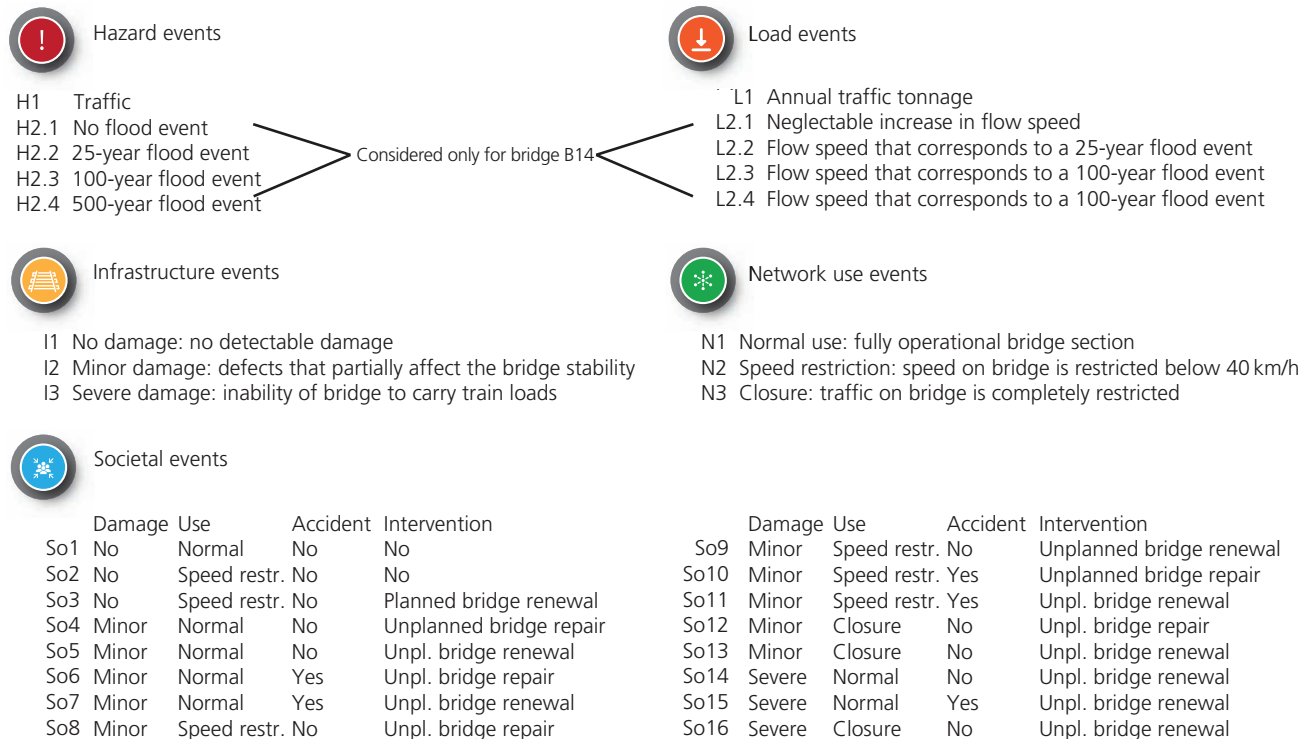


Figure 6. Events considered to estimate the risk related to bridges. rest., restriction; unpl., unplanned

any visible damages. According to the railway-management regulations in Ireland, in this case, the deteriorated asset must be renewed even though there is no visible damage.

- For each asset type, different minor corrective interventions were defined. There are two distinct types of corrective interventions for the track, tamping or rail replacement and tamping. For the switches and bridges, only one type of minor corrective intervention is defined.

Determine scenarios

By developing the event trees for each asset type and subtype, the scenarios to be examined were identified. As an example, the scenarios considered for the track sections for failures due to traffic are noted in Figure 7. For example, according to scenario 11, Sc11, traffic (H1) on track section T1 leads to traffic loads according to the timetable (L1), causing minor damages on the track section (I2), the restriction of the maximum speed (N2) and consequently accident, damages, corrective intervention on the track and delays (So11).

Determine the initial state

The assets were considered to be in one of four initial states:

- state 1: excellent – that is, like new
- state 2: good – that is, slightly deteriorated asset
- state 3: acceptable – that is, significantly deteriorated asset
- state 4: poor – that is, severely deteriorated asset.

The asset states were defined by Irish Rail and the asset-management regulations of the case study network. Trains can operate on the assets in all four of these states, but a different probability of failure is associated with each of these states. The assets are assigned to a state based on various factors – for example, design parameters, condition, performance, history of failures and maintenance history. Guidelines developed by Irish Rail regulate this process for each asset type. The state of the assets is shown in Figure 8.

Determine models to be used for each relationship between the events

As the aim of this work was not to develop new models to estimate the asset, network and service reliability and safety but to utilise information from existing tools, the models used in this case study were either developed for the EU project Destination Rail, based on data and existing models that were available to Irish Rail or based on expert opinion. The following subsections give further information on the models used to assess the relationships between the event types.

All the models used in this case study considered that the events could occur within the same 1-year period. The events were further specified for each asset type to be modelled with a sufficient level of accuracy. Examples of specific events used in the modelling of failures due to traffic for all the three asset types are presented in Table 7.

