DISS. ETH NO. 20250

Methodology for assessing the structural and operational robustness of railway networks

A dissertation submitted to

ETH ZURICH

for the degree of Doctor of Sciences

presented by

ROBERT DORBRITZ

Dipl.-Math. oec., University of Kaiserslautern

24th November 1981

citizen of Germany

accepted on the recommendation of

Prof. Dr. Ulrich Weidmann, examiner

Prof. Dr. Martin Haag, co-examiner

Prof. Dr. Anita Schöbel, co-examiner

2012

Abstract

Railway networks are critical infrastructures since their non-availability induce severe financial, societal and economic impacts on a national level. Both, stations and tracks can be put out of service due to severe natural, technical or social hazards. Long-term construction works are other events degrading railway operation. During the last decades, railway transport is more often threatened by such events since they are more likely to occur in Switzerland. Railway systems are extensively interconnected and become more complex, such that severe events have larger impacts on railway transport. Before these events occur it hence is essential to anticipate their consequences for reducing response times, for increasing the preparedness of railway networks and for minimizing the time needed for counteractions. Such measures aim to reduce the time span until the system performance of railway operation returns to the pre-disaster level and hence increase the robustness of railway networks.

This study introduces a new methodology that combines procedures for analysing the structural impacts of such events and for the quantification of the operational consequences. This increases the level of understanding of the robustness of railway networks against severe events by identifying the critical stations and tracks, whose removals have the most severe impacts on operation. The developed method is also useful for finding the bottlenecks in degraded operation, i.e. the corridors offering important rerouting alternatives. The results give valuable information about where to focus protection and counteraction efforts and where to locate emergency units. The study provides essential insights for the prioritisation of investments and the consequences of deconstructions on the robustness of railway networks.

The structural impacts of threatening events on critical infrastructures were already analysed in various studies, for instance for power grids, nutrition webs and social networks. Typically, nodes and links are removed from the topologies for representing the consequences of hazards on network structures. Measuring the changes of parameters assessing the network integrity is commonly used for quantifying the severity of such removals and the level of integrity degradation. For most analysed networks similar characteristics of such removals were found: If the removed elements are randomly distributed among all nodes, the networks are likely to remain in a large connected component even for large fractions of such removals. For biased removal strategies focussing on the most important elements, i.e. nodes with highest degree, networks disintegrate very fast such that the integrity is promptly reduced.

In most cases, available studies focus on analysing and manipulating railway topologies, i.e. networks representing the *Infrastructure* subsystems of railway systems. This study introduc-

es a multi-level representation of railway networks, also integrating the *Traffic Operation and Management* subsystem (specifying operational data such as the capacity thresholds of links), the *Control-command and Signalling* subsystem (specifying from where stations are remotely controlled or whether they are locally operated) and the *Energy* subsystem (showing from where traction current is provided).

On the one hand, this study verifies that the topological observations also hold for the topologies of railway networks, such as the Swiss railway network and the Zurich tramway network. On the other hand, recent methods are not sufficient for assessing the consequences of threatening events on railway operation. In railway networks, flows are not arbitrarily routed through the network, neither in planned nor in degraded operation. This study develops a method for simulating the decisions of railway operators about how to reroute affected lines, whether to truncate their line paths or put entire lines out of service. A robustness analysis tool is implemented in *R* that calculates degraded operation states mimicking real-world dispositive efforts. The amount of degradation of railway operation is quantified by a single value integrating several measures that assess the connectivity of the degraded networks (such as number of served stations, number of stations in largest connected component…) and the changes of the capacity utilization (such as number of trains needed for operation, number of links utilized above specific capacity thresholds…). The introduced measure hence allows to quantify the level of degradation of railway operation and to compare the operational impacts of different hazard scenarios. The results can also be used for simulating the impacts of multiple simultaneously occurring events such that rules of actions can be formulated and degraded operation states can be visualised, which both increase the preparedness of railway operators.

The results show that there are stations whose removals have major topological impacts while the system performances in degraded operation is only slightly reduced. The study identifies the most vulnerable stations and tracks from an operational point of view. The developed method can also be used for comparing the capacity utilizations of links in planned and degraded operation such that important rerouting corridors and bottlenecks in degraded operation are identified. The results verify that there are corridors rarely used in planned operation, but extensively used in degraded state. If such corridors are not longer available, rerouting lines will potentially be hindered such that additional lines are truncated.

