Report on
Decision Support Tool D3.3

Authors
* Zaharah Allah Bukhsh, Irina Stipanovic, Lorcan Connolly, Bryan Adey, Natalia Papathanasiou, Ken Gavin, Karlo Martinovic, Vijay Ramdas, Aaron Barrett, Andreas Schoebel

*Corresponding author: z.allahbukhsh@utwente.nl

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Executive Summary

This deliverable reports the development of decision support tool (DST) that aims to facilitate infrastructure managers in maintenance planning. Reliability assessment framework, risk assessment framework and whole life cycle cost analysis are main building blocks of the DST. These models form the core functionality as well as provide the decision logic to the DST. Each of the models is developed independently by project partners, but have a strong dependency as the output of one model is often used as an input to another model. For instance, the reliability index of an asset computed by reliability assessment framework is required by risk assessment framework to quantify the risk associated with an asset. A variety of tasks were performed to make the coupling and information dependency of these models explicit in the DST and to provide the computerised implementations.

Firstly, the data needs of each of the models are analysed by conducting semi-structured interviews with twelve project partners. These interviews defined the scope of the database, the data required by frameworks/models being developed in DESTination RAIL and identified the assets, their properties and inter-relationships among them. Following this, a central database repository is developed which consists of data of stations, bridges, switches and crossings, and tracks line. At the moment, the database is being updated with the computed risk scores of the individual assets. Secondly, considering the strong dependency among these frameworks/models, the information flow is defined which explicitly delineate the data input and data output for each of the framework/model. Moreover, the system architecture of the DST is developed which defines the structure and components of the system that will work together to provide the functionality as a whole. The overall system is structured into three-tier architecture, where the information management system forms the data layer, the developed frameworks/models yield decision logic and form the application layer, and an innovative GIS-based user interface forms the presentation layers of DST. Finally, user interactions with the DST in terms of decision questions and functionalities supported by DST is illustrated by the use cases and interaction diagrams.

Currently, the DST provides the detailed GIS-based interface to visualise, locate and select the assets from the Irish rail network for analysis. Future developments for the DST include the implementation of reliability and risk assessment frameworks. In addition, the interfaces to interact with the whole life cycle costing and traffic delay model will be developed as a part of the DST. The proof of concept of the DST will be demonstrated with a case study of assets from the Dublin region consisting of 73 tracks, 90 bridges, 134+ switches and crossing, 41 cutting and 25 embankments. It is worth mentioning that the developed decision logic by models as well as the computerised implementations is generic so as to enable to specific data from any railway agency to be processed. This deliverable fulfils the requirements of Task 3.4 of the Destination Rail project.
1 Introduction

The railway is a complex and integrated network, where the railway infrastructure and its operations are tightly coupled. A minor failure in infrastructure very often leads to operational disruptions, which propagates to the (parts of) network. According to EuroStat (2016), railway passenger transport performance continues to progress by 6.4 billion passenger-kilometres between 2013 and 2014 (+1.5%). On one hand, the acute utilisation of railway operations imposes the high demands of improved service quality, while on the other hand, the railway infrastructure is exposed to aging and adverse climate change, where approximately 95% of railway infrastructure was built before 1914 (European Railway Agency 2014, 2013). A few recent accidents due to heavy rainfall (BBC News, 2014), coastal flooding (The Telegraph News, 2014) and bridge scouring (Bray, 2009) are examples of adverse climate effects on railway infrastructure. With the increasing service demands and aging infrastructure, infrastructure managers are under increased pressure not only to provide a safe operational network but also to take smart maintenance decisions that improve network availability and prolong the overall service lifetime of infrastructure assets.

Traditionally, the decisions to perform maintenance have been based on the infrastructure managers' observations, judgments and choices which are derived by available budgets, planned schedules and abrupt failures (Dhillon, 2002). However, maintenance based on these drivers often leads to undue maintenance of increased cost. For this reason, predictive maintenance is considered to be a most effective maintenance policy that suggests to perform maintenance only where it is promptly needed (Khan and Haddara, 2003). However, predictive maintenance poses decision-making challenges on the infrastructure managers, particularly for railways whereby the maintenance decision-making is a difficult task due to a widespread network of diverse railway objects (e.g. constituting tracks, bridges, switches and crossing, tunnels, electrification system, etc.), availability demands, possession time, deterioration rate and budget constraints. Such infrastructure maintenance requirements pose decision-making dilemmas to the infrastructure managers, where maintenance planning is challenged by the number of conflicting issues (Lidèn, 2015). For instance, demand to keep the network available conflicts with increasing rate of deterioration, limited budget vs. aging network, the risk of failures vs. traffic intensity over an asset, and so on.

These maintenance decision-making dilemmas are difficult to handle based only on experts' choices and on techniques that over-rely on expert judgment. Decision support approaches that are based on predefined decision rules over-rely on infrastructure managers' judgments. Therefore, a trend towards the use of the computer-based system, namely decision support system (DSS) has arising in recent decades. However, computerised decision support systems inherently suffer from a number of limitations: i) they focus on one class of assets only (e.g. steep slopes (GDG, 2014), level crossings (RODIS, 2012), track defect management (Uzarski et al.,1993); ii) the data used for decisions are mostly inadequate and over rely on visual assessment, iii) they ignore the effects of any disruption on traffic flow, iv) suffer from a lack of a system-wide database of asset condition and performance; and v) provide the output in ambiguous quantitative numbers only. Current decision support
approaches and support tools do not systematically account for a comprehensive decision-support model that considers assets' assessment data, network as a whole, an effect on network operations due to maintenance, and a number of other factors that are required to be taken into account for a robust maintenance decision making.