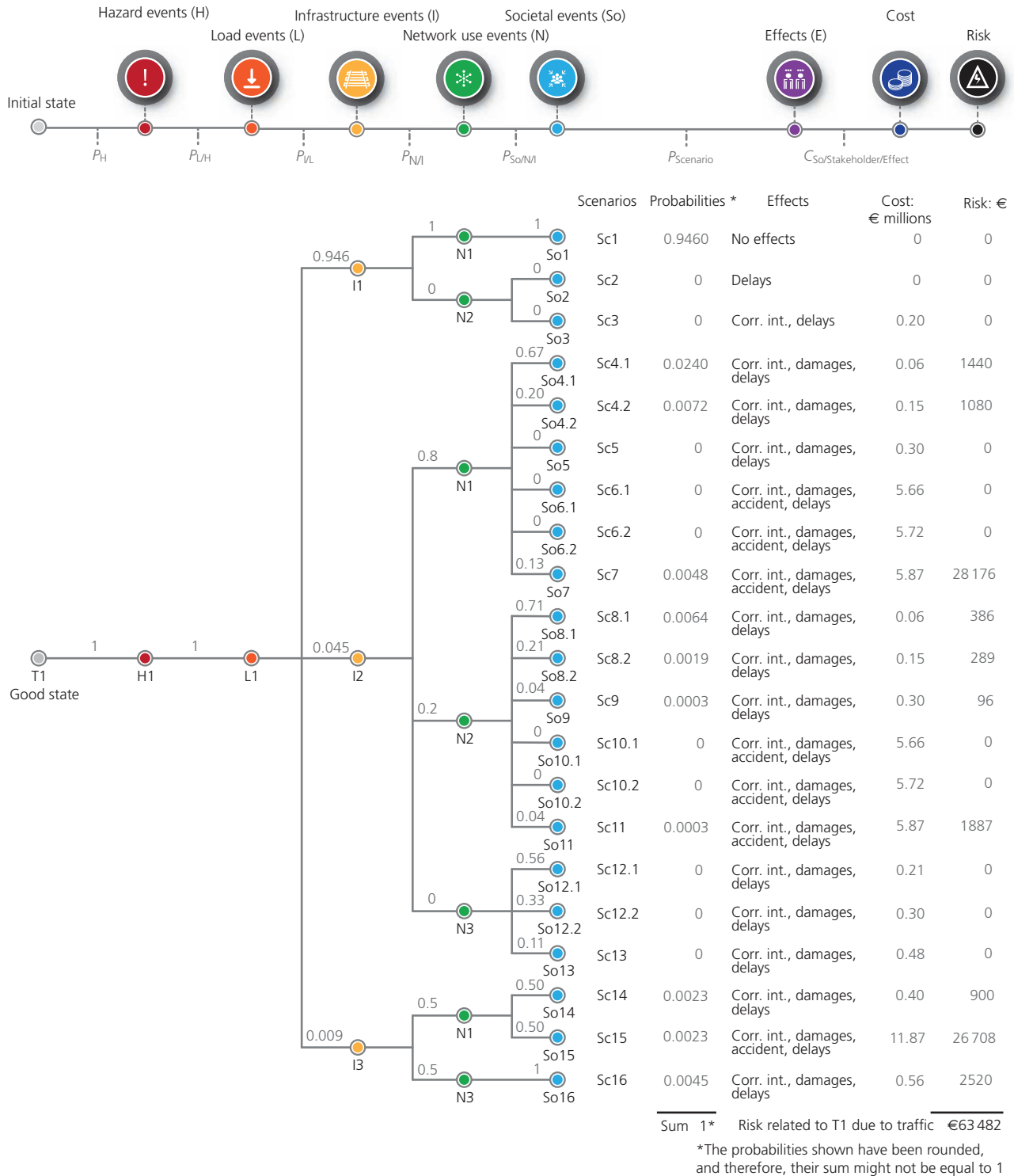


Figure 7. Risk estimates related to track section T1 due to traffic. Corr. int., corrective intervention

Hazard events

As a hazard, traffic was considered to occur always on all the assets on the network – that is, probability equal to 1. This means that the risks related to all assets due to failures caused by traffic loads that did not exceed the timetable train traffic were considered. The

occurrence of extreme heat was expressed using an ambient temperature of four ranges. The probabilities of the four ranges of ambient temperatures to occur were approximated based on daily meteorological data at the airport area for the years 1985–2015 (Met Éireann, 2018). The sum of the probabilities of the different