In this sense, the developed method provides an innovative approach for assessing the impacts of severe events on railway operation in a quantitative way. It provides valuable information how to increase the robustness of railway networks and how to improve the preparedness of railway systems before threatening events occur, which is beneficial not only for railway operators, but also for customers and the society in general.

Zusammenfassung

Bahnnetze gehören zu den kritischen Infrastrukturen, deren Ausfall grosse finanzielle, wirtschaftliche und gesellschaftliche Folgen hat. Die Verfügbarkeit von Bahnhöfen und Strecken wird von verschiedenen technischen, sozialen oder Naturgefahren bedroht. Auch geplante Ereignisse, wie langdauernde Bau- und Unterhaltsmassnahmen können dazu führen, dass Knoten oder Kanten nicht mehr befahrbar sind. Die Verwundbarkeit von Bahnverkehren gegenüber schweren Störereignissen hat dabei in den letzten Jahren zugenommen, einerseits durch die erhöhte Frequenz solcher Ereignisse in Folge der Klimaveränderung. Andererseits sind Bahnsysteme anfälliger gegenüber schweren Ereignissen geworden, da Prozesse zunehmend automatisiert, komplexe Teilsysteme verknüpft, Eingriffsmöglichkeiten zentralisiert und Puffer reduziert werden. Besonders vor dem Auftreten solcher schweren Ereignisse ist es daher wichtig, die Systemstabilität zu erhöhen sowie Schwachstellen und Engpässe im reduzierten Betrieb zu identifizieren. Solche Massnahmen sollen die Antwortzeit reduzieren, die Ereignisvorsorge und das Störfallmanagement verbessern, um gestörte Bahnnetze schneller in den Normalbetrieb zurückzuführen.

Die vorliegende Studie stellt ein Verfahren vor, welches sowohl die strukturellen Auswirkungen als auch die betrieblichen Konsequenzen schwerer Störungen auf Bahnnetze untersucht. Die Erkenntnisse können genutzt werden, um die Widerstandsfähigkeit von Bahnnetzen gegenüber schweren Störungen zu erhöhen. Die Studie zeigt beispielsweise, wie kritischste Elemente identifiziert werden, deren Ausfall die grösste Minderung der Betriebsqualität bewirkt. Zudem hebt die Studie bedeutsame Ausweichstrecken und Umfahrungsalternativen hervor. Die Studie leistet damit auch einen wichtigen Beitrag, um die Wirkungen von Ausbau- oder Rückbaumassnahmen auf die Robustheit von Bahnnetzen zu quantifizieren und Massnahmen zur Erhöhung der Systemstabilität zu testen und zu priorisieren.

In existieren Studien wurden bislang die topologischen Auswirkungen von Störungen auf die Netzstruktur untersucht, beispielsweise im Bereich der Energie- und Nahrungsversorgung sowie für soziale Netzwerke. Typischerweise werden dabei einzelne oder mehrere Knoten und Kanten von den Topologien entfernt und die Veränderung der Netzstruktur gemessen und bewertet. Meist werden die Veränderung der Knotenanzahl in der grössten Komponente und die Veränderung der kürzesten Wege quantifiziert, um die strukturelle Widerstandsfähigkeit dieser Netze abzuleiten. Trotz der Verschiedenheit der untersuchten Netze konnten charakteristische Stabilitätseigenschaften abgeleitet werden: Bei Entfernung zufälliger Elemente bleibt das Netz auch bei hohen Anteilen entfernter Knoten stabil, d.h. das Netz bleibt in einer gros-

sen zusammenhängenden Komponente und die gemessenen Kennwerte verändern sich nur gering. Werden hingegen bestimmte, wichtige Knoten entfernt, beispielsweise solche mit einem hohen Grad, so zerfällt das Netz schnell in zahlreiche kleine, miteinander nicht verbundene Komponenten. Die vorliegende Studie bestätigt diese Beobachtungen auch für zwei untersuchte Bahnnetze: das schweizerische Normalspurnetz und das Zürcher Tramnetz.