To address these pressing needs, the DESTination RAIL project has developed a holistic decision support tool that provides the solutions for the common infrastructure problems encountered in diverse regions of Europe, e.g. deterioration and scour damage to bridges, slope instability, damage to switches and crossing, etc. This is achieved by developing a number of novel techniques and systems for identifying, analysing, predicting and remediating rail infrastructure. The final goal of this project is to integrate the improved monitoring methods, probabilistic models, risk assessment framework, information management system, whole life cycle cost analysis and traffic flow modelling in a computerised decision support tool. This tool will assist infrastructure managers in assessing the current state of assets, predicting the assets' performance over time, executing diverse maintenance scenarios, and will provided maintenance planning recommendations.

This document introduces the conceptual framework and development procedure of Decision Support Tool (DST). The conceptual framework outlines the information flow and integration of data and models developed in WP1, WP2, WP3 and WP4. The developed DST aims to assist rail infrastructure managers in the following ways:

- Provides the central data repository of asset registers (geometry, location, etc.), their current condition, maintenance records, failure history, processed sensor data as well as store the dynamic data, generated as a results of different analysis, for later use.
- Runs the reliability-based assessment of assets performance.
- Performs risk assessment of single assets to determine the risk related to each asset.
- Provides a link to execute the probabilistic life cycle analysis tool linked to a traffic flow model to consider what-if scenarios for making investment decision on network level.
- Assists in maintenance decision making by recommending maintenance treatments and maintenance plans as a result of following the procedural flow of defining the scope, objective(s) and budget, selecting the assets on network, analysing the assets state by probabilistic models and risk assessment framework, and prioritising assets based on defined objectives by using the methods of multi-criteria decision analysis.

Since infrastructure managers mainly derive decision-making processes, the developed DST has high demands of interactivity. Therefore, the DST is not aimed to generate single maintenance plan but can be interacted at various levels, e.g. to overview assets’ risk level, or to execute various what-ifs scenarios, etc.

The remainder of the report is structured as follows: Section 2 provides the brief description of each of the models and frameworks developed in DESTination RAIL, which will provide the decision logic to DST. Section 3 outlines the implementation details of DST with system
2 Decision Support Tool Framework

The DST is an integrated computerised system, which consists of many building blocks that support investment and maintenance decision making. Each of these blocks has dedicated functionality, demand specific data inputs and provides explicit outputs either directly to users or other building blocks in the pipeline. In this section the DST framework outlines the information and interaction flow among these building blocks. Moreover, the brief description of these building blocks and how they are relevant for the development of DST is provided in following subsections. The description of the techniques that form the DST logic is not discussed here in detail as each of these subsections represent the complete task/WP of the project.

2.1 DST Information Map

In this section, the information flow between the project tasks is outlined in order to integrate development of these tasks in DST. Figure 1 outlines the information flow of all the tasks to/from the Information Management System (IMS) and final DST. The integration details of each task is provided below:

- An IMS is developed which acts as a central database repository for all the other tasks of project. The IMS provides the input data to all the systems and techniques being developed and stores their final output (see the two-way arrow heads between Task 3.1 block and other blocks)
- The reliability-based assessment of assets performance based on the improved condition ratings are being developed in Task 2. In addition to the link with IMS block, the output of WP2 tasks provide inputs to compute whole life cycle cost analyses (Task 4.4) and risk assessment (Tasks 3.2 and 3.3).
- A risk assessment methodology is developed in Tasks 3.2 and 3.3 that takes into account the probability of failure multiplied with the consequence of failure quantified into monetary value. The probability of failure is based on the reliability assessment of the assets provided by Tasks of WP2. Moreover, to estimate the consequences on network operations in case of failure, the input from the traffic flow model is provided (notice the input links).
- Whole life cycle cost analysis model is developed in Task 4.4, which aim to investigate the application of alternative maintenance regimes on railway structure to estimate the cost, risk and operational effect. Like others, this task is also dependant on the Tasks of WP2 and Task 3.3 (notice the input links).
- To integrate all the developments made in other tasks, an integrated computerized DST is developed that is able to integrate reliability based assets assessment, risk assessment methodology and whole life cycle cost analysis. The final goal of this step is to enable the user interaction with DST, to execute what-if scenarios for the
maintenance planning and investment decision-making. The DST is built on the static data of railway assets and computed values stored in IMS. It is important to mention that, in addition to execute what-if scenario and facilitating in overall maintenance planning, the DST aims to provide separate outputs to the user generated from WP2, WP3 and WP4. For instance, GIS map of reliability based assessment from WP2, a
Figure 1: DST Information map outlining the information flow among project tasks
GIS risk map from WP3.2 and 3.3 and a map of suggested maintenance alternative for each asset from WP4.

2.2 Information Management System (IMS)

The IMS refers to a software program that is designed to store, organize and retrieve information. The purpose of the IMS in the context of DESTination RAIL is to provide a central data repository of all the data of network assets to fulfil the data needs in maintenance planning and decision-making procedures. To develop such a domain-specific IMS requires in-depth domain knowledge and this was gained during the various development phases of IMS. We followed the simple waterfall development cycle, where the output of one stage provides an input to the next stage (Pressman, 2005). The development procedure for IMS is outlined in Figure 2, which consists of five phases.

![Image of IMS Development Life Cycle (Waterfall model)]

2.2.1 Planning Phase

The planning phase determines the purpose of the IMS. To fulfil the needs with respect to a data input and output, and interoperability between the different techniques and systems, the IMS stores and organize the required data relating to the individual railway assets for a specific network to support decision-making.