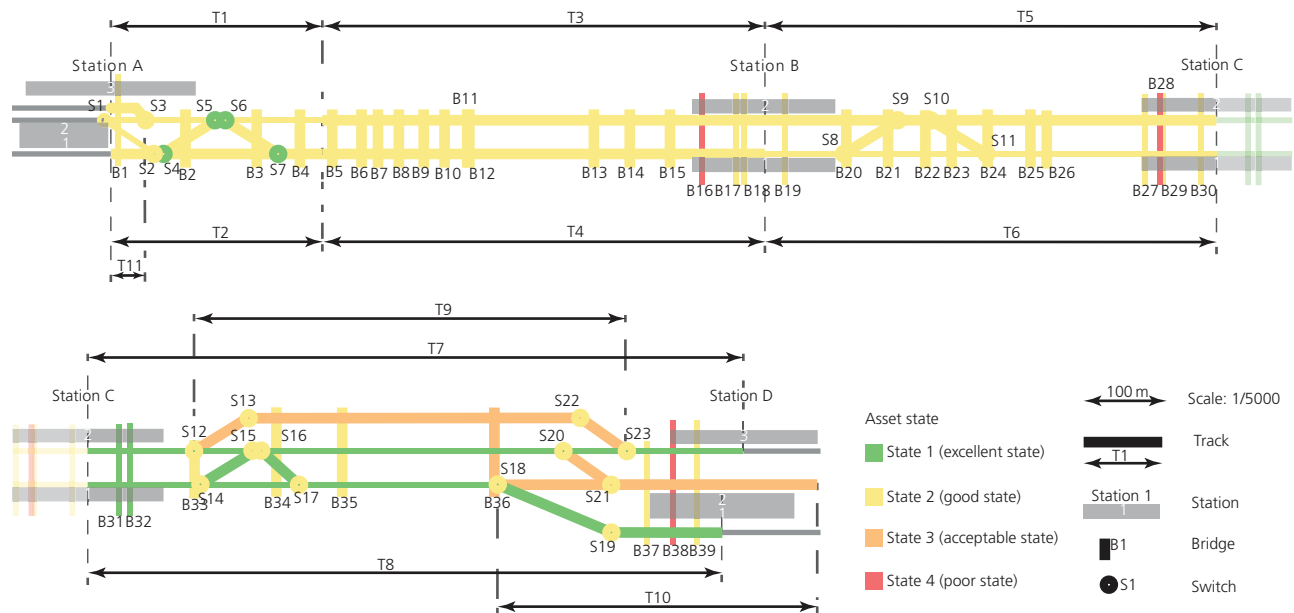


Figure 8. Initial state of assets

ranges of ambient temperatures to occur is 1. The rainfall was assumed to result in flood events with different return periods. The probabilities of the flood events to occur were approximated based on historical data and adapted after consulting with experts. The sum of the probabilities of the different flood events to occur is 1. The occurrence of a hazard event was considered independent of the state and subtype of the asset.

Hazard to load events

Different models were used to assess the relationship between the hazard and the load events for each hazard type – that is, traffic for all the assets, ambient temperature for the track sections and the switches and flood for bridge B14, which crosses a river. All the hazard and load events are listed in Figures 4–6. The traffic was considered to result in one loading level according to the timetable. This loading was expressed with a different loading scheme for each asset type. It was assumed that this loading scheme definitely occurs on all the network assets – that is, probability equal to 1. The probability that each ambient temperature range results in a different temperature on the rail or the switches was approximated after consulting with track experts. Scour was expressed by modelling three flood events with different return periods. Each flood event was assumed to result always in the same level of stream velocity at the bridge foundation – that is, probability equal to 1. The occurrence of a hazard event was considered independent of the state and subtype of the asset.

Load to infrastructure events

For all the asset types, three infrastructure events were considered. However, depending on the different types of load events, different models were used to quantify the probability of different

infrastructure events. These models are presented in Table 8. They consider the occurrence of an infrastructure event dependent on the state and subtype of the asset.

Infrastructure to network use and network use to societal events

The relationships between the infrastructure and the network use events and the relationships between the network use events and the societal events were modelled based on historical data on similar failures and expert opinion. To estimate these probabilities, the state, the type and subtype of the assets were considered.

Estimate the probabilities of the events

Using the previously defined relationships and models, the probability of each event occurring within a scenario was estimated. As an example, the probabilities used in the scenarios for the estimation of risk due to traffic and related to track section T1 are presented in Figure 7.

Effects on service

The second part of the methodology is estimating the effects of the scenarios on the stakeholders. This part consists of four tasks (Table 5). The following five subsections describe the implementation of tasks for the case study described in the section headed ‘Description of the case study’.

Determine stakeholders

For this case study, two main stakeholders were considered, the manager of the infrastructure and the network passengers. Although this is a subset of the stakeholders described in the

Table 7. Asset-type-specific load, infrastructure and network use events for failures due to traffic

General event type	Case-study-specific event types	Model-specific events		
		Track	Switches	Bridges
Load	Traffic load	Annual tonnage on the track based on the timetable	Annual wheel load on the switches due to train movements based on the timetable	Normalised annual traffic loads due to the daily traffic based on the timetable
Infrastructure	No damage	No noticeable damages on the track section due to the load event	No noticeable damages on the switch due to the load event	No noticeable damages on the bridge due to the load event
	Minor damage	Damages that partially affect track geometry or rail	Damages that partially affect either the condition of the elements or the switch operation	Damages that partially affect the structural stability
	Severe damage	Potential lack of stability of the track section to support the dynamic wheel load according to the required speed	Damages that significantly affect either the condition of the elements or the switch operation	Potential lack of structural stability
Network use	Normal use Maximum speed restriction	Fully operational track section The operation of the track section is possible only with a speed of 40 km/h	Fully operational blocks The operation of all affected blocks is possible only with a speed below 40 km/h	Fully operational block The operation of the block where the bridge is located is possible only with a speed below 40 km/h
	Closure	Closure of track section and all the blocks located on this track section	Closure of the switch and all the blocks affected by this switch	Closure of the bridge and all the blocks affected by this bridge
Societal	No damage, maximum speed restriction, no accident and major corrective intervention	No damage, maximum speed restriction, no accident and track replacement	No damage, maximum speed restriction, no accident and switch renewal	No damage, maximum speed restriction, no accident and bridge renewal
	Minor damage, maximum speed restriction, no accident and minor corrective intervention	Minor damage, maximum speed restriction, no accident and tamping	Minor damage, maximum speed restriction, no accident and gridding or welding	Minor damage, maximum speed restriction, no accident and bridge repair
	Severe damage, normal use, accident and major corrective intervention	Severe damage, normal use, accident and track replacement	Severe damage, normal use, accident and switch renewal	Severe damage, normal use, accident and bridge renewal
	Severe damage, closure, no accident and major corrective intervention	Severe damage, track closure, no accident and track replacement	Severe damage, switch closure, no accident and switch renewal	Severe damage, bridge closure, no accident and bridge renewal

paper by Papathanasiou *et al.* (2020), it was considered sufficient to demonstrate the proposed methodology.