Gleichzeitig zeigt die Studie aber auch, dass bekannte bisherige Verfahren nur unzureichend die *betrieblichen* Folgen schwerer Störungen abbilden können. Es existieren beispielsweise Knoten, deren Ausfall schwere strukturelle Folgen hat, während die betrieblichen Konsequenzen weniger gravierend sind (und umgekehrt). Um die betrieblichen Folgen von Störungen abzubilden und zu messen, wurde ein daher Verfahren entwickelt, mit welchem gestörte Betriebszustände simuliert werden können. Dabei werden alle von einer Störung betroffenen Linien umgeleitet, verkürzt oder eingestellt. Die berechneten reduzierten Betriebszustände bilden reale Dispositionsentscheide realitätsnah ab. Die kalkulierten Abweichungen vom geplanten Betrieb werden mithilfe verschiedener Indikatoren erfasst und bewertet. In der Studie werden Indikatoren unterschieden, welche einerseits die Veränderung der Verknüpfung des Netzes im reduzierten Betrieb messen (z.B. die Anzahl der bedienten Stationen, Anzahl der Stationen im Hauptnetz) und die Netzauslastung andererseits (z.B. Anzahl eingesetzter Züge, Kanten mit Überschreitung definierter Kapazitätsschwellen). Die entwickelte Methode erlaubt also, reduzierte Betriebszustände zu berechnen, sowie die Minderung der Systemleistung zu bewerten, und damit, verschiedene Störungsszenarien miteinander zu vergleichen.

Während bisherige Verfahren die Topologie, also das Teilsystem *Infrastruktur* von Bahnnetzen untersuchen, werden in dieser Studie mehrere Teilsysteme miteinander verknüpft und ein ein mehrschichtiges Netzwerk integriert: Das Teilsystem *Infrastruktur* wird mit den Teilsystemen *Verkehrsführung und Verkehrssteuerung, Zugsteuerung, -sicherung und Signalgebung* sowie *Energie* verknüpft und Störungen in diesen Teilsystemen simuliert, sodass z.B. die Folgen eines Ausfalls von Stellwerken oder der Fahrstromeinspeisung simuliert werden können.

Die Studie zeigt, dass bisherige topologie-basierte Verfahren nicht ausreichen, um die Robustheit von Bahnsystemen gegenüber schweren Störungen vollumfänglich zu untersuchen. Stattdessen werden in dieser Studie auch die Auswirkungen auf den Bahnbetrieb simuliert und bewertet. Dies erlaubt es, reduzierte Betriebszustände auch für mehrere parallele Störungen zu generieren und zu visualisieren. Dies erhöht das Systemverständnis und identifiziert kritische Netzteile und Engpässe. Die Wirkungen von Veränderungen der Struktur auf die Systemstabilität können untersucht und die Massnahmen entsprechend bewertet und priorisiert werden. Von Massnahmen zur Erhöhung der Stabilität von Bahnnetzen profitieren sowohl die Netzbetreiber als auch deren Kunden sowie die gesamte Wirtschaft eines Landes.

Acknowledgement

First of all, I would like to thank Prof. Dr. U. Weidmann for employing me, for sharing my interest in public transport networks and analysing their capacity and robustness. I am very honoured and thankful that he gave me the opportunity to write a dissertation at ETH Zurich. In several projects he supported me by his trust, his motivation and the possibility to work and lead many interesting projects analysing public transport systems and their operation. He always supported the interdisciplinary approach not only in this project and encouraged me by providing valuable inputs in many fruitful discussions. He also gave me the opportunity to present the study in various articles and at several conferences to transport experts.

I also want to thank my both co-supervisors Prof. Dr. M. Haag and Prof. Dr. A. Schöbel for the cooperation, their contributions and their interest in both, the research topic and the applied methods. They gave me the opportunity to discuss not only the approach and the results but also the application areas of the evaluated methodology. I appreciate that Prof. Dr. A. Schöbel inspired me to apply my mathematical and analytical skills to optimization problems in the field of transportation when I was a student at the Technical University Kaiserslautern and for supporting me not only during my diploma thesis but also in this dissertation.

I am thankful to Prof. Dr. Grêt-Regamey from ETH Zurich for chairing my doctoral examination. Brigitte Cuperus and Martin Paul Hänger-Trottmann helped me whenever I had questions about the doctoral studies. I thank the SNF for supporting this project.

