Resilience assessment model of optimised investment

Deliverable 7.4

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ABOUT SAFETY4RAILS

SAFETY4RAILS is the acronym for the innovation project: **Data-based analysis for SAFETY and security protection FOR detection, prevention, mitigation and response in trans-modal metro and RAILway networkS**. Railways and Metros are safe, efficient, reliable and environmentally friendly mass carriers, and they are becoming even more important means of transportation given the need to address climate change. However, being such critical infrastructures turns metro and railway operators as well as related intermodal transport operators into attractive targets for cyber and/or physical attacks.**The SAFETY4RAILS project delivers methods and systems to increase the safety and recovery of track-based inter-city railway and intra-city metro transportation.** It addresses both cyber-only attacks (such as impact from WannaCry infections), physical-only attacks (such as the Madrid commuter trains bombing in 2004) and combined cyber-physical attacks, which are important emerging scenarios given increasing IoT infrastructure integration.

SAFETY4RAILS concentrates onrush hour rail transport scenarios where many passengers are using metros and railways to commute to work or attend mass events (e.g. large multi-venue sporting events such as the Olympics). When an incident occurs during heavy usage, metro and railway operators have to consider many aspects to ensure passenger safety and security, e.g. carry out a threat analysis, maintain situation awareness, establish crisis communication and response, and they must ensure that mitigation steps are taken and communicated to travellers and other users. **SAFETY4RAILS will improve the handling of such events through a holistic approach.** It will analyse the cyber-physical resilience of metro and railway systems and deliver mitigation strategies for an efficient response, and, in order to remain secure given everchanging novel emerging risks, it will facilitate continuous adaptation of the SAFETY4RAILS solution; this will be validated by two rail transport operators and the results will support the re-design of the final prototype.

TABLE OF CONTENT

List of tables

List of figures

Executive summary

The D7.4 regards building a budgetary scenario set–up where there will be determined the components that contribute to budgetary implications of potential infrastructure threats. It is presented a methodology study for analysing different cost investment scenarios on infrastructure cases and proceeded with an evaluation of the model in terms of (a) feasibility to represent the interdependencies of the components, the cascading effects and (b) performance in determining faulty components and updating related parameters to resilience and vulnerability as indicated in T7.1 – T7.3. The proposed methodology regards simulating and evaluating hypothetical scenarios that affect the functional condition of railway infrastructures and their corresponding budgetary implications. In this context, it is examined two hypothetical disaster scenarios taking into account infrastructure cascade disaster effects, the corresponding resilience and the respective budgetary impact. The proposed methodology comprises of two approaches: (a) A coarse grain analysis where infrastructure condition is considered to be of two states, Working/Non-Working, (b) a more realistic analysis where for the condition of infrastructure components is considered as scalar, where it is taken into account the physical decay, disaster impact and time/cost to be repaired. It also includes budgetary simulation scenarios that RMIT could use using CAMS to optimise budget for a given level of resilience planning under S4RIS platform. The document concludes with the evaluation of the two different analytical study approaches on the two scenario use cases and proposes recommendations for further extensions of the proposed methodology.

1. Introduction

1.1 Overview

D7.4 presents the results of the analysis framework developed in T7.4 to identify the elements with the greatest influence and impact on rail operations under environmental threats, such as flood, wildfire, or earthquakes, using Fault Tree analysis and Bayesian Inference Models which are well tested methodologies for Fault Analysis in large infrastructures. The results of the analysis framework in D7.4 are used to predict failure of the components of the asset under flood. The prediction results are then used by CAMS to estimate cost of repair of the asset in case of failure (flood in particular is considered in Deliverable D7.5 – Figure 3. Based on cost estimates of repair in case of failure generated by CAMS and constrained by the available budget, the allocation of the available funds can be optimized in order to minimize the expected impact in case of failure by reinforcing elements of the asset that are critical for it is resilience in case of a natural disaster. This approach was used in the flood impact analysis referenced above.

The main objective of this document is to demonstrate a methodology study for analysing different cost investment scenarios about infrastructure cases and proceeds with evaluation of the model in terms of (a) feasibility to represent the interdependencies of the components, the cascading effects and (b) performance in determining faulty components and updating related parameters to resilience and vulnerability as indicated in T7.1 – T7.3. In accordance with the deliverables of WP7, under the leadership of RMIT, the complete system specifications for the enhancement of the current capabilities of CAMS for rail assets, including all the scenarios and vulnerable asset components, will be developed in D7.5.
Finally, the document concludes with recommendations of optimising cost investments based on candidate scenarios and requirements regarding infrastructure utilisation, cost and resilience and indicates potential further actions as future steps.

1.2 Connection with other tasks

T7.4 corresponds to a proposed methodology for enhancing the budgetary investment optimisation procedure, by consuming the assets taxonomy and hierarchy as categorised and prioritised by T7.1 and WP3 and applying a cascading effects model in order to infer probable infrastructure components impact and corresponding cascading effects due to a potential hazard. These assets impact would be a more fine grained determination, based on the proposed in T7.4 methodology, of the impact matrix as stated in D7.3 (Figure 2 in [10]). In further these estimated impact scores will lead to the respective budgetary impact following the cost per damage relation that is proposed in T7.3. Finally, the results will conclude to T7.5 in order to optimise the budgetary investment. The T7.4 contribution in WP7 workflow is depicted in Figure 1.

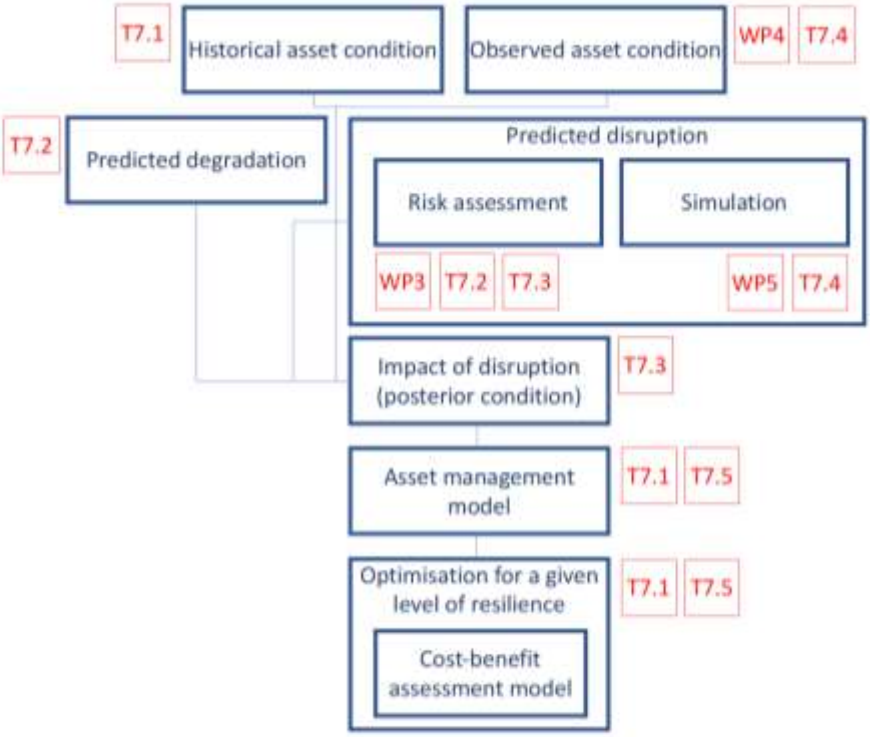


FIGURE 1 WP7 RELATIONSHIP DIAGRAM

T7.4 supports the WP7 workflow in two ways: (a) by calculating the cascading effects of disaster incidents which in further will be translated into budgetary implications based in T7.3 proposed procedure, (b) by providing the capability of simulating disaster impact scenarios with different severity impacts and different cascading effects, which in further will lead to different impact scenarios that at the end will correspond, based on T7.3 to different cost effects. To demonstrate the synergy of WP7, CAMS used the flood scenario described in this report in a Milan simulation exercise to assess different flood scenarios and their budgetary impact (See Figure 11 below and Table 12 in D7.1)

In this regard, CAMS used data has been fed with a variety of budgetary scenarios, according to the different setups of T7.4 and different costs and environmental situations that affect the budgetary impact, (see Data For CAMS in Table 12 in D7.1; Component Condition is defined by 1 in columns as the CAMS input data for asset condition. Also, J column "Dependencies" in table 12 of D7.1 was generated by NCSRD flood scenario). This pool of budgetary scenarios will further be consumed by T7.5 in order to conclude on optimised budgetary investment strategies. The proposed procedure relies on Fault Tree analysis and Bayesian Inference Models which are well tested methodologies for Fault Analysis in large infrastructures. In this document moreover, the two models are compared for the two type of disaster incidents, physical and human caused, indicating their contribution performance for each model. The goal is to leverage the budgetary investment optimisation as supported by T7.1 – T7.3 and finally performed in T7.5, by providing the capability of estimating fine grained components condition levels for different simulated disaster scenarios. T7.4 along with other WP7 and the iCrowd simulator can act as a digital twin[1] of railway infrastructures for disaster

[1]The iCrowd Simulator uses detailed 3D model of a rail station and it is surrounding environment, in any desired level of detail and accuracy, to simulate both physical and cyber infrastructures of a rail station and its operations, crowd behaviour, and physical and cyber attacks against an infrastructure. The iCrowd simulator is also a platform that allows to take into consideration the output from other simulators simulating other physical events that may affect the rail infrastructure such as bomb blast simulators, fire simulators, CBRN incident simulator, etc., and incorporate their impact in the overall simulation of a physical or cyber attack against a rail infrastructure. In the context of SAFETY4RAILS, the iCrowd simulator, alongside side with DMS, was used as a digital twin for exchanging data to and from the simulator and the S4RIS tools and providing a realistic simulation environment for a rail infrastructure and the outcome of a physical or cyber attack against it during the Madrid and Ankara rail pilots. For example, in the Madrid Metro (MDM) pilot, iCrowd, communicated through DMS, with the BB3D S4RIS tool to (digitally) detonate a bomb at an agreed upon by the pilot scenario time and location, and receive data from the evolution of the detonation in real time. This data was taken into consideration to provide a more realistic evacuation simulation of the metro station in the agreed upon "safe areas"

management optimisation, where disaster scenarios lead to different disaster impact along with the corresponding cascading effects on the different assets of railway infrastructures, as calculated by T7.4 using assets taxonomy, decay model and resilience, as provided by T7.1. Then such results are translated in cost terms according to T7.3 definitions and the result. Inferred mitigation measures performance can be estimated based on T7.4 impact inference models translated in budgetary terms via T7.3 models. In this regard, T7.5 may examine a variety of mitigation measures along with the corresponding performance for each measure in order to calculate the respective optimized mitigation plan.

1.3 Structure of the deliverable

The following sections of this document describe the development of a comprehensive approach to resilience, preparedness, and prevention, including financial and budgetary elements related to WP7 of SAFETY4RAILS project:

- **Section 2**: In this section it is described the proposed methodology and the different scenarios and analytical formulations that were used for approaching these scenarios.
- **Section 3**: In this section there are determined two indicative scenarios of the two types of hazard threats (a) physical natural threats, (b) terrorism. Moreover, the proposed methodology is applied in order to demonstrate the different scenarios evaluation and the corresponding variation in terms of cost/budgetary investment.
- **Section 4**: In this section there are presented the comparison results from the Section 3 analysis from the two proposed approaches. These results are further evaluated regarding their feasibility to represent the interdependencies of the components and the cascading effects, and the capability for contributing to optimization of budgetary plans and strategies, which then get forwarded to CAMS that generates its numerical results based on the T7.4 results. (See CAMS table 12 in D7.1)

specified by the scenario outside the metro station. In the Ankara Metro pilot, iCrowd, alongside with DMS, was used as a digital twin to simulate a cyber attack by a perpetrator evading surveillance cameras, reaching a computer room, comprising the metro control room, causing an interruption in the train flow, access to the station control system, and inducing a major confusion to the metro station, initiating an evacuation process. Upon leaving the metro station, the perpetrator(s) were caught on the surveillance cameras despite their effort(s) to evade being detected. An anomaly detection software could have been used to detect the perpetrator(s) using footage from the (simulated) surveillance cameras.