Determine effects on service

For each stakeholder, manager and passengers, a set of effects on service was considered, as presented in Tables 9 and 10, respectively.

Determine models to be used for each effect

Simplified models were developed for this case study to estimate the effects on service. These models were based either on data collected for the EU project Destination Rail or on Irish Rail data. The effects on service were further specified in costs to be modelled, as shown in Table 9. The models used in this case study considered the effects

Table 8. Models used to quantify the probability of infrastructure events to occur based on the load events

Asset type	Load event	Corresponding failure	Reference of the model
Track	Tonnage	Track geometry irregularities and rail defects	Track-asset-management model developed and used by Irish Rail Dobney <i>et al.</i> (2009)
	Temperature	Track buckling	
Switches	Tonnage	Wear of switch elements	Switch scoring system developed and used by Irish Rail
	Temperature	Switch malfunction	
Bridges	Tonnage	Instability	Connolly <i>et al.</i> (2018) and Connolly and O'Connor (2017) Fragility curves adapted from Lamb <i>et al.</i> (2017)
	Stream velocity		

Table 9. Effects on service and cost types for the manager

Effect on service	Description of cost	Symbol	Unit cost: €					
			Track		Switches	Bridges		
			(a) Tamping	(b) Rail replacement and tamping		Concrete	Metal	Masonry
Corrective interventions	Cost of executing minor corrective intervention in one unit of an asset	C ₁	6/m	95/m	10 000	1000/m ²	3000/m ²	1000/m ²
	Cost of executing major corrective intervention in one unit of an asset	C ₂		623/m	250 000	7000/m ²	5000/m ²	8000/m ²
Damages	Cost of preparing the site and restoring secondary damages after minor damage for a minor corrective intervention	C ₃	10 000		1000	100 000	100 000	150 000
	Cost of preparing the site and restoring secondary damages after minor damage for a major corrective intervention	C ₄	20 000		1000	500 000	300 000	400 000
	Cost of preparing the site and restoring secondary damages after severe damage for a major corrective intervention	C ₅	100 000		4000	1 000 000	800 000	1 000 000
Accident	Cost of cleaning up the site after an accident	C ₆	1 000 000		500 000		10 000 000	
	Cost due to damages on adjacent structures after an accident due to minor damage	C ₇	10 000		10 000		1 000 000	
	Cost due to damages of adjacent structures after an accident due severe damage	C ₈	5 000 000		1 000 000		50 000 000	

Table 10. Effects on service and cost types for the passengers

Effect on service	Description of cost	Symbol	Unit cost: €					
			Track		Switches	Bridges		
			(a) Tamping	(b) Rail replacement and tamping		Concrete	Metal	Masonry
Delays	Delay cost related to 1 h speed restriction of a section per passenger delay minute	C ₉			0			
	Delay cost related to 1 h closure of section per passenger delay minute (Figure 9)	C ₁₀	0.515 × passenger delay minutes for weekday or weekend					
	Delay cost related to the duration in minutes of traffic disruption due to the execution of planned intervention in one unit of an asset (Figure 9)	C ₁₁	0.515 × passenger delay minutes for 24 h weekend					
	Delay cost related to the duration in minutes of traffic disruption due to the execution of minor corrective intervention in one unit of an asset	C ₁₂	0.001/h and m	0.005/h and m	1.54/min	0.7/min and m ²		
	Delay cost related to the duration in minutes of traffic disruption due to the execution of major corrective intervention in one unit of an asset	C ₁₃	0.004/h and m		18.53/h	37.1//min and m ²		
	Delay cost related to the duration of the preparation works after minor damage and until minor corrective intervention is started	C ₁₄	1.54/h	2.57/h	0.51/h	5.1/h		
	Delay cost related to the duration of the preparation works after minor damage and until major corrective intervention is started	C ₁₅	3.09/min		1.54/min	61.8/h		
	Delay cost related to the duration of the preparation works after severe damage and until major corrective intervention is started	C ₁₆	3.09/min		1.54/min	86.5/h		
	Accident	Cost due to an accident	C ₁₇	10 000 000		5 000 000		50 000 000
Cost due to a secondary collision after an accident due to minor damage		C ₁₈	10 000		10 000		500 000	
Cost due to a secondary collision after an accident due to severe damage		C ₁₉	1 000 000		1 000 000		10 000 000	

on service due to failures within 1 year. All the effects on service within this time were modelled, even if they extended beyond this analysis period. For example, if a bridge failure occurred on the last day of the analysis period and resulted in a service disruption in the following years, this would be considered. However, if a failure occurs at the end of this 1 year, then all the effects were quantified until the restoration service.