Dr. Lorenz Fahse from ETH Zurich introduced the software *R* in a lecture that I attended when I started this project in parallel. This inspired me to use this software in this study. Prof. Dr. J. Lüthi and his collegues from the Institute for Operation Research (ETH Zurich) provided valuable scientific inputs at several meetings and discussions together with the Swiss Federal Railways (SBB). I also thank Peter Grossenbacher and Salvador Ruprecht from the SBB for providing essential data for modelling and representing the Swiss railway network. Daniel Reichen from the SBB gave invaluable insights in the Business Continuity Management project, which inspired me in many ways in the context of this study. I thank René Frommenwiler and Somchai Yimvuthikul from Zurich Public Transport (VBZ) for providing information and the data that helped me to modell the VBZ tramway network. I am thankful that Marco Arpagaus invited me to the VBZ operation center. He discussed the calculated results of a specific case study in the Zurich tramway network and explained how the VBZ deals with threatening events in real-world scenarios. This helped me to identify potential application areas as well as extensions and limitations of the implemented tool and the developed methodology.

All my collegues at the IVT gave not only essential contributions in many discussions, they always motivated me and provided inspiration during this study. Additionally, they all made the time at the Institute special and unforgettable for me. Namely, I would like to thank Marcus Rieder for helping me when implementing the case study networks, for being uncomplaining when binding the different versions of this document and for his friendship during the last years (Merci beaucoup!). I also want to thank Stephan Moll, Olga Fink, Viola John, Dietlind Jacobs and Uwe Kirsch for their support, their motivation and the much fun we had at several Volleyball sessions, board games evenings, dinners and other events. They all became good friends. My collegues Dr. Dirk Bruckmann and Dr. Sonja-Lara Bepperling gave valuable inputs in many fruitful discussions. I also thank Ruth Bertschi, Valerie Willimann, Ursi Hörner and Edith Ringer for motivating me, when I needed someone to talk to.

I am very thankful for the support of all my friends during the last years, in particular Uscha, Stephan, Andreas and Wolfgang. You gave me the motivation, strength, trust and confidence to successfully finish this project during the last years.

This dissertation is dedicated to my grandmother Ilse.

Table of Contents

List of Tables

List of Figures

Abbreviations

BC	Betweenness centrality
CCS	The *Control-command and Signalling* subsystem
CHF	Swiss Franc
EK	Event category
h	Hours
Hz	Hertz
km	Kilometres
min	Minutes
SBB	Swiss Federal Railways (Schweizerische Bundesbahnen)
SFN	Scale-free network
SOB	Südostbahn
TOM	The *Traffic Operation and Management* subsystem
VBZ	Zurich Public Transport (Verkehrsbetriebe der Stadt Zurich)

Symbols

$\delta_{i,j}$	Kronecker delta
$a_{i,j}$	Entry of adjacency matrix (Are the nodes i and j connected?)
C^1	Clustering coefficient according to triangle definition
C^2	Clustering coefficient according to subgraph definition
$d_{i,j}$	Shortest path length between node i and node j

E	Efficiency
k_i	Degree of vertex i
$l_{i,j}$	Spatial distances between node i and node j
m	Number of links in the original, non-degraded network
n	Number of nodes in the original, non-degraded network
r	Assortative mixing by degree value
R^2	Coefficient of determination

Methodology for assessing the structural and operational robustness of railway networks

Dipl.-Math. oec. Robert Dorbritz
ETH Zurich
Institute for Transport Planning and Systems (IVT)
Wolfgang-Pauli-Strasse 15, HIL F 14.1
CH – 8093 Zurich (Switzerland)

http://www.ivt.ethz.ch/people/robertd
robert.dorbritz@ivt.baug.ethz.ch

ISBN: 978-3-905826-19-7

Abstract

Railway transport is a critical infrastructure since its non-availability induces severe financial, societal and economic impacts up to a national level. This study evaluates a methodology for quantitatively assessing the robustness of railway networks and applies it to the Swiss railway system and the Zurich tramway network. While present transportation resilience studies are rare and solely focus on topology analysis methods, this study analyses the operational impacts of severe events threatening railway operation.

The study shows how multiple subsystems can be integrated into a multi-level representation of the railway system. The software *R* is used for simulating the impacts of threatening events on railway operation by the application of implemented procedures for systematically calculating degraded operation states. This gives essential information about the most critical network elements and allows prioritizing investments in the network.