2. Methodology

This document presents a methodology for simulating and evaluating hypothetical scenarios that affect the functional condition of railway infrastructures and their corresponding budgetary implications. In this regard, two hypothetical disaster scenarios are examined against which the infrastructure cascade disaster effects, the corresponding resilience, and the respective budgetary impact, have been tested. The proposed methodology comprises of two approaches: (a) a coarse grain analysis where infrastructure condition is considered to be of two states, Working/Non-Working, and (b) a more realistic analysis where the condition of infrastructure components is expressed as a continuous value scalar, by taking into account the physical deterioration, the disaster impact, and the time/cost for repair. The outcome of the impact analysis is then used the CAMS tool to provide optimised mitigation measures for a given level of resilience planning under the S4RIS platform, see D7.1 Table 12.

2.1 Hypothetical Scenarios

Disaster incidents are divided into two main groups: (a) physical disasters, where due to a natural phenomenon (e.g. rain, earthquake, etc) several infrastructure components are damaged, and (b) disasters due to terrorist attack(s). In this document both categories are proposed, via a representative hypothetical scenario for each case. The first case corresponds to a case of a heavy rainfall where two railway lines have failed which consequently affect the railway utilisation, and the second to a sudden bomb attack in a metro station which resulted in several components being damaged.
As a test case we examine the following toy railway/metro network which comprises of eight Metro stations, twelve Railway stations and two multi – modal stations. The interconnections among stations are referred as lines which correspond to the different train paths: (a) two metro lines (green and blue line) and (b) two railway lines (red and yellow). The interconnections are indicated as ***line***$_i$, corresponding two a line section between two stations (Figure 2).

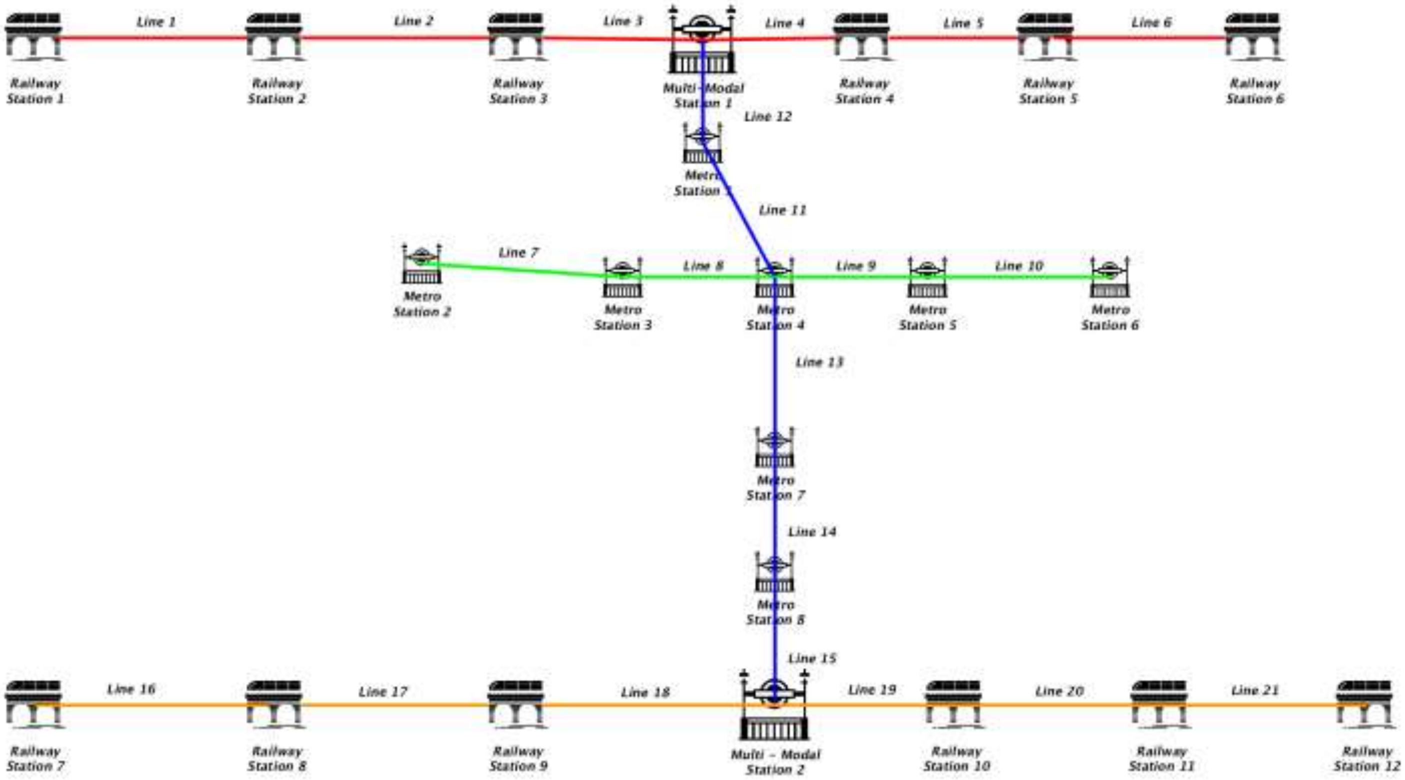


FIGURE 2 TRAIN NETWORK MODEL

For modelling the railway infrastructure, it is used the railway assets taxonomy as presented in D3.1 (Figure 3.2 Branch Chart Assets). Based on this taxonomy the train network generalizes to a general assets network where the interdependencies follow the D3.1 [6] assets taxonomy. As a result, the train network is modelled as a Directed Acyclic Graph (DAG) where each asset point to the ones that it depends on. The proposed train model is depicted in Figure 3 and Figure 4.

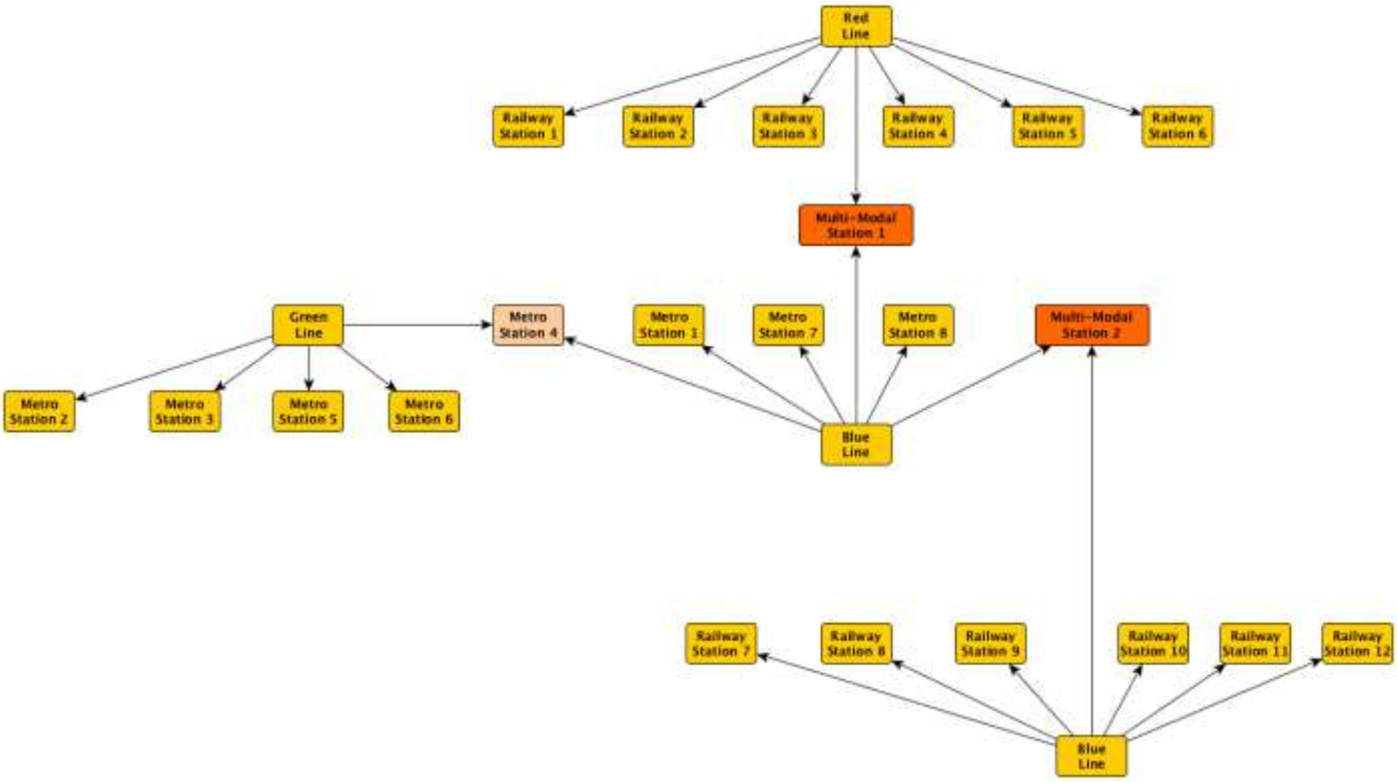


FIGURE 3 DAG MODEL OF TRAIN NETWORK (STATION NODES ARE EXPANDED IN FIGURE 4)

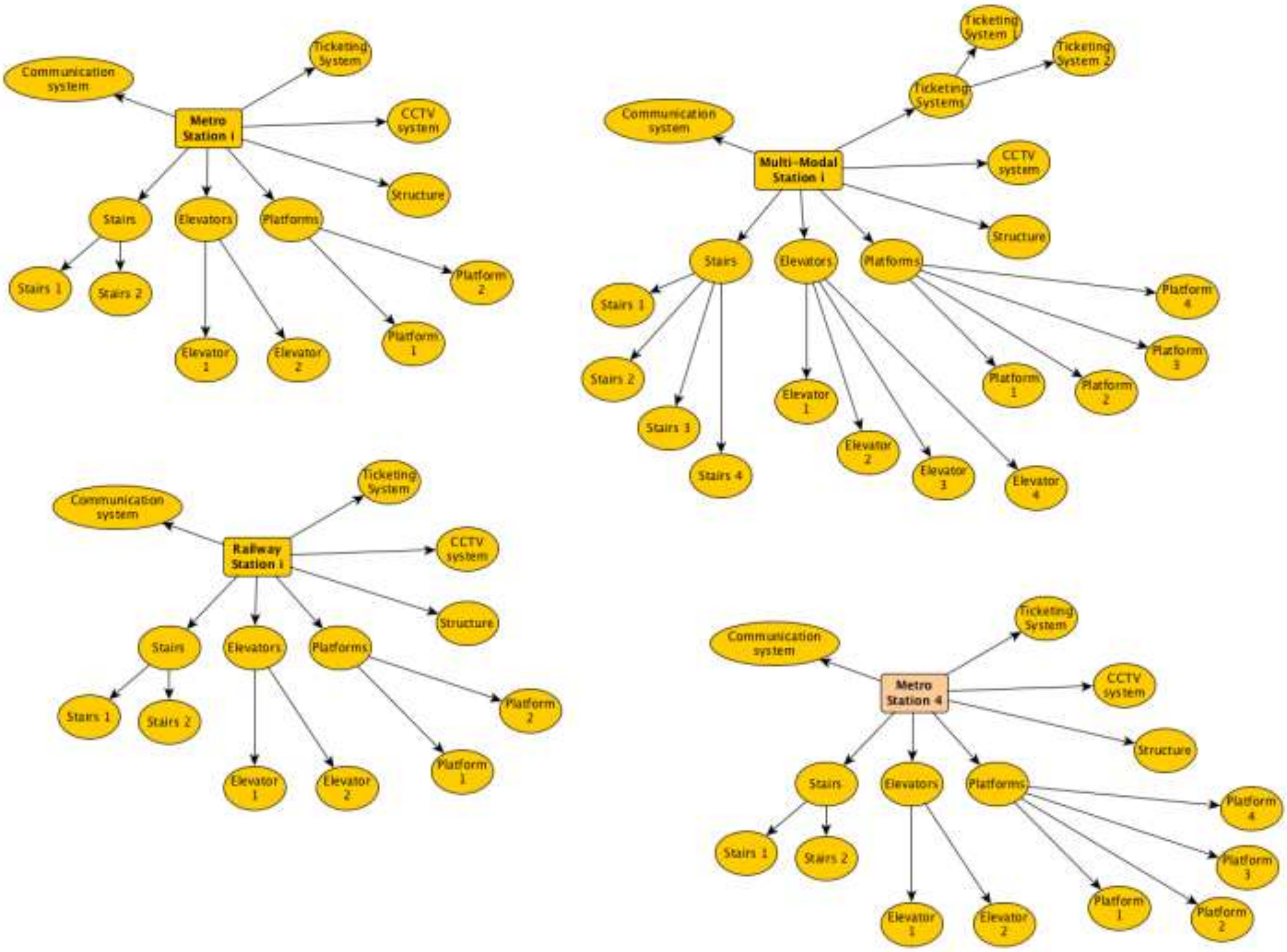


FIGURE 4 DAG MODEL OF STATION NODES

The above-mentioned graphs describe the hypothetical train network (Figure 2) where each node corresponds to an asset and edges refer to the respective dependencies between two assets. For example, A→B reflects the dependence of asset A to asset B. In other words, the functional state of B influences the functional state of A.