Corrective intervention model

A simple model was developed to estimate the duration and cost of corrective interventions. This model assesses for each asset the cost, C , of the corrective intervention, Int , of a scenario i based on a function of their extent e , type g and the corrective intervention type, Int , defined by the societal event, So , of the scenario (Equation 2).

$$2. \quad C_{Int\ i} = C(e, g, Int|So_i)$$

The duration, D , of traffic disruptions due to the execution of corrective interventions, Int , of a scenario i is assessed using a function of their extent e , type g , and the corrective intervention type, Int , defined by the societal event, So , of the scenario (Equation 3).

$$3. \quad D_{Int\ i} = D(e, g, Int|So_i)$$

For all the corrective interventions, it was assumed that they are to be executed in the entire extent of the asset. Hence, the effects of corrective interventions were not modelled as a function of the extent of the damage. The effects related to the extent of damage were modelled independently. To estimate the C_1 , C_2 , C_9 and C_{10} with a sufficient level of accuracy, it was necessary to consider the extent of the assets.

Damage model

The cost, C , to restore the damages, Dam , of a scenario i is calculated using a function of their extent e , type g and the damages defined by the societal event, So , of the scenario (Equation 4).

$$4. \quad C_{Dam\ i} = C(e, g, Dam|So_i)$$

The duration, D , of traffic disruptions due to the restoration of the damages, Dam , of a scenario i is assessed using a function of their extent e , type g and the damages defined by the societal event, So , of the scenario (Equation 5).

$$5. \quad D_{Dam\ i} = D(e, g, Dam|So_i)$$

Based on historical data and approximations made by experts, the cost and duration of preparing the site after damage occurs was modelled. The cost and duration of preparing the site after damage occurs were assumed to be dependent on the extent of damage and the extent of corrective intervention that will follow

and independent of the asset size. C_3 , C_4 , C_5 , C_{11} , C_{12} and C_{13} were approximated using a fixed value that depends on the asset type and subtypes. It is important to note that asset damages might lead to significant secondary damages on the site. For example, bridge damage might lead to damages on the track sections and switches supported by this bridge, as well as damages to any structures below the bridge – for example, roads and buildings. The damage model considered such damages to be secondary damages on other assets and structures, and their effects were included in the costs C_3 – C_6 and C_{14} – C_{16} .

Accident model

The cost, C , due to accidents, Acc , of a scenario i is calculated using a function of the asset type g and the accident costs due to fatalities, injuries and damages according to the societal event, So , of the scenario (Equation 6).

$$6. \quad C_{Acc\ i} = C(g, Acc|So_i)$$

The duration, D , of traffic disruptions due to accidents, Acc , of a scenario i is assessed using a function of the asset type g and the time to restore the site after an accident according to the societal event, So , of the scenario (Equation 7).

$$7. \quad D_{Acc\ i} = D(g, Acc|So_i)$$

Historical data and approximations made by experts were used to estimate the costs related to accidents. The costs of accidents for the manager and passengers – that is, C_6 and C_{14} – were considered dependent only on the asset type. The costs due to secondary damages on adjacent structures and secondary collision were considered dependent on the asset type and the extent of the damage. Hence, the costs C_7 , C_8 , C_{15} and C_{16} were approximated for each asset type.

Delay model

The cost, C , due to delays is the sum of the duration of traffic disruptions due to corrective interventions, damages and accidents according to the societal event, So , of the scenario multiplied by the unit cost per minute of delay, u_D (Equation 8).

$$8. \quad C_{D\ i} = (D_{Int\ i} + D_{Dam\ i} + D_{Acc\ i}) \times u_D$$

A model was developed to estimate the delays corresponding to each asset, considering its location in the network based on the information presented in the report by Aksentijevic *et al.* (2017). When an asset is unavailable, trains might be required either to be delayed or, if this is not possible, to be cancelled. If a train must be delayed, the expected delayed minutes per train were estimated due to the implementation of speed restriction or closure for 1 h and were modelled for each asset by considering the signalling map and the traffic in trains during peak and off-peak hours on a weekday and on a day on the weekend. If a train must be cancelled, it was considered

that the passengers would arrive at their destination using other means with a 30 min delay. The number of passengers per train was estimated based on the traffic volume of the most significant station in the analysed network, station C. One-third of this volume was considered traffic through this station. As an example, the expected passenger delay minutes due to implementing a 1 h closure for each asset are shown in Figure 9.

Estimate the cost of each effect on service

The 16 costs were estimated for each asset using the unit costs in Table 9 and the extent of the assets, where necessary.

Risk estimates

The outputs of the models were used to estimate the risks related to each asset. This part consists of four tasks (Table 5). The following five subsections describe the implementation of tasks for the case study described in the section headed ‘Description of the case study’ using the results produced, as described in the sections headed ‘Estimate the probabilities of the events’ and ‘Delay model’.

Estimate the probabilities of each scenario

The probability of the occurrence of each scenario is the product of the probabilities related to each event in the scenario, as shown

in Equation 9. As an example, the probabilities related to the track section T1 scenarios are given in Figure 7.

$$9. \quad P_{\text{Scenario } i} = P_{\text{Source}}^{\text{Scenario } i} \times P_{L/\text{Source}}^{\text{Scenario } i} \times P_{I/L}^{\text{Scenario } i} \times P_{N/I}^{\text{Scenario } i} \times P_{\text{So}/N/I}^{\text{Scenario } i}$$

Estimate the costs for each scenario

The cost for each scenario is the sum of all the effects, expressed in costs, occurring when the scenario occurs. They are calculated as the sum of the cost and effects on service due to the execution of corrective interventions, damages, accidents and delays, as shown in Equation 10. For example, the effects of all the scenarios for the track section T1 are given in Figure 7.

$$10. \quad C_{\text{Scenario } i} = C_{\text{Int } i} + C_{\text{Dam } i} + C_{\text{Acc } i} + C_{\text{Del } i}$$

Estimate the risks for each scenario

The risk related to each scenario is the product of the probability of the scenario to occur and the costs due to the occurrence of the scenario, as given by Equation 11. For example, the effects of all the scenarios for the track section T1 are given in Figure 7.