Key words

Critical infrastructures, complex systems, railway networks, robustness analysis, *R* software

Preferred citation style

Dorbritz, R. (2012) *Methodology for assessing the structural and operational robustness of railway networks*, Dissertation, Institute Reports, **155**, ETH Zurich, Institute for Transport Planning and Systems (IVT), March 2012.

1 Introduction

1.1 Motivation

Critical infrastructures

Modern societies depend on functioning infrastructures supplying for instance food, energy or transport services. As [Kröger, 2008] states, these essential infrastructures *«have witnessed a greater integration of service supply systems, a higher degree of interconnectedness and simultaneously an increased social vulnerability in case of accidental or intentional disruption»*. [Linger et al., 2000] adds that *«such systems improve efficiency by permitting entire new levels of organizational integration, but they also introduce elevated risks of intrusion and compromise»*.

These essential systems are called *critical infrastructures* since severe blockades or large-scale service and supply disruptions *«would have serious impacts on public health, public and political affairs, the environment, security and social and economic well-being»* ([CH, 2009]). [IRGC, 2007] states that an *«infrastructure becomes critical when it provides some service without which society or economy cannot engage in normal operation»*. Critical infrastructures are threatened by several hazardous events such as social, technical or natural disasters that often initially cause service disruptions on the local level. However, failures may globally spread such that even initially unaffected system elements loose functionality. Disastrous events hence have the potential to initiate cascading effects threatening the availability on the system level. This induces immense costs and menaces the economic well-being of both providers and customers (see [IRGC, 2007] or [Petermann et al., 2011]).

Besides transportation, [PCCIP, 1997] identifies the following critical infrastructures: oil and gas production and storage, water supply, emergency services, government services, banking and finance, electrical power and telecommunications.

System of systems

Critical infrastructures are networks *«of independent, large-scale man-made systems that function collaboratively and synergistically to produce a continuous flow of essential goods and services»* ([PCCIP, 1997]). During the last decades, originally interdependent systems were successively integrated into large-scale systems (so-called *systems of systems*) without entirely understanding the interdependencies within or the occurring vulnerabilities.

Railway transport and other large-scale, man-made systems are of complex type and their resilience against internal or external perturbations is of high interest, i.e. the abilities of systems to withstand the impacts of severe threatening events. Railway systems comprise multiple subsystems, each of complex structure [Zhu, 2000] such as the *Infrastructure*, *Energy* or *Control-command and Signalling* subsystem (see section 3).

Complex networks

Critical infrastructures and other systems can be mathematically modelled as complex networks consisting of a set of nodes that are connected by links if there is interaction between them [Buzna et al., 2006]. *Complex networks* are graph theoretical representations of the analysed complex system and are widely used for a systematic topological resilience analysis of the networks (and hence the resilience of the system). The study of complex networks by application of topology analysis methods has the potential to give important information about the underlying processes responsible for the observed macroscopic behaviour [Xu et al., 2008]. The applied methods typically allow to systematically manipulate graphs and to measure the dynamics of basic topology measures due to node or link removals. The network analysis results imply valuable information about the ability of the modelled systems to withstand perturbations.

When representing railway networks, nodes may symbolize stations that are connected by links if there are tracks between them (without passing an immediate other represented station). So far, operational aspects such as line path restrictions for determining degraded operation states are neglected when the resilience of transport systems is analysed.

Hazardous events

«Disastrous events are bothering mankind from the earliest days» [Buzna et al., 2007]. Critical infrastructures including railway transport are threatened by various social, technical and natural hazards [IRGC, 2007]. For instance, Switzerland comprises many mountains and Alpine regions and hence is notably exposed to natural hazards [Denzler, 2009]. Previous natural hazards like the winter storm *Lothar* or the floods in 2005 and 2007 gave indications about the vulnerabilities of living spaces [ARE, 2007]. Current forecast data indicates that the number of natural hazards in Europe will even increase within the next years, at least for specific areas ([Stutz, 2007], [Petermann et al., 2011]). Hence, it is of major interest to anticipate the impacts of threatening events, to identify the most critical network elements and to be able to test and prioritize the benefits from resilience enhancing measures for system operators, their owners, customers and manufacturers.

Even though hazards usually occur unexpected, it was found that they share characteristic features ([Helbing et al., 2003], [Buzna et al., 2006], [Helbing et al., 2005]): While the initial hazardous event typically has local impacts, failures may spread such that stable systems may turn into instable ones ([Helbing et al., 2003], [Harrald, 2007]).