Scenario 1

The first scenario of a flooding incident, a natural incident that affects seriously the utilisation of train network by reducing the functionalities of each several assets and in several cases, produces more permanent failures where repairment actions are mandatory. The hypothetical flooding disaster results after a heavy rainfall in the area of Multi-Modal Station 1 and the line section that connects Multi-Modal Station1 with Railway Station 4. The consequence of this is that the line section is out for 3 hours, water has entered the Multi-Modal Station and put out of service the platform 1 and 2 and damaged the elevator 1. After several hours line section, and platforms utilization has been restored and remain only the elevator damage. Based on this scenario, CAMS assessed possible flood scenarios and their impact on the budget in recovery (see D7.5 Figure 3).

Scenario 2

The second scenario regards a bombing incident that results in severe damage to two platforms of **Metro Station 4** and for precautionary reasons the other two platforms are closed for maintenance. Given the fact that **Metro Station 4** corresponds to a node that connects the blue and green **Metro Line**, the specific disaster results in cascading effects that affect not only the normal condition of **Metro Station 4** but also the utilization of blue and green lines which are rely on **Platforms 1&2** and **Platforms 3&4** respectively. **The Platforms 1&2** have been seriously damage and need to be repaired, which results in time spending and financial cost. The **Platforms 3&4** are evaluated and validated for being in the right condition for normal use, which costs much less in time and money.

2.2 Approaches

In this deliverable it is demonstrated a computational methodology for evaluating budgetary implications of disaster cases and related variations in terms of infrastructure performance with different budgetary costs that influence each asset's utilisation, which can be defined and categorised in CAMS input. In this context, the proposed methodology comprises two approaches: (a) A coarse grain approach, where assets' condition is treated as Boolean and only disaster incidents and their cascading effects are considered when determining condition, (b) a more meticulous study where assets' condition is determined by a 5 scale metric and is determined by physical condition (considering physical deterioration) and disaster impact as well. The proposed methodology is demonstrated by applying the two approaches to the two above-mentioned scenarios, where by testing different disaster settings and resilience and mitigation strategies, the budgetary consequences can be optimized differently in Task 7.5.

3. Analysis

3.1 Approach 1

In the first approach we treat assets' condition as binary (Good/Faulty). (It was used by CAMS on D7.1 Table 12 and then in D7.5 Figure 3 based on the D7.4 flood scenario.) It is independent of any physical deterioration, but only dependent on damage effects. In this regard, disaster incidents effects are modelled via a Fault Tree relying on the Train network model that is proposed in section 2. The Fault Tree model maps to each node the train network infrastructure's assets and the edges correspond to the interdependencies of assets. Each node value is determined by either the logical AND or logical OR of its children values. Logical AND is used for a node if it is needed all its children to be in a good condition, in order to have good condition. Otherwise the node's condition should be faulty.

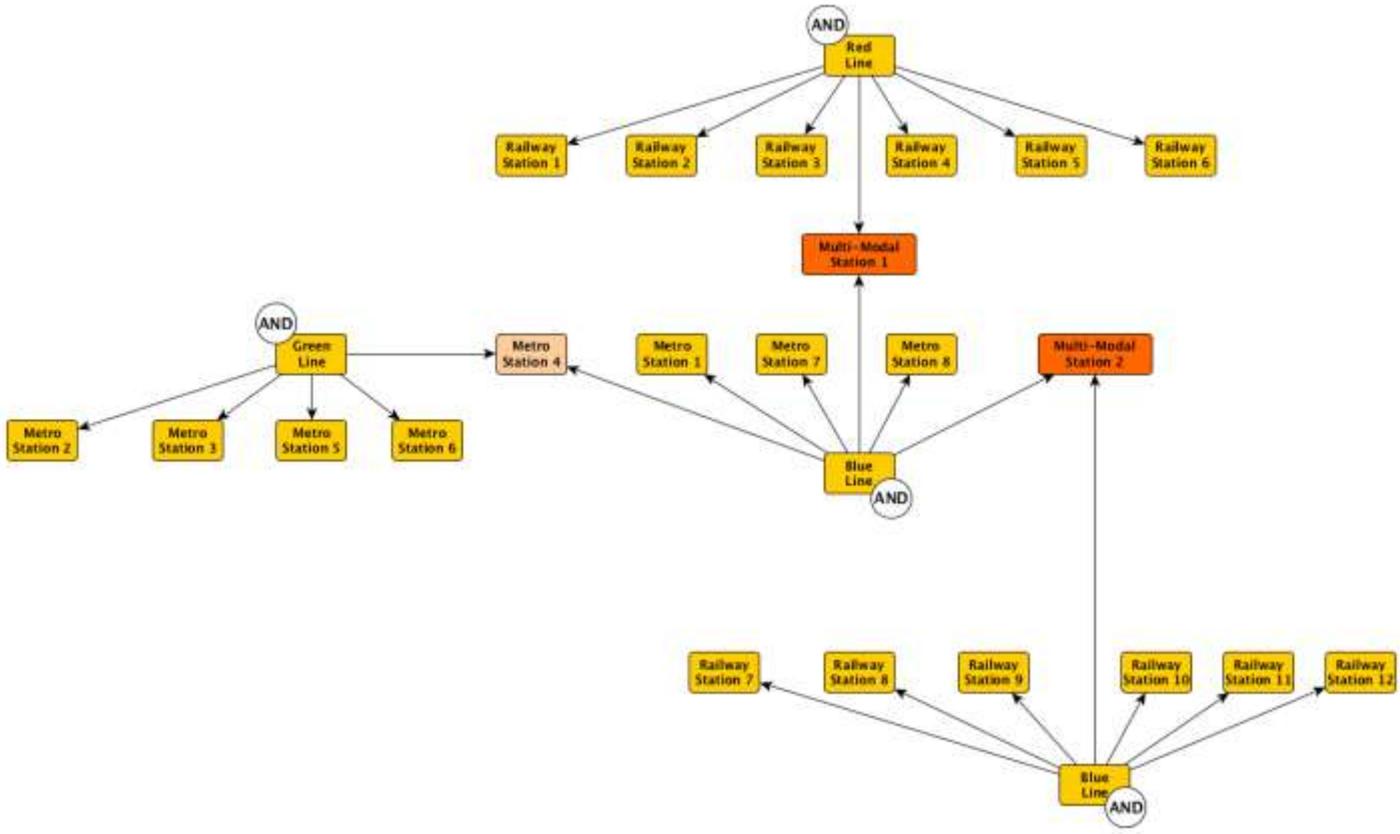


FIGURE 5 FAULT TREE GRAPH OF TRAIN NETWORK MODEL (STATION NODES ARE EXPANDED IN FIGURE 6)