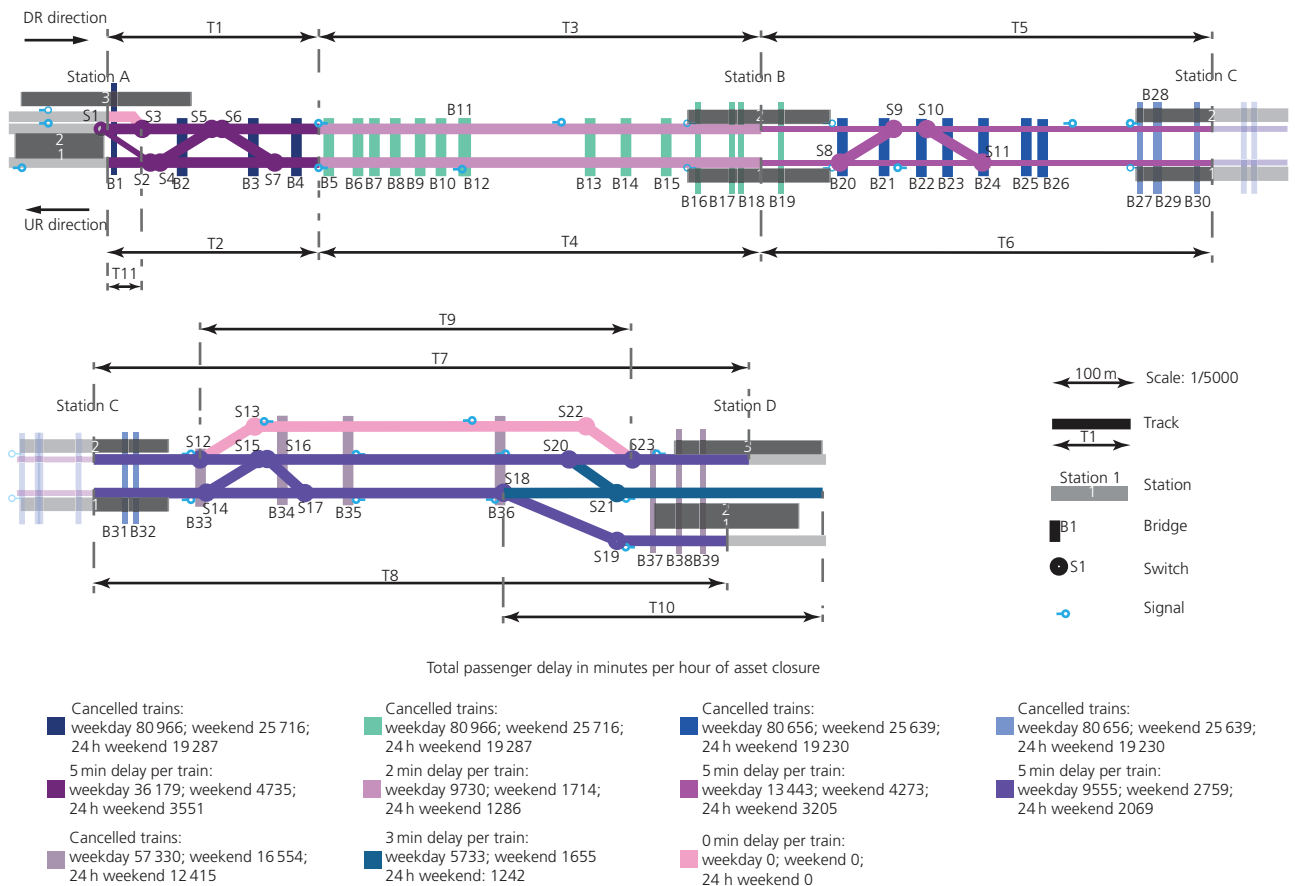


Figure 9. Passenger delay minutes for each asset per hour of asset closure

$$11. R_{\text{Scenario } i} = P_{\text{Scenario } i} \times C_{\text{Scenario } i}$$

Aggregate the risks per asset

The risk, R , related to an asset, a , is the sum of all the risks related to all the hazards and all the scenarios examined for this asset.

$$12. R_a = \sum_H \sum_i R_{a|H|\text{Scenario } i}$$

The risk related to the track section T1 due to traffic as a hazard is €63 482. The risk related to the same asset due to ambient temperature is €0. Consequently, the risk related to T1 due to both traffic and ambient temperature is €63 482.

Figure 10 shows the risks related to the assets in four groups of different risk ranges. As all the risk estimates are expressed in costs, it is possible to estimate the total risk related to this part of the network and identify which assets have the highest risks. Given all the assumptions made in this case study, the risk of this part of the network is €410 million, of which

- 99.5% is related to bridges
- 0.33% is related to switches
- 0.15% is related to tracks.