This study integrates both, the deterioration of network integrity and the consequences for railway operation. Events are considered that may remove entire stations or tracks from the railway network. Irregularities such as timetable deviations are not in the scope of the study. Beside unwanted hazards, also planned events such as maintenance or construction works can significantly reduce the performance of systems and hence are considered [Moser, 2010].

Hazard consequences

[PCCIP, 1997] states that the *«disruption of any infrastructure is always inconvenient and can be costly and even life threatening»* and adds: *«Major disruptions could lead to major losses and affect national security, the economy, and public good.»*

For railway networks, severe hazardous events may threat passengers, employees, vehicles, infrastructure elements or railway transport and may have direct (such as deaths, injuries, damage, loss of property) or indirect consequences (such as image loss). Even though system-wide blackouts or severe service disruptions usually have small probabilities of occurrence, they typically induce immense costs and inconvenience [Kröger, 2008]. If a threatening event puts a station out of service such that trains do not traverse it anymore and assuming that this event affects 20'000 commuters affected per hour, then the economic damage is approximately 20’000 * 15 CHF per hour[1] = 300'000 CHF per hour.

The SBB’s energy crash in 2005 blockaded train movements on a national level. According to [SBB, 2005], 200’000 passengers and 1’500 trains were involved. The costs due to customer claims and replacement services were estimated to be approximately three million Swiss Francs. In Germany, strikes in freight transport for 62 hours caused a financial damage of between 50 and 80 million Euro [Welt, 2007].

Current resilience analysis methods for transportation networks

«A moderate amount of work has been done on the structure and function of transportation networks (...)» [Newman, 2010]. All available studies solely focus on topological aspects when analysing the resilience of transport networks or critical infrastructures in general. For the resilience analysis of railway networks, operational conditions (such as link capacities and

[1] From [Hess et al., 2008]

line path restrictions) and consequences on degraded operation states are neglected. But these requirements are highly important since in degraded operation pre-defined line paths have to be maintained as much as possible. Present resilience studies of transport networks solely analyse the underlying topologies and typically consider routings of units along shortest paths. This can give misleading or even wrong results for railway and other public transport networks since the most critical elements from a structural point of view do not necessarily coincide with operational ones. This study shows how the consequences on railway operation can be analysed by introducing a model for systematically calculating degraded operation states.

1.2 Hypotheses

Based on the current lack of analysis methods for assessing the operational robustness of railway networks, the following hypotheses are formulated representing the major research questions of this study:

Hypotheses 1

The structures of railway networks share the topological features of the so-called *scale-free networks*: The network remains in a large connected component even if many nodes are removed at random choice. On the contrary, for biased-removal strategies focussing on the most important nodes, networks disintegrate fast.

Many real-world systems and networks were successfully shown to have scale-free topologies: Nodes with very high degrees are likely to exist while the vast majority of nodes have very small degrees. Characteristic shapes of the degree distribution functions show that the networks belong to the set of scale-free networks. Since the topology structure strongly affects the network integrity and the distribution of flows within, useful information about the resilience of the represented system from a topological point of view is included. If railway networks also have scale-free topologies, existing analysis methods for network structures can be applied and extended for assessing the structural and operational robustness.

Hypotheses 2

The structural and operational consequences of removing a specific node can significantly differ, i.e. the topological importance and the operational one do not necessarily coincide. Hence, existing structural robustness analysis methods are not suitable for assessing the operational robustness of railway networks.

The hypothesis assumes that it is possible to identify the nodes, whose removal induces the most severe operational consequences, i.e. the rerouting of lines or their truncation. Removing nodes with major consequences for network integrity does not necessarily imply the most significant operational consequences. In fact, elements of minor structural importance exist whose removal induces severe operational consequences such as rerouting and truncation of line paths or even putting multiple lines out of service. Hence, present topology analysis methods are not suitable for entirely assessing the operational robustness of railway networks.

Hypotheses 3

Railway systems can be modelled and it is possible to systematically calculate degraded operation states and hence to simulate and quantify the impacts of threatening events on railway operation.