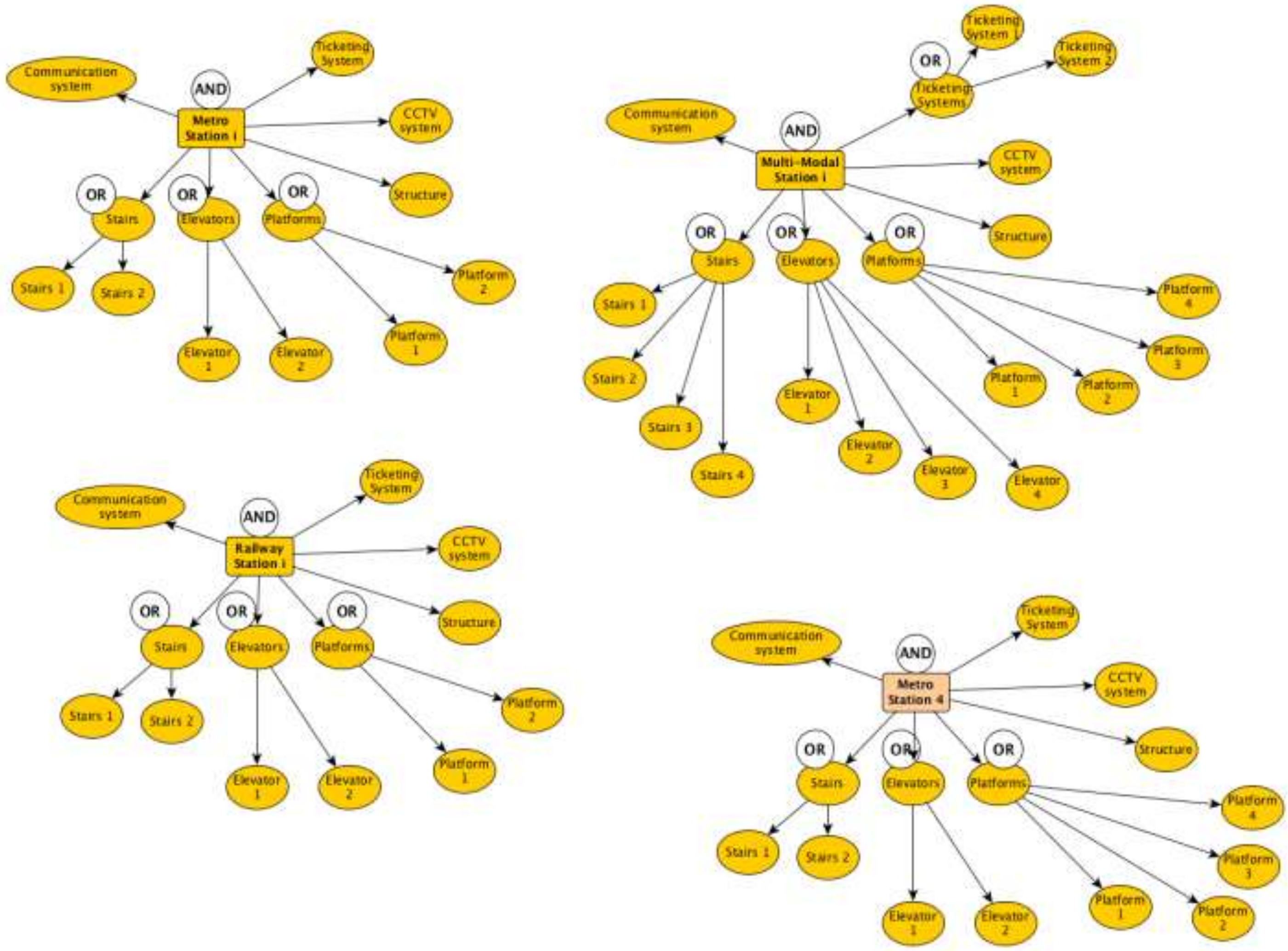


FIGURE 6 FAULT TREE GRAPH OF STATION NODES

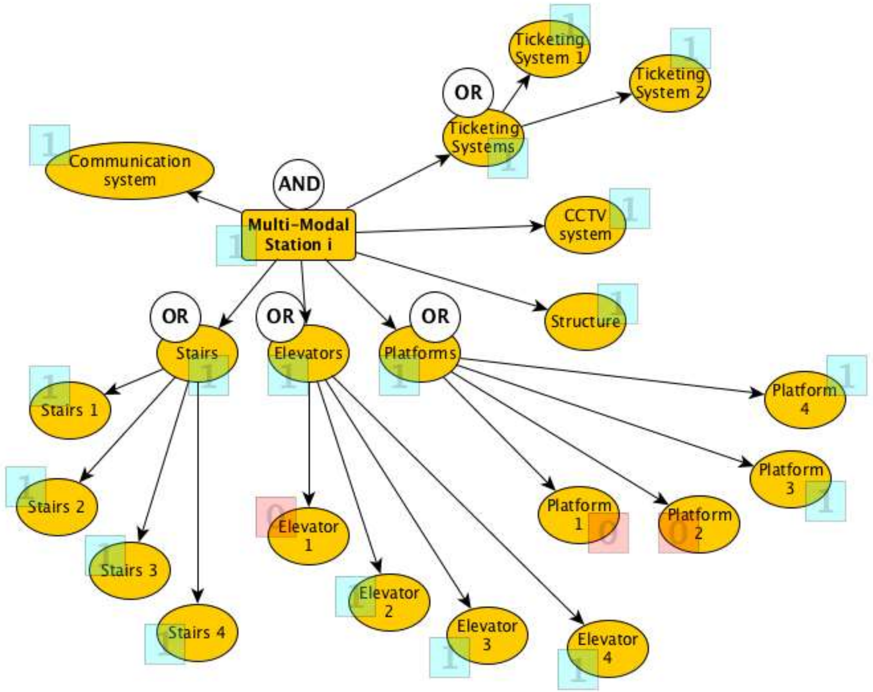
It is presented, in Figure 5 and Figure 6,how the FaultTree Graph models the hypothetical Train network model. The selection of AND or OR « gates » is based on the utilisation requirement of whether it is mandatory for all children nodes to be fully functional, in order for a node to be in Good condition, or it is needed for at least one child node to be in Good condition, using the assets' condition categorisation as presented in D7.1 for CAMS data. In this regard, there is only one mitigation strategy for recovering disaster damages, the assets' full repairment which has a pre-defined cost value C_i.where i : Asset ID [6]

$$Total\ Cost = \sum_{i}^{\substack{all\ Faulty\\ assets}} C_i$$

As a result the two above-mentioned disaster scenarios are formalised as follows:

Scenario 1

Based on Scenario 1 script, initially there is damage at **Platform 1&2**, **Elevator 1** and line section between **Multi-Modal Station 1** and **Railway Station 4**. In the Train Network Fault Tree Model then, all leaf nodes take the value **1 (True)** except **Elevator 1**, **Platform 1** and **Platform 2** of **Multi-Modal Station 1**, and **Red Line**, which take value **0 (False)**. Based on the proposed Fault Tree (which CAMS used flood scenarios in the Milan SE, (D7.1 table 12), the estimated cascading effects of the pre-mentioned assets failures lead only to the **Red Line**. According to the Fault Tree model, **Multi-Modal Station 1** is functional because only **Platforms** node is not **False** because there is at least one of the **Platforms** functional. The same goes with **Elevators** node. **Red Line** node's status is determined by the AND aggregation of its own status and its children. In this regard, all its children have **True** value except its own value (Figure 7).



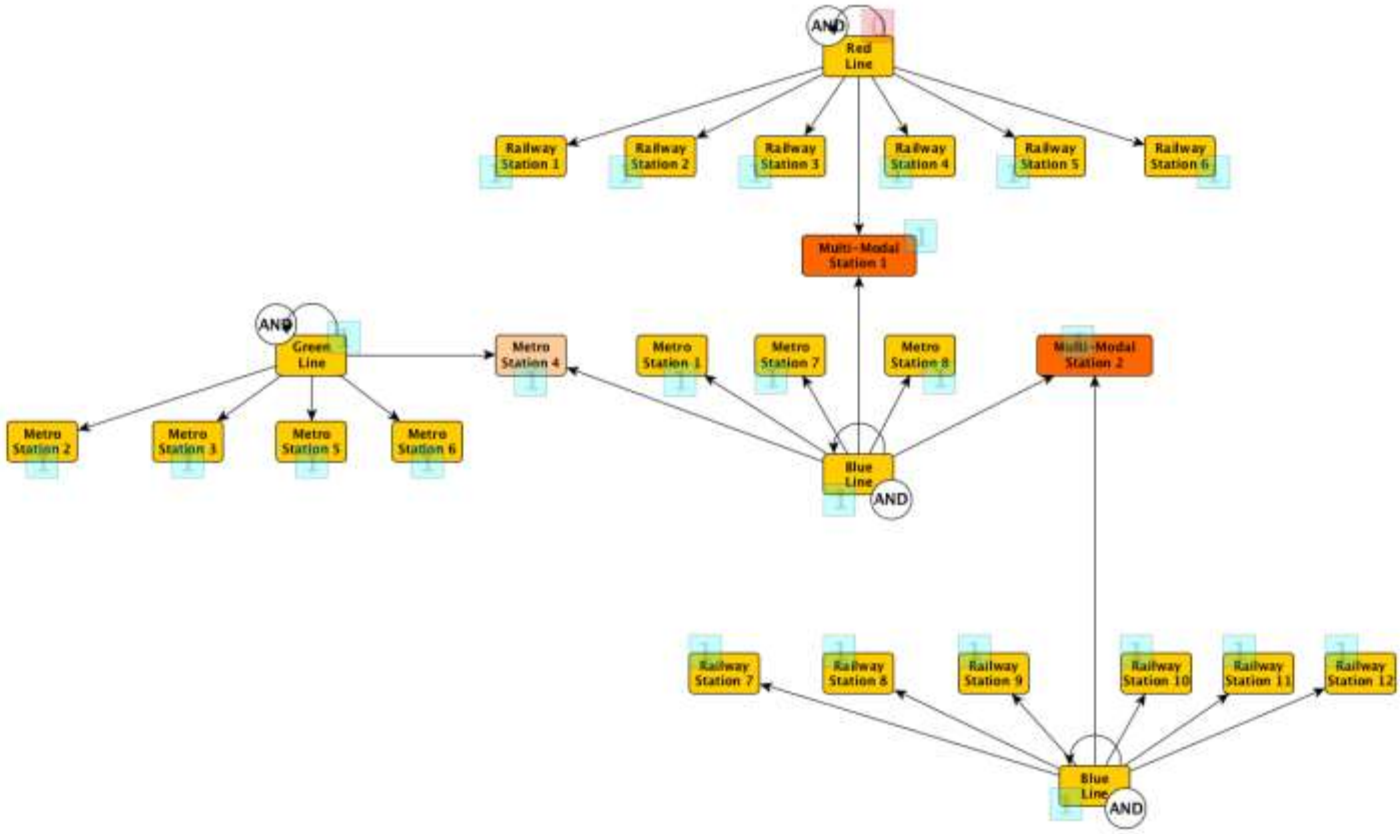


FIGURE 7 FAULT TREE ANALYSIS FOR SCENARIO 1. THE TRANSPARENT BOXES (BLUE/RED) INDICATE THE BOOLEAN STATE VALUE OF EACH ASSET.

As a result, the outcome is that the **Red Line** is out of service until it gets restored (i.e. after 3 hours). Although this approach does not reflect the implications of having **Elevator 1** and **Platform 1&2** out of service, it can give a reasonable general estimate of what components have « fatal » impact of train network utilisation and should be restored as first priority compared to others. The benefits of this approach can be displayed even more clearly by analyzing several variations of assets fault mitigation plans and checking out the corresponding budgetary implications.

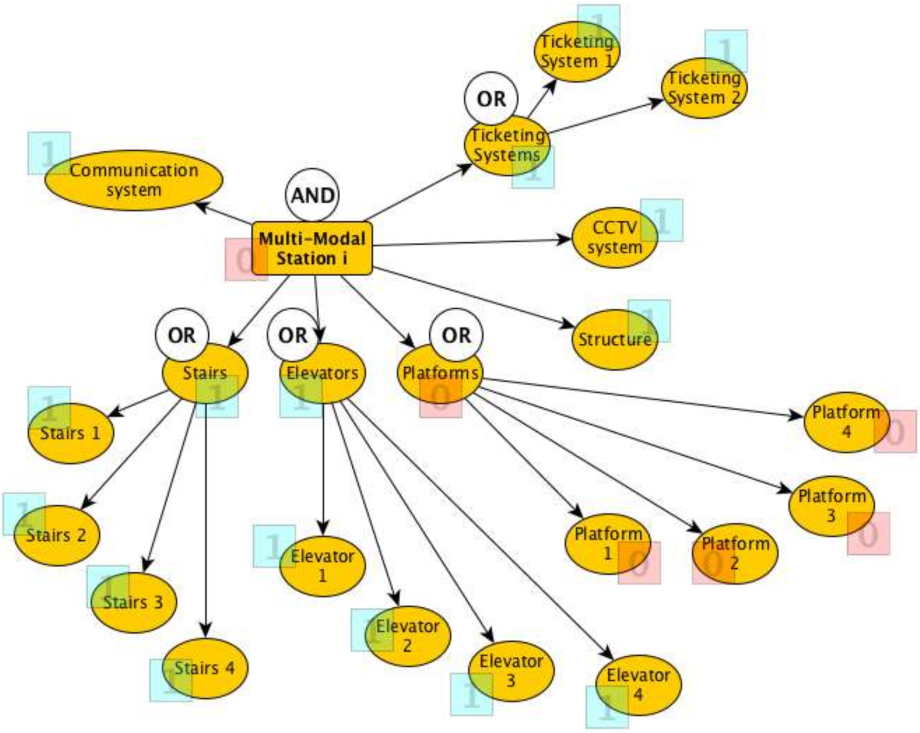
TABLE 1 COMPONENTS RESTORATIONS SIMULATION FOR SCENARIO 1

Elevator 1	Platform 1	Platform 2	Red_Line	Cost	Utilization (In terms of Line sections)	Comments
NO FIX	NO FIX	NO FIX	NO FIX	0	75%	3 out of 4 lines are functional
NO FIX	NO FIX	NO FIX	FIX	C_Line	100%	All lines functional which corresponds to a fully functional training network based on Fault Tree Model
FIX / NO FIX	FIX / NO FIX	FIX / NO FIX	FIX	C_Line + C_Platform*Num_Fixed_Platforms + C_Elevator*Num_Fixed_Elevators	100%	All lines functional which corresponds to a fully functional training network based on Fault Tree Model
FIX / NO FIX	FIX / NO FIX	FIX / NO FIX	NO FIX	C_Platform*Num_Fixed_Platforms + C_Elevator*Num_Fixed_Elevators	75%	3 out of 4 lines are functional

In Table 1 it is recorded several faults mitigation strategies in order to restore the Train Networks functionality. According to Fault Tree the only damaged component that affects whole infrastructure functionality is only the **Red Line** section between **Multi-Modal Station 1** and **Railway Station 4** which disables the whole **Red Line**. At this point, it should be stated that for simplicity, without violating generality, it is considered that each train route is one way, and the reverse route takes place only after each train reaches the end of its destination. Consequently, if any line fails at any section, the line is out of order. Moreover, it is pointed out that the Fault Tree Model treat components utilization as Boolean (Functional / Non – Functional) and does not reflect the reduced utilization of an asset which is caused in case that any of its supporting assets is failed. As a result, the benefit of supporting components is not reflected, and restoring a non-crucial component (such as **Elevator** and **Platform 1&2** in our example) does not make a difference but, on the contrary, increases costs, as shown in CAMS output in D7.1 [7]. Additionally, the method successfully distinguishes the most critical components from the less crucial ones and provides a coarse estimate for the cost of restoring a critical asset that has been damaged.