Of the risk related to bridges, a considerable amount of this risk is related to bridge B28, which is currently in a poor state, and the risk related to this state is €222 million. One hundred fifty-eight million euros of risk is related to a second bridge, B16, which is also in a poor state. The remaining risks related to bridges are only €30

million. Interestingly, by improving the state of these two bridges just by one state, the network risks will be reduced to almost €41 million.

According to the results and given all the assumptions made for this case study, the failures due to traffic were estimated to lead to significantly higher risks than the failures due to extreme ambient temperatures, for track and switches, but significantly lower risks when compared with flood for the bridges. More than 99.9% of their total risk was found to be related to failures due to traffic for the track sections. For the switches, this percentage is slightly lower, at 99%. However, less than 5% of the risk related to bridge B14 is due to traffic.

Discussion

This paper shows that it is possible to produce comparable risk estimates for railway assets of different types by utilising existing models. The methodology is based on the systematic definition of scenarios using event trees that link infrastructure failures to their effects on railway service and the systematic quantification of these effects for different stakeholders. The use of the methodology for the case study demonstrates that the risk estimates produced for assets of three different types and due to three different hazards are directly comparable.

The methodology uses an event-tree structure to link the asset failures to their causes and effects on railway service. Although there may be perhaps other methods to link the occurrence of hazards, infrastructure and service failures – for example, binomial trees – the proposed event-tree structure, with its systematic sequence of hazard, load, infrastructure, network use and societal events, offers a flexible way to incorporate the relationships analysed by a wide range of existing models. Its modular character allows the output of different

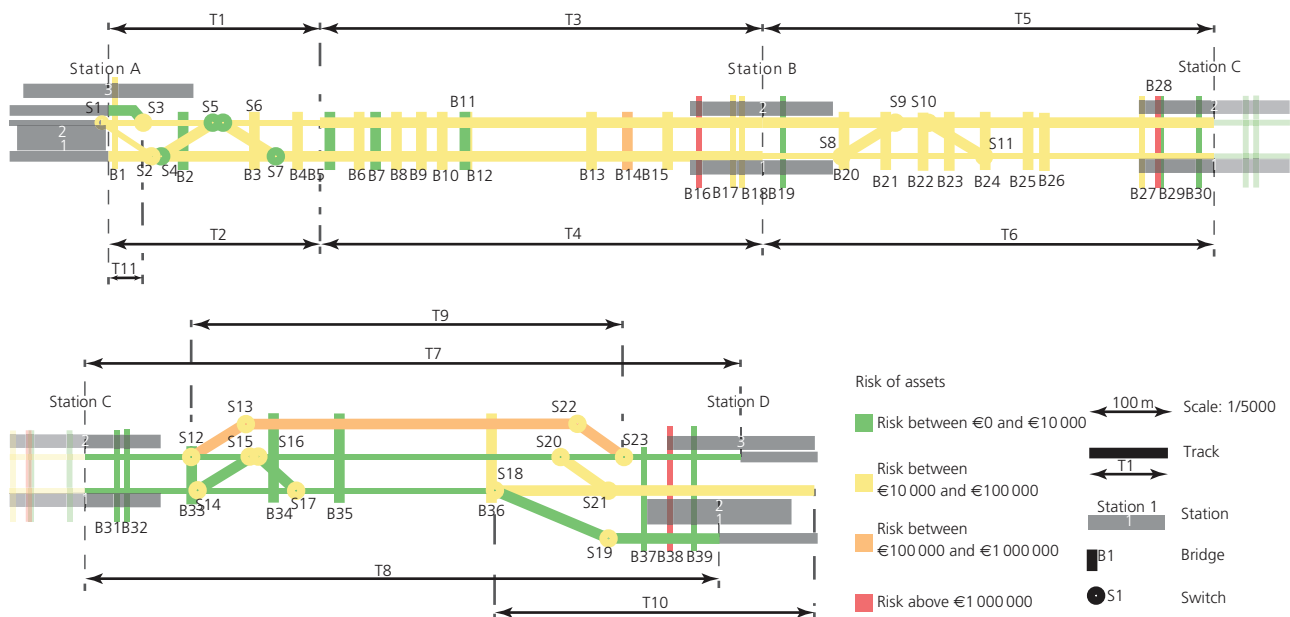


Figure 10. Illustration of the risks related to the assets of the network

models to be used and updated when needed. It also provides a clear structure that can be used to communicate the analysed scenarios, which is essential when agreeing with stakeholders about which scenarios are to be considered and the risks related to them. This ensures that the manager can have an overview of the analysed risks and the models that are used in the process.

The methodology requires the use of models that estimate the probability occurrence of certain events (e.g. the probability of delays to occur due to a closure of a section), the extent of the specific effects on service (e.g. the delays per hour of closure) and the unit cost of these effects, the cost per 1 h of delay. However, these values can often not be readily estimated with confidence, as predicting these events is related to a high uncertainty level. In situations where there is no single value that can be used with high confidence to express a probability, or a cost, a range or a distribution of values can be used. Alternatively, one could consider modelling in detail specific scenarios or parts of scenarios to reduce this uncertainty. An example of how this can be done for roads is presented in the paper by Hackl *et al.* (2018). The trade-offs between using simplified, and perhaps less accurate, values in the risk assessment; the resources required to estimate these values; and the computational effort required to model scenarios in detail should be considered. Despite the difficulties in estimating many relationships between the events and their effects with confidence, the systematic way proposed to examine scenarios helps build an overview of where available models can be used, which relationship models should be developed and what level of accuracy is required from these models.