In order to understand the data needs of the techniques and systems that were aimed to be developed in the DESTination RAIL projects, we organised semi-structured interviews with twelve key project partners from nine different institutes. All of these participants are responsible for different work packages and tasks of the DESTination RAIL project and, hence, possess knowledge of different requirements for the IMS. We made use of a semi-structured questionnaire to guide the interview process. The questionnaire consisted of questions related to railway infrastructure and the data requirements of interviewees. The interviews were conducted in September 2015 over Skype and telephone that lasted between 30 to 60 minutes. The results of the interviews gave us a sound understanding of data needs and data requirements of systems and techniques that are aimed to be integrated into DST.
2.2.2 Designing phase

The designing phase specifies the structure of the system by various design concepts. We developed information models for the design of IMS. The designed information model is intended to serve as the structure for designing database containers that organise, store, and retrieve data, including translating it into useful information for a specific railway network. Therefore, the information model needs to consist of objects, relationships, rules, constraints and operations in a way that describes the railway management domain purposefully (Lee, 1999). Objects of the information model can describe physical entities of the railway infrastructure, such as track or bridge, or conceptual entities related to railway asset management tasks, such as failure reasons. In addition to representing the physical objects, the information model also represents important attributes of these objects and relationships between the objects. To keep the information model simple, we have omitted operational details, such as train schedules or railway stocks, for now. The Unified Modelling Language (UML) has been used for supporting the model development process and for representing the model (Lee, 1999). The details of design steps and information models dedicated to specific aspects of railways can be found in Deliverable 3.1 (Allah Bukhsh, et al., 2015).

2.2.3 Analysing phase

The analyses phase mainly deals with two aspects, a) assessment of data needs, specified in the planning phase, and b) decision on selection of implementation technology. Since this IMS is dedicated to fulfilling the data requirements of systems and techniques developed in the DESTination Rail project, we aimed to select a database implementation technique, which is flexible enough to accommodate the changing data structure, inter-relationships among entities and addition of data attributes. Initially, MongoDB, a document-based database, was chosen due to its schema-less nature that does not introduce the complex joins to define the entities interrelationships. The main reason to select the MongoDB was to support the continuous development efforts (i.e. changing data needs and to store computed values e.g. risk, reliability) undertaken in various tasks of the project. As the developed systems and techniques of projects are matured over time, the final IMS is being developed in rational database i.e. MySQL server – which is free and open source database management system.

MySQL server provides the concrete structure to the data of most of the railway assets (e.g. bridges, switches), however, it is difficult to structure the track data in rational database format. This is because the track data provides the detailed coordinates information of each piece of track beginning and track ending along with the coordinates of any track curves. Such nested nature of data is well-suited to the document-styled database structure provided by MongoDB.

2.2.4 Developing phase

As mentioned earlier, the final IMS is being developed in MySQL server. IMS consists of data from Irish Railway network. Currently IMS have data of stations, bridges, and switches
and crossings. Irish Rail divides the bridges into overbridges and underbridges, where an overbridge represents the bridge that is over the railway line (e.g. Road Bridge) and underbridges are actual rail bridges.

The following is the overview of the number of assets along with number of stored properties in IMS:

- Stations – Instances 87, Attributes 5
- Overbridges – Instances 833, Attributes 14
- Underbridges – Instances 1212, Attributes 15
- Switches and Crossings – Instances 951, Attributes 32

For the aforementioned assets, the data stored in IMS consist of equipment number to uniquely identify the asset, position coordinates to locate assets on the map, type, construction material, function, line status etc. The data of each asset can then be updated with the computed values e.g. risk, reliability levels, etc. In contrast to other assets, the tracks data is structured in RailML format and stored in separate JSON format where a single node presents a list of coordinates, their functional location, and unique identification code. Irish Rail have 776 lines of track where 35 lines are categorized as station track, 496 lines as siding tracks, 134 as connecting and 111 as main line tracks.

2.2.5 Testing phase

The developed IMS will be tested against the data requirements defined by project participants in the planning phase. The final testing phase is delayed until the complete processing logic of DST has been developed and implemented. Though, at the moment, IMS provides the structures to the stored information and facilitate the information retrieval by techniques and systems developed in DESTination Rail.

2.3 Reliability Assessment Framework

The probability based multi criteria performance optimisation technique developed in Task 2.1 will form a key input to the risk assessment framework and ultimately, the DST. The methodology is described in Figure 3.

The process starts with determination of the critical limits states. This should be performed by a competent engineer using advanced analysis techniques as described in Deliverable 2.1 (Connolly, et al., 2016). Probabilistic modelling need not be performed at this stage. The next step is to define the required reliability index. Recommendations are given in Deliverable 2.1 and can be built into the DST. Stochastic modelling of the load and resistance variables is then performed. Recommendations are provided in Deliverable 2.1, and this can be based on reported probabilistic models in the literature, as a first pass. Next, the reliability index is calculated for the system in question, for each limit state assessed. This should ideally be done with a combination of simulation, FORM and/or SORM analysis, as described in Deliverable 2.1.

Should the reliability index and/or risk be found to be within acceptable bounds, a sensitivity analysis should always be performed to identify critical variables and ensure that the
analysis is not overly sensitive to any variable, as this can indicate an overly simplistic analysis. Should the reliability and/or risk be found to be unacceptable, the analysis should be performed again, incorporating additional information. This is where the monitoring information from WP1 feeds into the overall methodology. Consideration of monitoring such as strain measurements, vibration, water content or site testing allows a much more accurate calculation of the reliability, and will often show the infrastructure to have significantly greater capacity than previously calculated. The information can be considered stochastically in the analysis using maximum likelihood estimation of distribution parameters or Bayesian statistical updating of the previously calculated statistical models.

Should the risk still be found to be unacceptable, repair and remediation strategies can be considered in the reliability and/or risk domain to optimise their design. Finally, probabilistic deterioration models were also developed in order to consider, for example, structural steel pitting corrosion and deterioration in the strength of engineered slopes.

**Figure 3: Probabilistic Basis**

At present, Infrastructure Managers make safety critical investment decisions based on poor data and an overreliance on subjective visual assessment. Therefore, their estimates of risk are highly questionable. The probabilistic methodology developed for hazard assessment
allows an accurate calculation of the failure probability which, when applied alongside the
detailed whole life cycle costing of WP4, provides a much more reliable calculation of risk.