Scenario 2

The second scenario corresponds to a terrorism incident where the disaster incident damages seriously **Platform 1&2** of **Metro Station 4**, which in further creates the necessity of performing extraordinary maintenance procedures on **Platforms 3&4** for security reasons. To this end, the Fault Tree model for this scenario takes the following form:



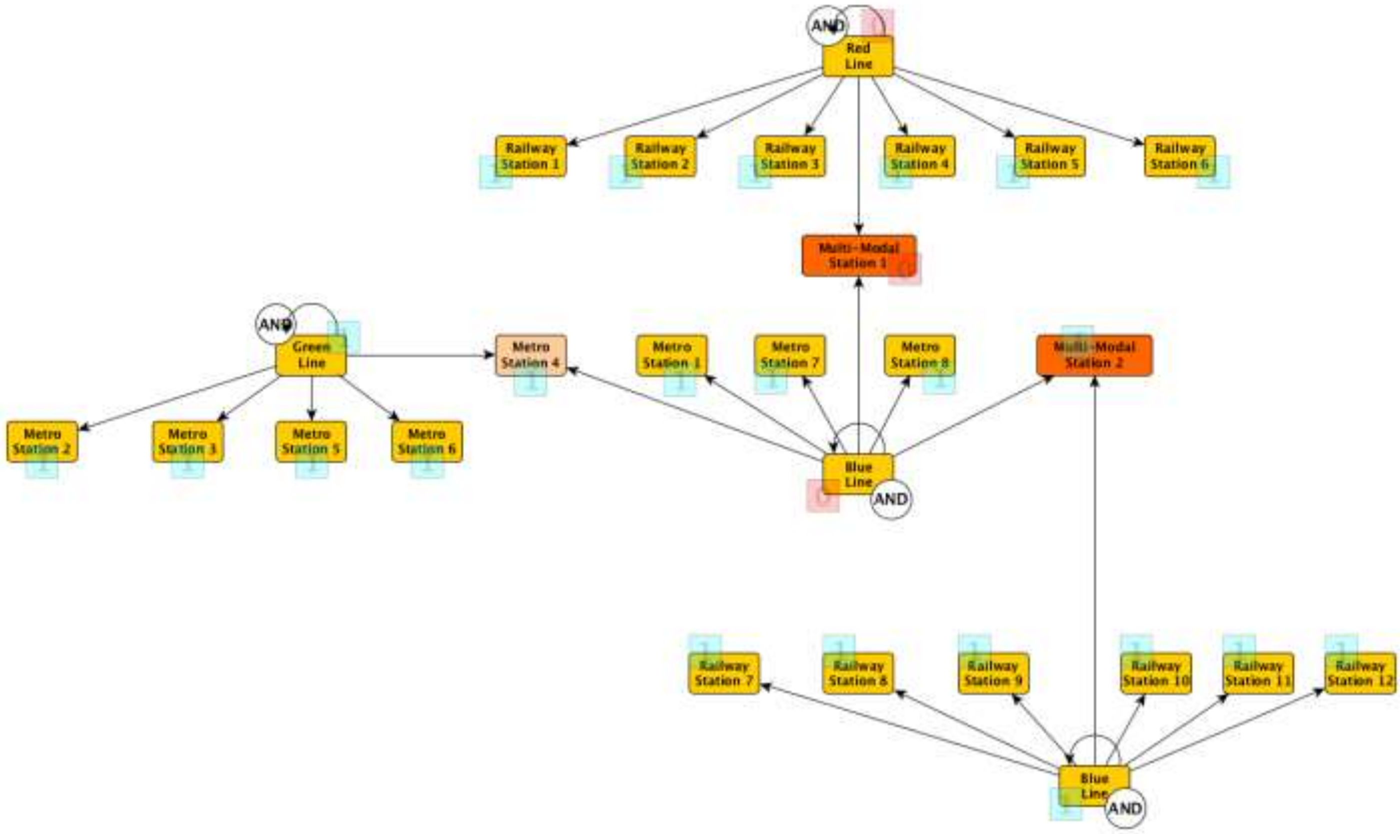


FIGURE 8 FAULT TREE ANALYSIS FOR SCENARIO 2. THE TRANSPARENT BOXES (BLUE/RED) INDICATE THE BOOLEAN STATE VALUE OF EACH ASSET.

In this case, the damage to **Metro Station 4** platforms disables the station operation, which in turn causes the **Blue Line** and **Green Line** to be out of service because of a (the) cascading effect. Mitigation strategies for this use case are described in Table 2 below.

TABLE 2 COMPONENTS RESTORATIONS SIMULATION FOR SCENARIO 2

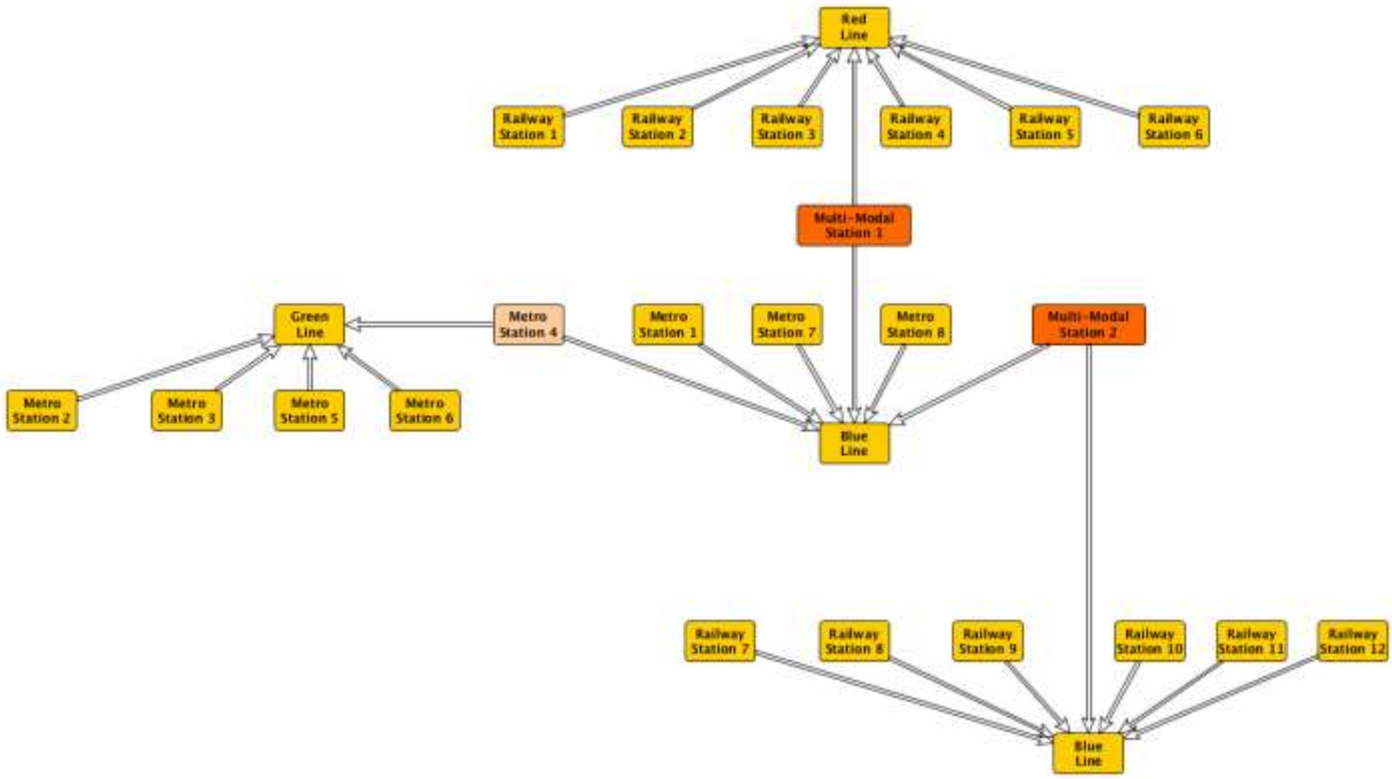
Platform 1	Platform 2	Platform 3	Platform 4	Cost	Utilization (In terms of Line sections)	Comments
FIX	FIX	FIX	FIX	C_Platform_1 + C_Platform_2 + C_Platform_3 + C_Platform_4	100%	Cost for repairing all Platforms
FIX	FIX	FIX	NO FIX	C_Platform_1 + C_Platform_2 + C_Platform_3	100%	Cost for repairing the damaged Platforms and one non-damaged for precautionary reasons
FIX	FIX	NO FIX	FIX	C_Platform_1 + C_Platform_2 + C_Platform_4	100%	Cost for repairing the damaged Platforms and one non-damaged for precautionary reasons
FIX	FIX	NO FIX	NO FIX	C_Platform_1 + C_Platform_2	100%	Cost for repairing the damaged Platforms
FIX	NO FIX	FIX	FIX	C_Platform_1 + C_Platform_3 + C_Platform_4	100%	Cost for repairing only one damaged Platform and the two non-damaged for precautionary reasons
FIX	NO FIX	FIX	NO FIX	C_Platform_1 + C_Platform_3	100%	Cost for repairing only one damaged Platform and one of the non-damaged ones for precautionary reasons
FIX	NO FIX	NO FIX	FIX	C_Platform_1 + C_Platform_4	100%	Cost for repairing only one damaged Platform and one of the non-damaged ones for precautionary reasons
FIX	NO FIX	NO FIX	NO FIX	C_Platform_1	100%	Cost for repairing only one damaged Platform
NO FIX	FIX	FIX	FIX	C_Platform_2 + C_Platform_3 + C_Platform_4	100%	Cost for repairing only one damaged Platform and the two non-damaged for precautionary reasons
NO FIX	FIX	FIX	NO FIX	C_Platform_2 + C_Platform_3	100%	Cost for repairing only one damaged Platform and one of the non-damaged ones for precautionary reasons
NO FIX	FIX	NO FIX	FIX	C_Platform_2 + C_Platform_4	100%	Cost for repairing only one damaged Platform and one of the non-damaged ones for precautionary reasons
NO FIX	FIX	NO FIX	NO FIX	C_Platform_2	100%	Cost for repairing only one damaged Platform
NO FIX	NO FIX	FIX	FIX	C_Platform_3 + C_Platform_4	100%	Cost for repairing the two non-damaged Platforms for precautionary reasons
NO FIX	NO FIX	FIX	NO FIX	C_Platform_3	100%	Cost for repairing only one of the two non-damaged Platforms for precautionary reasons
NO FIX	NO FIX	NO FIX	FIX	C_Platform_4	100%	Cost for repairing only one of the two non-damaged Platforms for precautionary reasons
NO FIX	NO FIX	NO FIX	NO FIX	0	50%	No cost
Color codes						
Highest Cost	Crucial High	Medium	Low	No Cost		
Crucial Very High	Medium High	Medium Low	Very Low			

According to Table 2 analysis, it is indicated that there is a trade-off between Train Network utilization and Restoration Cost. In case of no restoration (which means no restoration costs), there is only 50% infrastructure utilization. On the other hand, based on the Fault Tree analysis if we proceed restoring any Platform, the utilization returns back to 100%. However, depending on the Platform/Platforms we choose to repair, the respective costs differ.

Table 2 indicates that a proper strategy for restoring utilisation is to proceed with the maintenance of one of the two undamaged platforms which leads to the lowest cost.
However, similarly to the previous scenario, it can be noticed that the Fault Tree based approach is efficient in determining the crucial strategy in order to restore the worse case of utilization, due to the fact that this method considers assets' states as boolean. Consequently an asset state can be considered as functional or non-functional. In reality, nevertheless, the set of boolean values correspond to the upper and lower utilisation limit which most of the times are not the true picture of the assets status. As a consequence, its real status lies somewhere in the middle, influenced not only by damage incidents or dependent assets, but also by their resilience. In this regard, Fault Tree Analysis seems to be a quick and efficient way for distinguishing the crucial cases from the less crucial, which is important in urgent situations. The other cases, however, need more meticulous study of their status and the way they are influenced by other dependant assets, and external and internal factors.