Many simplifications were made when estimating the case study risks and simple models and input from experts were used. The case study analysis was built on the available information for this specific network regarding the definition of events. The relationships between the events and the probabilities and costs presented were used only to demonstrate the implementation of the methodology in the discussion, given the simple scenarios as shown. The definition of more complex scenarios and the use of more detailed models would present examples closer to the situations that railway managers face. However, the principle of how the scenarios are determined systematically across different asset types by linking failures to their causes and effects on stakeholders will be the same even when more complicated scenarios are assessed, requiring models with higher levels of accuracy and complexity.

Often in practice, railway managers use various indicators of directly quantifying the risk. These indicators are used to either estimate the probability of failures to occur (e.g. reliability and vulnerability), estimate the effects of failures on the service (e.g. exposure) or qualitatively indicate the most significant risk. Although these indicators require fewer data and simpler models to assess qualitatively the risks of the assets than the proposed quantification and monetisation of risks, such indicator have a significant drawback. The values of these indicators are not compatible with each other, and they cannot be directly compared with the costs of executing the risk-reducing interventions. This leaves railway managers with the

challenging task of deciding whether the execution of a risk-reducing intervention can be justified by improving the value of the indicator. Even in a situation when an acceptable level of risk must be defined according to regulations using, for example, methods such as 'as low as reasonably practical', the acceptable risk depends on the balance between the benefit and cost of executing a risk-reducing intervention (NEN EN 50126-1 (NEN, 1999)). This, in turn, requires estimating the risks with and without executing a risk-reducing intervention and comparing them with the cost of executing this intervention. This direct comparison is impossible if the risks and costs are not expressed in comparable units.

In contrast, when railway managers estimate the risks by directly quantifying the effects of failures in units comparable to the intervention costs, the benefit of executing a risk-reducing intervention becomes directly comparable with the intervention cost. This is addressed in the paper by Papathanasiou and Adey (2020a). It is shown that the proposed detailed quantification of risks allows evaluating the trade-offs between corrective and preventive interventions more accurately and transparently, compared with the current practice, and, therefore, making informed, data-based, transparent and justifiable decisions in railway asset management.

Although the case study is focused on risks related to single failures of infrastructure assets, it can also be used to consider failures of multiple assets simultaneously. However, when the dependencies between the simultaneous failures of multiple assets are considered, the proposed event-tree structure leads to a combinatorial expansion of the problem. This is a topic that should be addressed in future work.

Conclusions

This work focuses on the systematic definition of scenarios that link asset failures to their causes and effects on railway service. The aim of this work is not to develop a risk model to be added to the toolbox of models that infrastructure managers already have. Instead, this work aims to show clearly a systematic way of linking and using existing models, including reliability, hazard, safety, risk and traffic models, as well as the expertise that railway managers have to produce comparable risk estimates for all the assets across the network. Therefore, existing models were used in the case study to quantify the risks related to the defined scenarios.

The methodology presented in this work consists of systematically building scenarios related to asset failures to quantify their effects on railway service and produce comparable risk estimates across different asset types. The scenarios are built by creating sequences of five general types of events, hazard, load, infrastructure, network use and societal events, in an event-tree structure. The scenarios are then linked to the effects on railway service. The effects on railway service are quantified by expressing in costs the effects on stakeholders due to the occurrence of the societal events of each scenario. Existing models can be used to assess the relationships between the events within a scenario to occur and to assess the effects on railway service due to the occurrence of the scenario.

The real-world case study demonstrates how the methodology can be used to produce comparable risk estimates for track sections, switches and bridges due to traffic-, ambient-temperature- and flood-related failures. Although simple models were used for this case study, the infrastructure manager can choose to integrate more sophisticated models based on the scope of the analysis, the required level of accuracy of the risk estimates and the availability of resources and tools. The results show that it is possible to produce compatible and comparable risk estimates by utilising information from existing models to help infrastructure managers to develop optimal risk-reducing intervention programmes, as shown in the papers by Papathanasiou and Adey (2020b) and Burkhalter and Adey (2018, 2020).

Further work could include developing a case study that considers failures on multiple assets simultaneously and the cascading costs and effects on service related to these scenarios. Such an analysis will show the sensitivity of the risk estimate in the case study to the assumption of single-asset failures.

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Appendix

Table 11 provides the extent of the track sections and bridges. The extent of the track sections is equal to their length, and the extent of the bridges is equal to the deck surface area.

Table 11. Extent of track sections and bridges

Asset category	Asset	Extent	Asset category	Asset	Extent
Track section (measured in m)	T1	255	Bridge (measured in m ²)	B15	400
	T2	255		B16	640
	T3	533		B17	230
	T4	533		B18	230
	T5	543		B19	960
	T6	543		B20	320
	T7	764		B21	600
	T8	790		B22	330
	T9	521		B23	460
	T10	385		B24	450
	T11	41		B25	650
Bridge (measured in m ²)	B1	720	B26	720	
	B2	1130	B27	270	
	B3	470	B28	765	
	B4	320	B29	192	
	B5	372.4	B30	110	
	B6	166.6	B31	160	
	B7	166.6	B32	240	
	B8	350	B33	345	
	B9	500	B34	345	
	B10	250	B35	136	
	B11	350	B36	425	
	B12	1410	B37	187	
	B13	500	B38	187	
	B14	450	B39	255	

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