The probabilistic modelling of the input variables relating to both load and resistance
provides a robust platform to apply monitoring and testing information, where the uncertainty
can be accurately quantified. This also allows for a much more accurate calculation of the
reliability, providing Infrastructure Managers with greater levels of certainty in risk-based
decision making.

System-based analysis has been considered, allowing decision making to be based on the
risk level of individual elements as well as whole objects of the infrastructure. Finally, the
advanced engineering analysis techniques used in conjunction with stochastic modelling
allows remediation strategies to be designed in a manner that can optimise both cost and
safety.

2.4 Risk Assessment Framework

ETH will deliver for the DST the risk in monetary units related to the state of each asset that
is included in the case study. The risk will be the product of probability of failure and
consequences so that the risk related to assets of different types is comparable.

As currently the consideration of risk for, i) track, ii) switches and crossings, iii) earthworks
and iv) underbridges is at different stages, different steps of the risk assessment
methodology described in Deliverable 3.2 (Papathanasiou et. al., 2016) will be followed for
each class of assets.

2.4.1 Tracks

Currently Irish Rail does not assess risk related to the track. The ETH will, therefore, develop
a risk assessment model based on the available information provided by Irish Rail. The
states to be used for the track sections will reflect the states of the different track elements
currently considered by Irish Rail, e.g. based on the condition of the rail, ballast and sleepers
and failure history. The ETH will estimate the failure probability and the consequences of
failure in monetary units related to each state of the track sections. The product of the
probability and consequences will result in the risk in monetary units related to each state of
each track section.

2.4.2 Switches and crossings

Irish Rail already has a tool that is used to assess the risk related to switches and crossings,
namely the P&C evaluation tool. In this tool, the risk is expressed as combined risk score.
The ETH will define the states of the switches and crossings, based on the type of the switch
or crossing, the condition score, the ultrasonic defect and the maintainability score, and
estimate the failure probability and consequences of failure in monetary units related to each
state based on the factors used in the evaluation tool, i.e. type of the switch or crossing,
condition score, ultrasonic defect score, maintainability score, duty score, escalation
potential score for secondary collision and escalation potential score for structure. The
product of the probability and consequences will result in the risk in monetary units related to
each state of each switch or crossing. This model of assessing the risk related to switches
and crossings in monetary units will be then calibrated using the risk score produced by the evaluation tool, i.e. as best possible the model will produce risk estimates that show the same trends as the risk scores, i.e. an object with a high risk estimate will also have a high risk score.

2.4.3 Earthworks

Similarly, to the switches and crossings, Irish rail uses a tool to assess the risk related to earthworks, which was developed in collaboration with GDG. The output of this tool is the risk related to earthworks expressed as a risk factor. The ETH will develop a risk assessment model, based on this available tool, in order to express the risk related to the earthworks in monetary units. The states for the earthworks are defined by Irish Rail. The ETH will estimate the probability of failure and consequences of failure in monetary units related to each state based on the factors used in the tool developed by GDG, e.g. condition, slip history, train frequency, clearance. The product of the probability and consequences will result in the risk in monetary units related to each state of each earthwork. This model of assessing the risk related to earthworks in monetary units will be then calibrated using the risk value produced by risk tool.

2.4.4 Underbridges

Currently Irish Rail does not perform comprehensive assessments of the risk related to the underbridges. The ETH will develop a risk assessment model based on the available information provided by Irish Rail and RODIS. The states to be used for all the underbridges will reflect the reliability limits, i.e. above serviceability limit, between serviceability and ultimate limit and below ultimate limit. The ETH will estimate the consequences in monetary units of failure related each state of the underbridges, while RODIS will estimate the probability of failure for each state. The product of the probability and consequences will result in the risk in monetary units related to each state of each underbridge.

2.4.5 Link to DST and other WPs

For the successful development of the risk models, a tight collaboration is required between the different partners involved in the project and namely, Irish Rail (WP2), GDG (WP2), RODIS (WP2), UT (WP3), TRL (WP4) and Open Track (WP4).

For all the classes of assets, i.e. track, switches and crossings, earthworks and underbridges, Irish Rail (WP2) is responsible for the selection of assets to be included in the case study. Moreover, the states for each class should be defined taking into consideration the possible interventions to be executed in each state and the effect the maintenance options considered by TRL (WP4) have on the asset condition. Where applicable, data concerning the cost of restoration and the network disruption produced by TRL (WP4) and Open Track (WP4), respectively, will be used in the estimation of the consequences related to each asset state. Further collaboration between the ETH (WP3), who is developing the risk model, and three partners from WP2, Irish Rail, GDG and RODIS, who are working on the reliability assessment models, is required for the risk analysis of track, earthworks and underbridges, respectively. Regarding the track, the state definition of a track section will reflect the condition of the different track elements currently considered by Irish Rail (WP2),
e.g. based on rail, ballast and sleepers condition, failure history. The risk model will, therefore, consider track states that comply with the thresholds regarding track maintenance defined by Irish Rail (WP2). Regarding the switches and crossings, the risk model will use input from Irish Rail (WP2) with respect to the classification of switches and crossings in different types, the condition score, the ultrasonic score, the maintainability score, the duty score, the escalation potential scores and the computation of the combined risk score. Regarding the earthworks, the risk model will use input from GDG (WP2) with respect to the baseline probability, the hazard value probability for each state of each earthwork, the four vulnerability factors and the final vulnerability factor of each earthwork, for the estimation of the probability and consequences of failure related to each state of the earthworks. Regarding the underbridges, the risk model will use as input the failure probability related to each state of the underbridges, as estimated by RODIS (WP2).