3.2 Approach 2

The second approach uses the functional status of assets as a scalar measure between 0 and 1.0 to indicate the effectiveness of their utilisation. In this respect, the train network utilisation and resultant impact of sudden human-made or natural hazards is modeled using a Bayesian Network, which assumes the Markov property for the inter-dependencies between the components.



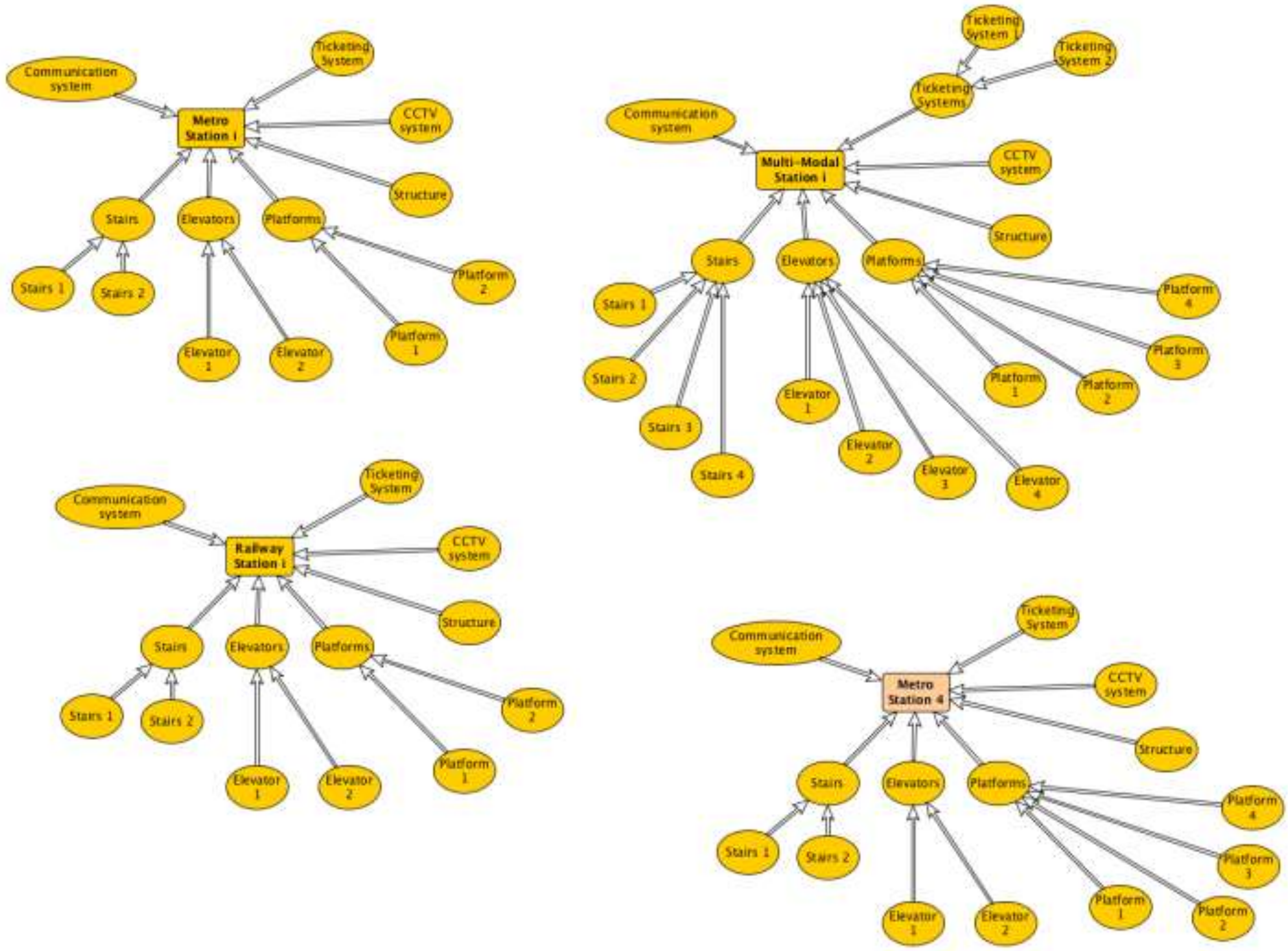


FIGURE 9 BAYESIAN NETWORK MODEL FOR TRAIN NETWORK

Each arrow maps each asset with the ones that influence their utilization.

$$P(node = 1) = \sum^{all\ children} P(node = 1 | children(node)) \cdot P(children(node))$$

The conditional dependencies between nodes and children are determined by pre – defined expert rules that define the effect of assets utilization on their parent assets. Finally, the leaf nodes (independent variables) reflect the assets' operational capability by taking into account physical deterioration and disaster incidents' impacts on their performance level. This performance Q(t,c,s) (where t : time, c : cost, s : status) is based on the performance determination methodology as proposed toward CAMS for categorisation and prioritisation[2] data that was generated under WP7's studies In this regard it is proposed the following conditional tables:

[2] CdM datasheet column I-M. In the last SE, CAMS used the Table 3 0-1 method for component cost and operational condition.

TABLE 3 CONDITIONAL TABLE FOR STAIRS GROUP THAT CONTAIN 2 STAIRS

Stairs=1	Stairs_1	Stairs_2	Expert Rule
1	1	1	If all Stairs are functional then Stairs module is considered fully functional
0,5	1	0	If one of the Stairs is functional then Stairs are considered functional to the extend depending on amount of functional Stairs.
0,5	0	1	If one of the Stairs is functional then Stairs are considered functional to the extend depending on amount of functional Stairs.
0	0	0	If no Stairs is functional then Stairs module is considered non-functional

TABLE 4 CONDITIONAL TABLE FOR STAIRS GROUP THATCONTAIN4 STAIRS

Stairs=1	Stairs_1	Stairs_2	Stairs_3	Stairs_4	Expert Rule
1	1	1	1	1	If all Stairs are functional then Stairs module is considered fully functional
0,75	1	1	1	0	If one of the Stairs is functional then Stairs are considered functional to the extend depending on amount of functional Stairs.
0,75	1	1	0	1	If one of the Stairs is functional then Stairs are considered functional to the extend depending on amount of functional Stairs.
0,5	1	1	0	0	If one of the Stairs is functional then Stairs are considered functional to the extend depending on amount of functional Stairs.
0,75	1	0	1	1	If one of the Stairs is functional then Stairs are considered functional to the extend depending on amount of functional Stairs.
0,5	1	0	1	0	If one of the Stairs is functional then Stairs are considered functional to the extend depending on amount of functional Stairs.
0,5	1	0	0	1	If one of the Stairs is functional then Stairs are considered functional to the extend depending on amount of functional Stairs.
0,25	1	0	0	0	If one of the Stairs is functional then Stairs are considered functional to the extend depending on amount of functional Stairs.
0,75	0	1	1	1	If one of the Stairs is functional then Stairs are considered functional to the extend depending on amount of functional Stairs.
0.50	0	1	1	0	If one of the Stairs is functional then Stairs are considered functional to the extend depending on amount of functional Stairs.
0,5	0	1	0	1	If one of the Stairs is functional then Stairs are considered functional to the extend depending on amount of functional Stairs.
0,25	0	1	0	0	If one of the Stairs is functional then Stairs are considered functional to the extend depending on amount of functional Stairs.
0,5	0	0	1	1	If one of the Stairs is functional then Stairs are considered functional to the extend depending on amount of functional Stairs.
0,25	0	0	1	0	If one of the Stairs is functional then Stairs are considered functional to the extend depending on amount of functional Stairs.
0,25	0	0	0	1	If one of the Stairs is functional then Stairs are considered functional to the extend depending on amount of functional Stairs.
0	0	0	0	0	If no Stairs is functional then Stairs module is considered non-functional

TABLE 5 CONDITIONAL TABLE FOR ELEVATORS GROUP THAT CONTAIN 2 ELEVATORS

Elevators=1	Elevators_1	Elevators_2	Expert Rule
1	1	1	If all Elevators are functional then Stairs module is considered fully functional
0,5	1	0	If one of the Elevators is functional then Elevators are considered functional to the extend depending on amount of functional Elevators.
0,5	0	1	If one of the Elevators is functional then Stairs are considered functional to the extend depending on amount of functional Elevators.
0	0	0	If no Elevators is functional then Elevators module is considered non-functional

TABLE 6 CONDITIONAL TABLE FOR ELEVATORS GROUP THAT CONTAIN 4 ELEVATORS

Elevators=1	Elevators_1	Elevators_2	Elevators_3	Elevators_4	Expert Rule
1	1	1	1	1	If all Elevators are functional then Stairs module is considered fully functional
0,75	1	1	1	0	If one of the Elevators is functional then Elevators are considered functional to the extend depending on amount of functional Elevators.
0,75	1	1	0	1	If one of the Elevators is functional then Elevators are considered functional to the extend depending on amount of functional Elevators.
0,5	1	1	0	0	If one of the Elevators is functional then Elevators are considered functional to the extend depending on amount of functional Elevators.
0,75	1	0	1	1	If one of the Elevators is functional then Elevators are considered functional to the extend depending on amount of functional Elevators.
0,5	1	0	1	0	If one of the Elevators is functional then Elevators are considered functional to the extend depending on amount of functional Elevators.
0,5	1	0	0	1	If one of the Elevators is functional then Elevators are considered functional to the extend depending on amount of functional Elevators.
0,25	1	0	0	0	If one of the Elevators is functional then Elevators are considered functional to the extend depending on amount of functional Elevators.
0,75	0	1	1	1	If one of the Elevators is functional then Elevators are considered functional to the extend depending on amount of functional Elevators.
0.50	0	1	1	0	If one of the Elevators is functional then Elevators are considered functional to the extend depending on amount of functional Elevators.
0,5	0	1	0	1	If one of the Elevators is functional then Elevators are considered functional to the extend depending on amount of functional Elevators.
0,25	0	1	0	0	If one of the Elevators is functional then Elevators are considered functional to the extend depending on amount of functional Elevators.
0,5	0	0	1	1	If one of the Elevators is functional then Elevators are considered functional to the extend depending on amount of functional Elevators.
0,25	0	0	1	0	If one of the Elevators is functional then Elevators are considered functional to the extend depending on amount of functional Elevators.
0,25	0	0	0	1	If one of the Elevators is functional then Elevators are considered functional to the extend depending on amount of functional Elevators.
0	0	0	0	0	If no Elevators is functional then Elevators module is considered non-functional

TABLE 7 CONDITIONAL TABLE OF PLATFORMS GROUP THAT CONTAIN 2 PLATFORMS

Platforms=1	Platform_1	Platform_2	Expert Rule
1	1	1	If all Platforms are functional then Platforms module is considered fully functional
0,5	1	0	If one of the Platforms is functional then Platforms are considered functional to the extend depending on amount of functional Platforms.
0,5	0	1	If one of the Platforms is functional then Platforms are considered functional to the extend depending on amount of functional Platforms.
0	0	0	If no Platform is functional then Platforms module is considered non-functional

TABLE 8 CONDITIONAL TABLE OF PLATFORMS GROUP THAT CONTAIN 4 PLATFORMS.