The cost of preventive maintenance interventions, and the risk of asset failure, including the execution of restoration interventions, both in monetary units, will be used in the DST for the selection of preventive maintenance interventions. By knowing at least two values of risk, related to the discrete states of each asset, i.e. the risk before a preventive maintenance intervention (state a), \( R_a \), and the risk after a preventive maintenance intervention (state b), \( R_b \), is the DST will estimate how much the risk is reduced when the preventive maintenance intervention is executed, i.e. \( \Delta R = R_a - R_b \). The comparison of this risk reduction value, \( \Delta R \), with the cost of the preventive maintenance intervention, \( C \), results in the net benefit, i.e. net benefit = \( \Delta R - C \). Net benefit can be used to determine if one risk reducing intervention program is better than another. It is, therefore, extremely useful for a decision-maker who needs to decide which interventions to execute on a network taking into consideration many assets of different types.

### 2.4.6 Example of risk model applied on slopes

The main aim of the model is to determine a relative risk value for each cutting and embankment asset. These risk values are used to rank the assets in order to identify the most critical ones. The risk here is defined as a product of hazard and consequence, as defined in Varnes (1984). Hazard is defined as a likelihood of failure (landslide) on each asset. Consequence describes the impact of potential landslide occurrence to the train operations. More specific, hazard only represents the susceptibility of an asset to failure without taking account of asset’s setting, line characteristics etc., while consequence introduces other parameters on which the level of potential impact relies, such as proximity of asset to the tracks, train frequency on that line, etc.

In this tool, hazard is calculated as a product of two separate hazard analysis steps, the first one involving objective slope stability calculations and second one introducing the influence of subjectively described slope observations, dubbed Degradation Factors. Each step results in a single numerical value. Similarly, a consequence value is calculated in the standalone step. Final risk result for each is then calculated as presented in the Equation 1.

\[
R = H \times C = H_1 \times H_2 \times C = \beta^* \times DF_{TOT} \times VF_{TOT}
\]  

[1]
Where R is risk, H is hazard, C is consequence, H₁ and H₂ are first and second hazard step respectively, β* is baseline reliability index (final product of hazard’s first step), DFₜₒₜ is a product of all Degradation Factor weights (final product of hazard’s second step), and VFₜₒₜ is a product of all Vulnerability Factor weights (final product of consequence analysis). The graphical representation of risk process is shown in Figure 4.

- **Hazard Analysis – Step 1**

In the first step of the hazard analysis, probabilistic limit equilibrium (2D) calculations for each asset. The calculations simultaneously calculate three failure modes for each asset: shallow translational slide, deep rotational slide, and rock wedge. Inputs for this calculation are assumed to come from the infrastructure managers (IM’s) asset database and include geometry (slope height, slope angle, adjacent angle, ...) and geotechnical properties attached to the soil type of each asset stored in the same database. Inputs data is described probabilistically, i.e. a mean value, coefficient of variation and distribution type are assigned to each variable.

Outputs of this step are baseline reliability index (β) and baseline probability of failure (Pₐ) (two correlated measures, meaning that any one of them can be used for expressing the hazard).

- **Hazard Analysis – Step 2**

The hazard calculations carried out in step one are based only on the slope geometry and geotechnical characteristics. In reality however slope stability depends on a much larger number of factors such as the drainage type and condition, vegetation cover, presence of weathering and erosion, etc.; all with varying degrees of influence. For that reason, the second step of the hazard model introduces the contribution of qualitative expert judgment. The twenty-one most important qualitative earthwork features are identified and their influence to slope stability quantified through assigning a numerical weight to each class (input option) of each feature (called Degradation Factor). The product of weights for each DF, which depends on the combination of features unique to each slope, is multiplied with

\[
β_H = β^* × DF_{tot} = β^* × \prod_{i=1}^{21} DF_i
\]  

**Figure 4: Diagram of risk model’s risk calculation process**

- **Consequence Analysis**

   CONSEQUENCE (C)

   Output: VFₜₒₜ

- **Risk Analysis**

   RISK (R)

   Output: R

   Where Fₗ is the level of consequence for each element of an asset with weight Wₗ for each level, Qₗ is the output of the consequence analysis as defined in (2), and C is the consequence for the whole asset. The graphical representation of consequence process is shown in Figure 5.
the baseline reliability index ($\beta^*$) from the Hazard Step 1 to obtain the hazard reliability index ($\beta_H$), see Equation 2.

Where $DF_{TOT}$ is a product of weights of each of 21 DFs.

- **Consequence Analysis**

From the relative risk ranking viewpoint, the consequence assessment considers the impact of potential landslides on the safe operation of railway operations. This depends on two main characteristics: the ability of landslide to reach the tracks and interfere with a train and the importance (or volume) of traffic on the affected section. Following this approach, four main features (called Vulnerability Factors) that exhibit influence on the vulnerability of line operations with regards to a landslide originating on the nearby earthwork asset were identified: clearance, line speed, train frequency per day and number of tracks. Each class of each VF was assigned a numerical weight using expert judgement. The total vulnerability factor ($VF_{tot}$) is then obtained as a product of appropriate vulnerability indices for each factor.

- **Risk Calculation and Results**

The final risk value for each asset is obtained as a product of its hazard and consequence values, described in Equation [3]:

$$\beta_R = \beta_H \times VF_{tot}$$

[3]

The risk reliability index $\beta_R$ can be used as a risk value R or it can then be transformed into the 'Pf-based' value.

The list of risk results describes a single point in time. The results are open to constant change in future given the update of IM’s asset database inputs following the new rounds of visual inspections, potential maintenance/remediation scenarios and subsequent re-run of the tool. It should also be reiterated that risk values obtained in the tool present only a relative measure between assets for ranking purposes and do not imply to any absolute level of risk of using the transport network.

### 2.5 Whole Life Cycle Cost Analysis

A network level whole life cost model (NWLCM) is the key output from Task 4.4. This model evaluates the whole life costs of alternative maintenance strategies for the management of rail infrastructure. This supports the prioritisation of maintenance works to deliver better value for money from the network maintenance budgets. An overview of the NWLCM analysis process is shown in Figure 5.
The model includes interactive facilities, which enable the user to:

- Select the sub-network of interest from the national rail network. This includes key categories of infrastructure assets, the rail track, bridges, earthworks and switches and crossings; and
- Define the analysis parameters e.g. analysis period and discount rates etc. The model includes two types of analysis periods; the whole life cost analysis period, used at the scheme level to calculate the whole life costs associated with any identified maintenance option for an asset category and the network analysis period, used for analysis of total annual budgets for the network under consideration. The scheme period is typically 40 years while the network period is shorter at about 5 years.

The NWLCM imports data related to infrastructure assets from the IMS and for each of the infrastructure category, this includes:

- Types of treatments and the condition thresholds for the consideration and application of the treatments;
- Condition states (with associated dates) representing the condition of the asset;
- Deterioration relationships to represent the change in condition with time and use;
- Costs of the different treatments and the durations (i.e. the time taken to carry out the treatments)

The maintenance needs of an asset are identified at the start of each analysis year and for the near future (defined by the user in terms of a ‘look ahead’ period of a few years, e.g. 2 years). These are identified by comparing the condition state against the treatment thresholds. The examination of maintenance needs in the ‘look ahead’ period enables the creation of maintenance schemes that combine assets in ‘poor condition now’ with assets expected to reach ‘poor condition’ within a short time (thereby avoiding maintenance schemes in close proximity within short timeframes). In general, in any year, due to limitations in the available resources and restrictions on the network, it is not always possible to carry out all of the required maintenance. It is therefore important to identify those
maintenance works that will give the best value for money from the available budget. To enable this, two options are generated for each identified scheme:

- ‘Do Something’ option: this represents the engineering solution based on the condition state and intervention rules;
- ‘Do Nothing/Do minimum’: ‘Do Nothing’ represents the postponement of the identified Do Something treatment by one year; where the postponement is not possible because the condition is below permitted functional levels set on the grounds of safety, the ‘Do Minimum’ option represents the minimum activity required to ensure the asset is safe to use until the next time maintenance is considered, e.g. this could be an increase in the frequency of inspections and/or the application of speed restrictions.

The future costs associated with the two options are determined over the defined whole life cost analysis period by simulating future behaviour using the deterioration relationships. The condition of an asset is aged a year at a time using condition deterioration relationships and when a maintenance intervention is carried out the condition is ‘reset’ as appropriate. The indirect costs resulting from delays to passenger and freight (e.g. due to increased journey times) and changed emissions (e.g. due to different speeds, journey lengths) are calculated by the traffic flow model. The different maintenance profiles of alternative maintenance options of an asset will leave the asset in different condition states at the end of the analysis period. Residual value (i.e. the value associated with the asset condition at the end of the analysis period) is calculated to take account of this difference and enable a more equitable comparison of the whole life costs of alternative options.

In comparing whole life costs of different options, it is not sufficient to consider only the total cost. A low total cost may be achieved by a high expenditure in the first year or a slightly higher total cost may result from a lower initial cost. Models incorporating whole life cost calculations therefore need a measure of value for money to accompany the total cost. An economic indicator is used to compare the Do Something and Do Nothing/Do Minimum options (a function of the initial and analysis period WLCs) to suggest which option provides greater value for money. The whole life costings of both options are reported to the DST.

The NWLCM is being developed as part of the Decision Support Tool (DST) (WP3.4). The model interfaces with the Information Management System (IMS) within the DST to import data related to the network selected for analysis. This data includes asset information/properties, treatments and treatment options collated by work packages 3 and 4 in collaboration with Irish Rail. The Irish Railway network has been defined using a railML file created from 2 other railML files. These were created by WP3 and WP4.3 respectively. Probabilistic Condition deterioration relationships defined in WP2 are used within the NWLCM to determine asset condition deterioration year on year. The NWLCM monetises the journey time delays and changes in CO2 emissions associated with maintenance schemes estimated by the Traffic Flow Model developed as part of WP4.3.

The model will provide key inputs to the Decision Support Tool on the whole life costs of alternative maintenance strategies. A whole life cost approach increases the effectiveness of decision making with regard to infrastructure maintenance strategies as a large proportion of the total costs over the lifetime of infrastructure assets is incurred after construction. The
pressure on budgets available to infrastructure managers has continued to increase over the past years. The ability to examine the whole life costs of alternative maintenance strategies of not just individual asset types but to also take into account the interaction between the different asset types has the potential to support effective decision making and deliver better overall value for money from the investment into the management of the assets.

2.6 Traffic Flow Modelling

To run the traffic flow model developed in Task 4.3 three kinds of input data are required: infrastructure, rolling stock and timetable. Infrastructure consists of track topology containing attributes like speed limits, gradients, signals. Rolling stock is specified by the so called tractive effort diagram and deceleration functions. Furthermore, the length and the weight of each train set is considered in the running time calculation. Timetable specifies arrivals and departures for all scheduled trains. Additionally, restrictions caused by any maintenance work have to be specified by the location between two main signals, the related time slot and the operational consequence (closure or slow speed zone at any certain limit). In comparison to state of the art in microscopic simulation tools Kronecker Algebra is applied to find optimal solution in terms of punctuality and energy consumption. Therefore, the results of the traffic flow model guarantee a deadlock free solution while an Infrastructure Manager can still set priority only on punctuality or only on energy consumption or any combination of both parameters.

Main input for the traffic flow model of Northern Line and Dublin Area were signalling maps provided by Irish Rail (IE). Speed limits were taken from Network Statement from the webpage of IE. Tractive effort diagrams of used train sets were also taken from the webpages of their manufacturers. The internal timetable including train IDs was also delivered by IE. Unfortunately, the railML file created in WP3 could not be used due to partly wrong orientation of switches and missing signals.