Platforms=1	Platform_1	Platform_2	Platform_3	Platform_4	Expert Rule
1	1	1	1	1	If all Platforms are functional then Platforms module is considered fully functional
0,75	1	1	1	0	If one of the Platforms is functional then Platforms are considered functional to the extend depending on amount of functional Platforms.
0,75	1	1	0	1	If one of the Platforms is functional then Platforms are considered functional to the extend depending on amount of functional Platforms.
0,5	1	1	0	0	If one of the Platforms is functional then Platforms are considered functional to the extend depending on amount of functional Platforms.
0,75	1	0	1	1	If one of the Platforms is functional then Platforms are considered functional to the extend depending on amount of functional Platforms.
0,5	1	0	1	0	If one of the Platforms is functional then Platforms are considered functional to the extend depending on amount of functional Platforms.
0,5	1	0	0	1	If one of the Platforms is functional then Platforms are considered functional to the extend depending on amount of functional Platforms.
0,25	1	0	0	0	If one of the Platforms is functional then Platforms are considered functional to the extend depending on amount of functional Platforms.
0,75	0	1	1	1	If one of the Platforms is functional then Platforms are considered functional to the extend depending on amount of functional Platforms.
0.50	0	1	1	0	If one of the Platforms is functional then Platforms are considered functional to the extend depending on amount of functional Platforms.
0,5	0	1	0	1	If one of the Platforms is functional then Platforms are considered functional to the extend depending on amount of functional Platforms.
0,25	0	1	0	0	If one of the Platforms is functional then Platforms are considered functional to the extend depending on amount of functional Platforms.
0,5	0	0	1	1	If one of the Platforms is functional then Platforms are considered functional to the extend depending on amount of functional Platforms.
0,25	0	0	1	0	If one of the Platforms is functional then Platforms are considered functional to the extend depending on amount of functional Platforms.
0,25	0	0	0	1	If one of the Platforms is functional then Platforms are considered functional to the extend depending on amount of functional Platforms.
0	0	0	0	0	If no Platforms is functional then Platforms module is considered non-functional

TABLE 9 CONDITIONAL TABLE FOR EACH STATION NODE

Station=1	Communication System	Stairs	Elevators	Platforms	Structure	CCTV system	Ticketing System	Expert Rule
1	1	1	1	1	1	1	1	If all components are functional then Station module is considered fully functional
0	0	0	0	0	0	0	0	If all Stairs are non-functional then Station module is considered non-functional
0	0/1	0/1	0/1	0/1	0/1	0/1	0/1	If at least one component is non-functional then the Station is disabled (non-functional)

TABLE 10 CONDITIONAL TABLE FOR EACH LINE COMPONENT

Line=1	Station (i)	Expert Rule
1	1	If all Stations are enabled then Line module is considered fully functional
0	0/1	If at least one Station is non-functional then the Line module is disabled (non-functional)

The next step is the application of the second approach to scenario 1 and 2 and the estimation of cost impact for restoring faulty lines. This time however it is taken into account the performance of each of the fundamental components (the leaves in the above-mentioned graph model) which indirectly depends on the natural condition of each component and disaster effects resulting from potential hazards (natural or human made, corresponding to scenarios 1 and 3 respectively). Cost model depends to resource consumption needs in order to fully restore each component, as proposed with CAMS demonstration (CAMS presentation, CdM simulation exercise, table 12 in D7, page 12) based on WP7's task studies, and it is formalized by the following graph:

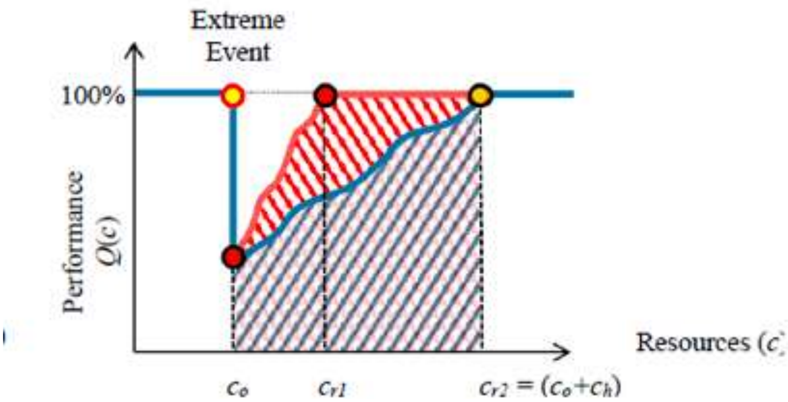


FIGURE 10 PERFORMANCE IN TERMS TO COST CONSUMPTION

Scenario 1

As discussed in the previous section, scenario 1 envisages a physical hazard (flooding incident) that impacts the section of the railway line between **Multi-Modal Station 1** and **Railway Station 4** and causes fatal damage to **Elevator 1**, **Platform 1** and **Platform 2** at **Multi-Modal Station 1**. In this regard, according to the second proposed approach, all assets (leaf nodes in the train network graph) are considered 100% except those that were damaged, which are mapped to **P(asset=1) =** $\mathbf{Q_0 + \Delta Q_{asset}(c_{asset})}$ **where** $\mathbf{Q_0}$ represents performance immediately following the disaster incident, and Qasset(casset) represents cost as the cost for full restoration. For the specific use case it is assumed two types of disaster impact: (a) "fatal impact" where performance reduces to zero, $\mathbf{Q_0}$ **=** 0.0and (b) «needing maintenance » where the asset has not been damaged, however should be tested and further maintenanced. In this case, it is assumed that $\mathbf{Q_0}$**=0.9.** To simplify scenario 1&2, it was considered that performance is affected only by disaster events and not by natural performance

decay. Otherwise, performance would not be steady to 100% in non-disaster cases, but in the progress of time there would be a natural deterioration of assets' condition and consequently their Q(t) which would need an extra cost investment in order to restore their Q(t) to previous levels.
Based on conditional tables, all nodes that are dependant to nodes that have performance 1.0 (100%), they correspond to performance 1.0 as well, given their dependant nodes values. As a result:

$$P(asset_{non-influenced} = 1) = \sum_{parent\ nodes}^{all} P(asset_{non-influenced} = 1|parents) \cdot P(parents) \xRightarrow{P(parents=1)=1.0}$$

$$P(asset_{non-influenced} = 1) = P(asset_{non-influenced} = 1|parents = 1) = 1.0$$

Where **$asset_{non-influenced}$**: all assets that the other assets theydepend on have 100% performance.
The assets that have been affected by flooding are : (a) **Elevator 1, Plaform 1, Platform 2** from **Multi-Modal Station 1** and (b) **Red Line**.
As a result, based on the second approach, utilizing the above-mentioned conditional tables and performing the necessary calculations, we arrive at the following results:

$$\textbf{P(Elevators=1)} = 0{,}75 + 0{,}25 \cdot \Delta Q_{Elevator_1}(c_{Elevator1})$$

$$\boldsymbol{P(Platforms = 1)} = 0{,}5 + 0{,}25 \cdot \Delta Q_{Platform1}(c_{Platform1}) + 0{,}25 \cdot \Delta Q_{Platform2}(c_{Platform2})$$

$$\boldsymbol{P(Multi-Modal\ Station\ 1 = 1)} = [0{,}75 + 0{,}25 \cdot \Delta Q_{Elevator_1}(c_{Elevator1})] \cdot [0{,}5 + 0{,}25 \cdot \Delta Q_{Platform1}(c_{Platform1}) + 0{,}25 \cdot \Delta Q_{Platform2}(c_{Platform2})]$$

$$\boldsymbol{P(Red\ Line = 1)} = \Delta Q_{Red\ Line}(c_{Red\ Line}) \cdot [0{,}75 + 0{,}25 \cdot \Delta Q_{Elevator_1}(c_{Elevator1})] \cdot [0{,}5 + 0{,}25 \cdot \Delta Q_{Platform1}(c_{Platform1}) + 0{,}25 \cdot \Delta Q_{Platform2}(c_{Platform2})]$$

$$\boldsymbol{P(Blue\ Line = 1)} = [0{,}75 + 0{,}25 \cdot \Delta Q_{Elevator_1}(c_{Elevator1})] \cdot [0{,}5 + 0{,}25 \cdot \Delta Q_{Platform1}(c_{Platform1}) + 0{,}25 \cdot \Delta Q_{Platform2}(c_{Platform2})]$$

$$\boldsymbol{Total\ Infrastructure\ Performance} = \frac{\sum_{i \in All\ Infrastructure\ lines} P(Line_i)}{4}$$

Scenario 2
The second scenario regards a terrorist attack where a bomb blast damages severely **Platform 1 & 2** of **Metro Station 4**, but for precautionary reasons **Platform 3 & 4** are out of service in order to be checked and maintenanced. In this regard, Platforms 1 & 2 are considered to have fatal damage:

$$\boldsymbol{P(Platform\ 1(or\ 2) = 1)} = \Delta Q_{Platform\ 1\backslash 2}(c_{Platform\ 1\backslash 2})$$

And **Platform 3 & 4** are closed for maintenance (**Q_0 =** 0,9):

$$\boldsymbol{P(Platform\ 3(or\ 4) = 1)} = 0.9 + \Delta Q_{Platform\ 1\backslash 2}(c_{Platform\ 1\backslash 2})$$

Similarly to scenario 1, based on 2nd approach and assuming that restoration cost and performace improvement in terms of cost for Platform 1&2 is approximately the same

$$\Delta Q_{Platform\ 1}(c_{Platform\ 1}) \approx \Delta Q_{Platform\ 2}(c_{Platform\ 2}) \approx \Delta Q_{12}$$

Similarly, we assume that performance improvement in terms of cost for maintenance reasons for Platforms 3 & 4 is approximately the same

$$\Delta Q_{Platform\ 3}(c_{Platform\ 3}) \approx \Delta Q_{Platform\ 4}(c_{Platform\ 4}) \approx \Delta Q_{34}$$

Consequently, the correponding results of the second approach when applied on scenari on 2 are the following:

$$P(Platform = 1) = \Delta Q_{12}^2 \cdot (\Delta Q_{34} + 0{,}9)^2 + 1{,}5 \cdot \Delta Q_{12}^2 \cdot (0{,}9 + \Delta Q_{34}) \cdot (0{,}1 - \Delta Q_{34}) + 0{,}5 \cdot \Delta Q_{12}^2 \cdot (0{,}1 - \Delta Q_{34})^2 + 1{,}5 \cdot \Delta Q_{12}(1 - \Delta Q_{12}) \cdot (0{,}9 + \Delta Q_{34})^2 + 2 \cdot \Delta Q_{12} \cdot (1 - \Delta Q_{12}) \cdot (0{,}9 + \Delta Q_{34}) \cdot (0{,}1 - \Delta Q_{34}) + 0{,}5 \cdot \Delta Q_{12}(1 - \Delta Q_{12}) \cdot (0{,}1 - \Delta Q_{34})^2 + 0{,}5 \cdot (1 - \Delta Q_{12})^2 \cdot (0{,}9 + \Delta Q_{34})^2 + 0{,}5 \cdot (1 - \Delta Q_{12})^2 \cdot (0{,}9 + \Delta Q_{34}) \cdot (0{,}1 - \Delta Q_{34})$$

$$P(Green\ Line = 1) = P(Blue\ Line = 1) = P(Metro\ Station\ 4 = 1) = P(Platforms = 1)$$

$$Total\ Infrastructure\ Performance = \frac{\sum_{i\, \in All\ Infrastructure\ lines} P(Line_i)}{4}$$

Following the above results, we proceed to test cost investment variations using approach 2 on scenario 1 and scenario 2. The results are presented below:

TABLE 11 COMPONENTS RESTORATIONS SIMULATION FOR SCENARIO 1

Elevator 1	Platform 1	Platform 2	Red_Line	Cost	Utilization (In terms of Line sections)	Row ID
NO FIX	NO FIX	NO FIX	NO FIX	0	0,59	1
NO FIX	NO FIX	NO FIX	FIX	C_Line	0,69	2
FIX / NO FIX	FIX / NO FIX	FIX / NO FIX	FIX	C_Line + C_Platform*Num_Fixed_Platforms + C_Elevator*Num_Fixed_Elevators	{ [2*(0,75+0,25*num_elevators) * (0,5+0,25*num_platforms)] + 2 } * 0,25	3
FIX / NO FIX	FIX / NO FIX	FIX / NO FIX	NO FIX	C_Platform*Num_Fixed_Platforms + C_Elevator*Num_Fixed_Elevators	{ [(0,75+0,25*num_elevators) * (0,5+0,25*num_platforms)] + 2 } * 0,25	4