In todays practice, decision-making on maintenance work is often done without looking at the operational impact or at least in a simplified manner. Of course, the impact of one single slow speed zone might be limited but the sum of all slow speed zones along a train run might sum up to a level which cannot be compensated by running time reserves. Using the scriptmode of OpenTrack would even allow today to send automated requests from the DST to a traffic flow model to run several simulations to evaluate operational impacts of maintenance works in a larger scale. That feature would help to significantly improve the quality of timetabling during maintenance work. For real time application the speed profiles calculated by Kronecker Algebra in Task 4.3 should be provided to train drivers to save energy even under harsh conditions and to achieve a minimum of delays.
3 Decision Support Tool Development

To develop a holistic management tool, few functional requirements of DST are defined. The final developed version of DST should be able 1) to support basic create, read, update, and delete queries on assets static and dynamic data, 2) should locate all the assets on the network via GIS model, 3) the models of reliability-based assessment, risk assessment, whole Life cycle cost assessment should either be implemented as a part of DST, or DST should be able to send service request(s) to these models, if deployed independently, 4) should support budget planning and maintenance planning, 5) enable the what-if scenarios and finally 6) should be able to report in variety of formats. Following the requirements of DST, this section outlines the DST design and development details. Section 3.1 provides the framework of DST and how the data and developed models are organized. Section 3.2 presents interaction diagrams to illustrate the use case scenarios on the functionalities provided by DST. Section 3.3 provides the implementation details and an update on the DST development so far.

3.1 DST System Architecture

System architecture of DST provides the conceptual model to define the structure and components of the system that will work together to provide the functionality as a whole. DST is mainly based on the logic provided by the systems and techniques mentioned in Section 2.3, 2.4, 2.5 and 2.6. As stated earlier, each of these models have to interact with each other to provide the output. In order to deal with the involved complexity while implementing these models, the DST is structured in three-tier architecture style where the separations of concerns is introduced by data layer, application layer and presentation layer.

Figure 6: DST System Architecture
Figure 6 shows the DST system architecture. Data layer provides the functionality to interact with database. In addition, data layer authenticates and validates all the data that is created to be stored in the database. The application base form the model base for DST, where the main decision logic is implemented. It is important to notice that not all of these models have been implemented in DST, but some models developed as stand-alone tools where DST send the request call with input and receive output. For instance, the DST will be able to send request to traffic flow model to run simulations in order to evaluate operational impacts of maintenance works on the network performance. Finally, presentation layer implements the logic to provide the user interface to the user. This also includes the input console to define the decision questions by infrastructure managers as well as the GIS interfaces to locate and select the assets on network by their functional locations.

3.2 Use case and Interaction diagrams of DST

With the definition of DST system architecture, this section presents the interaction diagrams in unified modelling language. The purpose of these diagrams is to illustrate the interactions of actors/users with the systems as well as to demonstrate the order in which different systems, components and process work together to provide a decision support to a DST user.

Figure 7 provides an abstract level data flow diagram between infrastructure managers, SAP manager to/from DST. This diagram shows how different actors may interact with DST with different purpose. For instance, a SAP manager can be only responsible to update and authenticate data whereas an infrastructure manager can be interested to execute various models, perform what-if scenarios to estimate costs, condition over time, etc. and generate maintenance plans.

An infrastructure manager can interact with DST with a variety of (decision) questions. For instance, which assets on the network are older than 40 years, when the maintenance of X switch was performed, which of the assets on the network have the highest risk, what is the reliability state of the assets in X functional location, what is the current condition of the
assets, and so on. To answer each of these questions, DST has to interact with a number of procedures to yield required functionality.

To illustrate the interaction among number of DST modules, use case scenarios and the interaction flow diagram from infrastructure manager, DST interface (Presentation layer), DST (Application layer) and IMS (Data layer) are developed. The purpose of use case and interaction diagram is to show how the DST will provide the functionality requested by user. The developed DST will allow the user to select implemented models without any definite order.

and Figure 8 provide the use case and interaction flow diagram to select and execute an individual model on selected assets.

**Table 1: Execute an Assessment Model (Use Case)**

<table>
<thead>
<tr>
<th>Use Case Name:</th>
<th>Execute an assessment model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actor:</td>
<td>Infrastructure manager</td>
</tr>
<tr>
<td>Description:</td>
<td>To execute an assessment model separately</td>
</tr>
</tbody>
</table>
| Preconditions: | 1. DST should be connected with internet  
2. Infrastructure manager/User must be registered. |
| Post conditions: | 1. Model is selected and model output is displayed to user |
| Normal Flow:   | 1. User will enter the credentials  
2. System will authenticate the credentials and navigate the user to main page  
3. User will access the GIS Interface to locate the assets on the map  
4. System will prompt the user to define the assets clusters by reliability, last maintenance, functional locations, etc.  
5. User will select the assets that he wants to include in analysis  
6. System will prompt the user to select the assessment model  
7. User will select the assessment model  
8. User will provide the input prompted by specific model  
9. System will execute the model and display the result |
| Alternate Flow: | If no asset is selected while analysis is initiated, system will consider all the objects of network by default |
| Assumption:    | 1. It is assumed that system is able to execute the models and send third party service call |

Infrastructure manager first sends the login request to the DST. The purpose of logins is not only to enable the system security but also to apply the information access levels, where not all the inputs and generated outputs are visible to every user of the DST. The login request is validated by IMS and access granted to infrastructure manager. Based on the UI (user interface) (see Figure 9), infrastructure manager initiates another process to access the GIS Map in order to locate the assets on the network. With GIS Map, there are two possibilities to execute the assessment model, either assessment is performed on all the assets of network or infrastructure manager can manually select the assets for assessment. Following interaction diagram shows the steps where the objects are selected manually and separate copy of selected objects is stored for further assessment. As mentioned earlier, DST will be
able to provide number of assessment models, therefore, DST interface allows the infrastructure manager to choose the type of assessment he/she wants to perform. The final results of assessment can be provided in simple text document or can be plotted on GIS Map.
Figure 8: Interaction among systems to execute models
To highlight the maintenance and budget planning functionality of DST, the use case scenario along with detailed interaction flow diagram is outlined in Table 1 and Figure 9, respectively.