TABLE 12 COMPONENTS RESTORATIONS SIMULATION FOR SCENARIO 2

Platform 1	Platform 2	Platform 3	Platform 4	Cost	Utilization (In terms of Line sections)	Row ID
FIX	FIX	FIX	FIX	C_Platform_1 + C_Platform_2 + C_Platform_3 + C_Platform_4	100%	1
FIX	FIX	FIX	NO FIX	C_Platform_1 + C_Platform_2 + C_Platform_3	99%	2
FIX	FIX	NO FIX	FIX	C_Platform_1 + C_Platform_2 + C_Platform_4	99%	3
FIX	FIX	NO FIX	NO FIX	C_Platform_1 + C_Platform_2	98%	4
FIX	NO FIX	FIX	FIX	C_Platform_1 + C_Platform_3 + C_Platform_4	88%	5
FIX	NO FIX	FIX	NO FIX	C_Platform_1 + C_Platform_3	86%	6
FIX	NO FIX	NO FIX	FIX	C_Platform_1 + C_Platform_4	86%	7
FIX	NO FIX	NO FIX	NO FIX	C_Platform_1	85%	8
NO FIX	FIX	FIX	FIX	C_Platform_2 + C_Platform_3 + C_Platform_4	88%	9
NO FIX	FIX	FIX	NO FIX	C_Platform_2 + C_Platform_3	86%	10
NO FIX	FIX	NO FIX	FIX	C_Platform_2 + C_Platform_4	86%	11
NO FIX	FIX	NO FIX	NO FIX	C_Platform_2	85%	12
NO FIX	NO FIX	FIX	FIX	C_Platform_3 + C_Platform_4	75%	13
NO FIX	NO FIX	FIX	NO FIX	C_Platform_3	74%	14
NO FIX	NO FIX	NO FIX	FIX	C_Platform_4	74%	15
NO FIX	NO FIX	NO FIX	NO FIX	0	73%	16
Color codes						
Highest Cost	Crucial High	Medium	Low	No Cost		
Crucial Very High	Medium High	Medium Low	Very Low			

In Table 11 are presented the same variations of investments management for repairing the broken assets as those presented for approach 1. Using Fault Tree analysis, it was shown that the crucial factor, **Red Line** section, that influences train network utilization was the only factor that affects the network's performance and as a result it is the only asset that should be restored. The Bayesian Network approach is much more sensitive. We can see that all factors affect network's utilisation. The most crucial factor remains the **Red Line** section, which means that the restored **Red Line** section results in greater network performance (rows 2 and 3). Additionally, any extra asset that is restored, increases network performance (row 3 gives better results than row 2). An interesting point is that row 4 which corresponds to non-restored **Red Line** section can result in higher performance than row 2, which corresponds to restored **Red Line** section only, in the case that the other assets (**Platform 1&2** and **Elevator 1**) are recovered. This is because approach 2 is sensitive to the contribution of the "non-fatal" damages, which, none the less, have a negative effect on network performance if their negative effects are aggregated with their parent assets. Of course, the question, if such a result is desirable or not, is something to be taken into account when: (a) selecting the performance function (Q(c)) and (b) fine tuning the model by determining the conditional probabilities in conditional tables. This however is something that should be aligned always by end users' knowledge and requirements.
Table 12 presented the variations of budget planning for scenario 2 using 2nd approach. This case study demonstrates the effectiveness of this approach in identifying minor or major damages to assets, as well as cascading effects caused by propagating damages from parent assets to children assets, which can be used by CAMS tool in S4RIS platform to plan budgets effectively. In this example we see that overall utilisation increases as cost investment increases, comparing to the Fault Tree method where overall utilisation was reduced only when a crucial set of assets for the functional capability of network, is harmed.

3.3 Integration with CAMS tool

Although the proposed analysis could be used as a standalone estimation of the corresponding cascading effects to the maintenance and repair of an infrastructure, in case of a sudden disaster incident, it is mainly designed for complementing the investment optimization procedure as performed by CAMS in T7.5. In this context, the proposed analysis purpose is to calculate the cascading effect of a disaster incident to infrastructure components and infer of the condition level of each component. In further this will be forwarded to CAMS in the appropriate input form (D7.5), in order to make an estimate on the time and cost for each infrastructure to be repaired, taking into account physical deterioration, repairing time and corresponding cost. The respective flow is depicted in Figure 11.

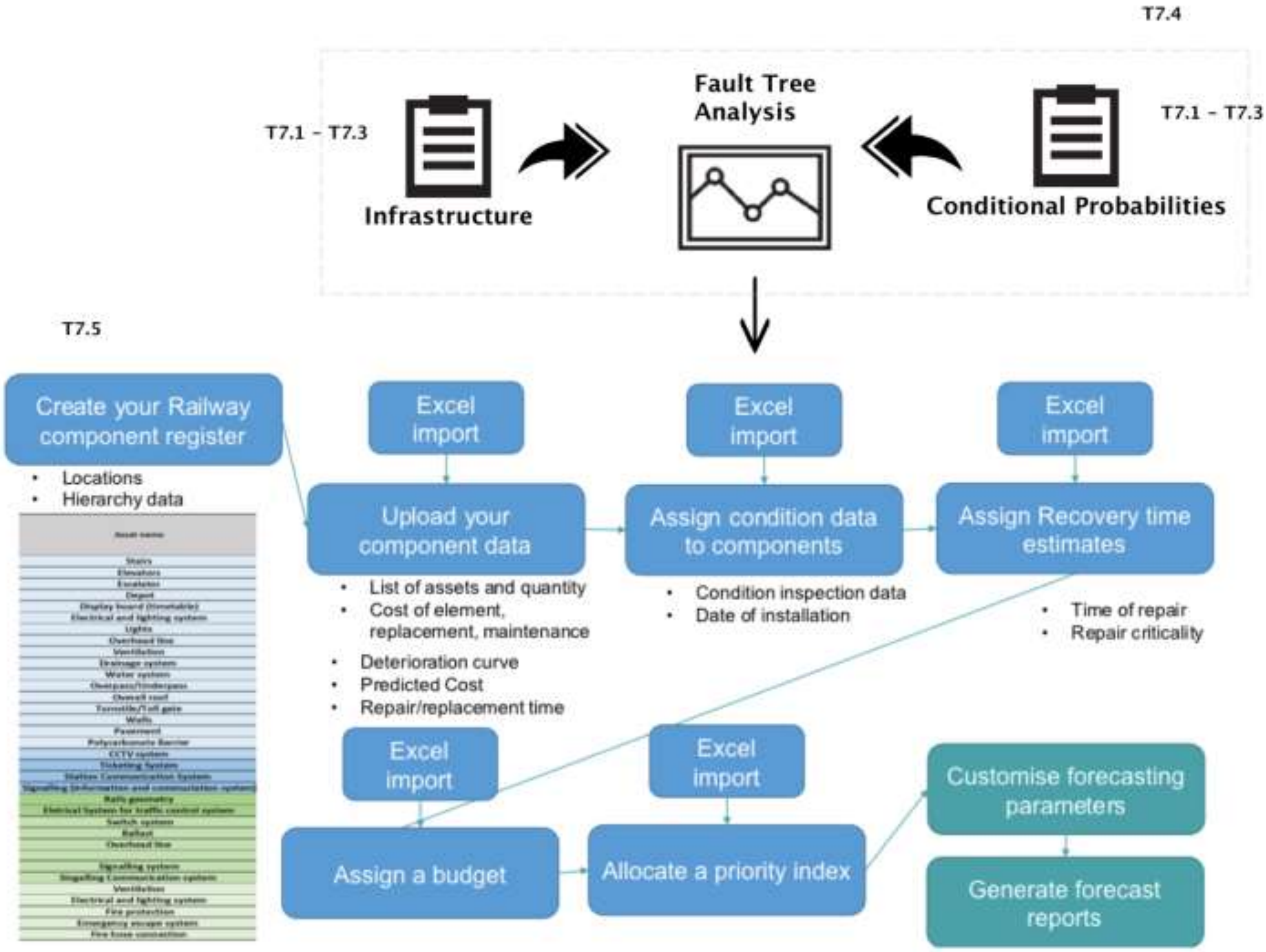


FIGURE 11 INVESTMENT OPTIMIZATION FLOW DIAGRAM

4. Discussions

A comparison of the two approaches can be summarised in

TABLE 13 COMPARISON OF TWO APPROACHES

Approach 1 (Fault Tree Analysis)	Approach 2 (Bayesian Network)
Fast Method which can be efficiently scale to large networks	*Much more difficult to scale, especially for large networks with many assets*
Good for detecting if crucial assets that affect network utilization, are damaged	*Good for detecting not only the crucial assets but also the effect of the performance of all assets to the whole network's utilization.*
Good for detecting mandatory cost investments quickly and efficiently, but not determining optimized investment solutions	*Reflects in a clear and explainable way costs effects in assets restoration and how each investment influence network's performance.*
This method considers assets condition as Boolean (functional / non-functional)	*This method treats asset's condition probabilistically, by modelling the state of an assets with the corresponding prior probability.*
This method does not take into account factors that influence the condition of an asset, such as physical deterioration of asset, sudden disaster incidents.	*This method is flexible for incorporating condition and performance models that take into account several aspects of assets' resilience, such as*

	environmental effects, physical assets decay, resilience to hazards, etc.

As stated in Table 13, each approach has its benefits, but also its drawbacks. Approach 1 is much more efficient and scalable, capable for detecting mandatory investments but fails to model investments effects in detail but only in a pass / no pass manner. Approach 2 on the other hand, is much more effective in modelling not only investment needs for ensuring functional state of train network but also the effects of each investment on whole system performance which is useful for optimisation investment strategies not only in short term for mitigating a sudden disaster effect, but also in longer terms by ensuring better resilience of systems. Consequently, a proposed direction that exploits both approaches and avoids as far as possible the burdens of each approach would be to apply Approach 1 to larger infrastructures in a real-time manner in order to make a first coarse grain analysis of potential cases that probably require attention, and then apply Approach 2 to assess several budget estimation scenarios to reduce damages and achieve better resilience in an efficient manner with optimized budget planning under more study in Task 7.5 by RMIT.

5. Conclusion

In this document there was presented a study of modelling metro/railway infrastructure, that reflects inter and intra connections and dependencies among the various components of the infrastructure. The first approach corresponds to a coarse grain Fault tree analysis which resulted to be efficient and scalable but useful only for detecting potential severe damages that need to be recovered in order to have the network back functioning. The second approach was based on a Bayesian Network that represents the various components and their depended ones. This method seems to be more accurate and effective, however it lacks of scalability capability. The proposed conclusion was to exploit the coarse grain first method as a first filter of potential disaster incidents that damage control is mandatory in order the network to return to a functional state. The second approach is recommended for analysing and researching various investment alternatives regarding network restoration, examining investment plans for enhancing resilience and optimising these strategies. Based on results from D7.4, CAMS needs specific data to calculate an optimised budget for restoring railway facilities after an incident. A sample of these data is attached in [8], [9].The conclusions of this study as well as other tasks under WP7 participants enabled the end-user to reach the successful implementation of action task T7.5 regarding optimising budget-related incidents.

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6. SAFETY4RAILS Deliverable 3.1
7. SAFETY4RAILS Deliverable 7.1
8. “Data required for CAMS”: Section 6.4, and Table 12 in SAFETY4RAILS Deliverable 7.1
9. “RFI Simulation Exercise 2022-06-01”: Section 6.3, and Table 11 in SAFETY4RAILS Deliverable 7.1
10. SAFETY4RAILS Deliverable 7.3

ANNEXES

ANNEX I. GLOSSARY AND ACRONYMS

TABLE 14 GLOSSARY AND ACRONYMS

Term	Definition/description
BN	Bayesian Network
FT	Fault Tree
DoA	Description of Action
ISO	International Organisation for Standardisation
S4R	SAFETY4RAILS
DAG	Directed Acyclic Graph
WP	Work Package
CAMS	Central Asset Manfgment System
CdM	Comune di Milano (City of Milan)
S4RIS	SAFETY4RAILS Information System
D	Deliverable
EGO	Ankara Metro
MdM	Metro de Madrid
RFI	Rete Ferroviaria Italiana

Partners:

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