**Table 2: Generate Maintenance Plans (Use Case)**

<table>
<thead>
<tr>
<th>Use Case Name:</th>
<th>Generate maintenance plans</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actor:</td>
<td>Infrastructure manager</td>
</tr>
<tr>
<td>Description:</td>
<td>To generate maintenance plans based on decision support model</td>
</tr>
</tbody>
</table>
| Preconditions:| 1. DST should be connected with internet  
                        2. Infrastructure manager must be successfully logged in. |
| Post conditions: | 2. Intermediate models output is generated  
                                        3. Maintenance schedule for the chosen year is generated  
                                        4. Maintenance plans (5 year) is generated if requested |
| Normal Flow:  | 1. User will choose the budget and maintenance planning option  
                        2. User will define the planning year(s) under consideration and available budget  
                        3. System will display the current reliability state of the assets  
                        4. System will prompt the user to define the assets clusters by reliability, last maintenance, functional locations, etc.  
                        5. User will select the assets that he wants to include in analysis  
                        6. User can use the risk assessment model to assess the risk values of selected assets  
                        7. System will display the risk (in monetary form) to user  
                        8. User will select the whole life cycle cost assessment for selected assets  
                        9. System will display the output of whole life cycle cost model to user  
                        10. System will prompt user to specify maintenance objective, if any  
                        11. System will rank the selected assets based on objectives  
                        12. User can ask for maintenance plans (5 years) and/or maintenance schedule (1 year) of selected assets  
                        13. System will generate the maintenance plans (5 years) and/or maintenance schedule (1 year) based on user input  
                        14. User can select traffic flow model to visualize the impact on network operations based on suggested maintenance plans |
| Alternate Flow: | 6 and 8. User is able to select assessment model without any definite order  
                              10. If user doesn’t define the objective of maintenance, the step 11 will be skipped and normal flow at step 12 will follows |
| Exceptions:   | 1. If no asset is selected while analysis is initiated system will consider all the objects of network by default |
| Assumption    | It is assumed that user is already logged in and have required access rights |
Figure 9: Interaction flow for maintenance planning
3.3 Screenshots of DST Interface

Currently, DST have full support of GIS-based interface that plot the assets on the Irish Railway network. The implementation of the reliability assessment model, risk assessment model and whole life cycle cost analysis is still under development. Figure 10 shows the main dashboard of DST after logged in by user.

![Dashboard – Decision Support Tool](image)

**Figure 10: Main Dashboard of DST**

Figure 11 shows the interface once a user has clicked on a GIS tile. The user is able to visualize all the station, overbridges, underbridges, tracks, and switches and crossings on the GIS Map. Each of the asset type is implemented as separate layer where any assets can be made visible or hidden with the help of the toggle button.

![GIS Map of Irish Railway Network](image)

**Figure 11: GIS of bridges for Irish Railway Network**
In addition, with details button, the user is able to perform the filtering on the assets by their type. For example, for the bridges the user can filter and visualizes bridges on the map that are at the specific functional location, by bridge material (e.g. steel, iron, concrete, brick, etc.), or by their function (e.g. public road, railway, station building, etc.). Figure 11 shows all the bridges of the network (at right side) and the filtered bridged by functional location (at left side).

Similarly, Figure 13 and Figure 13 shows the GIS of Tracks with the green markers depicting the station begin and end. Irish Rail have 776 lines of track where 35 lines are categorized as station track (depicted in red), 496 lines as siding tracks (depicted in cyan), 134 as connecting (depicted in blue) and 111 as main line tracks (depicted in black). The GIS Map yields very fine mapping of tracks line on the map as well as on the satellite view.
In addition, tracks can be further filter based on their functional location and unique equipment number.

Figure 14 shows the case study analysis user interface. The GIS of all the assets selected in case study is also visible in Figure 14. The user is able to filter the case study assets based on functional location where the separate layer switches and (under) bridges can be overlaid. The user is able to select the assets for the analysis using the function at the right side of the screen. It shows the list of four selected bridges two switches and one track line (depicted with green markers on map). The analysis button will lead to the next screen to select the assessment models as shown in Figure 15.
Figure 15: Interface for model selection (Dummy UI without implementation)

Figure 16 shows the risk map of all the bridges of the network. The colour codes represent the risk level on the asset where red depict the higher risk and green depict no risk. The current risk map is developed based on the randomly assigned risk values for the sake of demonstration only. Once the real risk assessment model has been implemented, the random values will be replaced with the real data.

Figure 16: Risk Map
4 Conclusions and Future Work

This document outlines the detailed framework and provides an update on the current functionalities implemented in Decision Support Tool (DST). It is a holistic management tool, which provides the automation and computerised support to the system and techniques being developed in the DESTination RAIL project. In addition to the central database repository of railway assets, the DST will enable the user to execute reliability assessment model, risk assessment model, access to the whole life cycle analysis, execute what-ifs scenarios and generate the maintenance plans. The DST comprises a three-tier system architecture, user interaction diagrams and use cases. Currently, the DST provides the detailed GIS of the Irish rail network, where stations, bridges, tracks, and switches and crossings are mapped in layered format on the GIS map. In addition, the DST is able to apply various level of filtering on the railway assets to access the information as well as to locate them on the map. Similarly, the assets can be selected based on location, material, function, etc. for the further analysis.

Further improvements of the DST include the implementation of the reliability assessment model and risk assessment model. Moreover, the interface to interact and send the service calls to third-party standalone software is under development. Finally, the proof of concept of DST will be illustrated with an on-going case study which consists of 73 tracks, 90 bridges, 134+ switches and crossings, 41 cutting and 25 embankments.
5 References