The railway system is a complex system containing several structural and operational subsystems and can be represented as a multi-level architecture. In this study, for the infrastructure topology operational data is specified, which is essential for calculating (realistic) degraded operation states and hence for quantifying the operational robustness of railway networks. A framework is developed suitable to systematically simulate the operational consequences of manipulating the modelled subsystems and to calculate feasible dispatching solutions mimicking those decided in real-world situations.

Hypotheses 4

Both, the structural and operational robustness of railway networks depend on the number of simultaneously removed nodes, the locations of the deleted elements and the existence of potential rerouting alternatives and their capacity utilizations.

The methodology shall be able to analyse the influences of several factors such as the number of simultaneously removed nodes and their positions on the structural and operational robustness of railway networks. The calculated results will provide useful information for transport operators and infrastructure owners: The most critical network elements and bottlenecks for degraded operation will be identified giving valuable information where to strengthen protection and enhancement efforts.

Hypotheses 5

There are routes not heavily used in planned operation, which are important bottlenecks in degraded operation by offering rerouting alternatives. These corridors contribute to the structural and operational robustness of the entire network.

Even routes that are not extensively used in normal operation can be of major importance for offering rerouting alternatives in degraded operation. The methodology will identify these routes and will compare the capacity utilizations of links in both, normal and degraded operation. This information is useful for identifying the bottlenecks in degraded operation and is valuable for the locations where protection efforts should be concentrated.

Hypotheses 6

The robustness of railway networks can be enhanced and the gained benefits can be quantified with the evaluated and implemented methodology.

The robustness of railway networks can be improved by preventive countermeasures, intervention or recovery strategies in both temporal and spatial dimension. According to [WEF, 2011], resilience enhancements *«comprise all initiating and supporting measures in the integrated planning process that make the system (more) resilient to current or potential future disasters»*. Since railway structures are already built and hence cannot be designed from scratch, a high cost-effectiveness of network extensions is of major interest for the infrastructure owners, the operators, the customers and the society in general. The implemented rrobustness analysis procedures are suitable for quantifying the benefits from resilience enhancing measures and hence provide essential information for the prioritization of investments in the network and for measuring the consequences of adaptations such as building new tracks or deconstructing existing ones.

1.3 Goals and purpose

«Waiting for a disaster is a dangerous strategy» as [PCCIP, 1997] states. The main goal of the study is to develop a methodology that can be used for simulating the consequences of threatening events on both, the topological integrity of railway networks and on railway operation. With other words, the evaluated procedures shall allow the manipulation of railway networks by removing nodes and links from the network, to calculate dispositive measures mimicking those in real-world situations and to quantify the impacts of the threatening events on the performance of railway transport. The latter term implies that it shall be possible to compare different hazard scenarios with respect to the connectivity of the degraded railway network and the capacity utilizations of links.

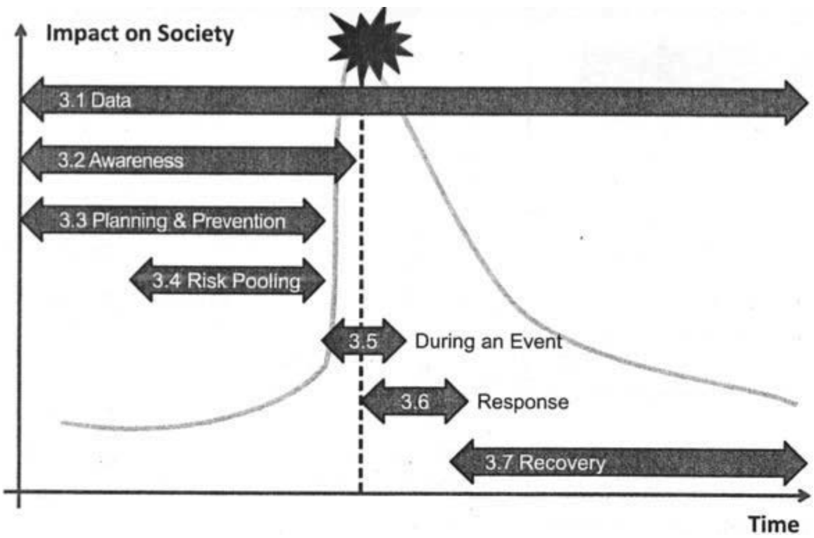
The derived methodology is implemented in the *R* software environment and applied to Swiss railway networks such that the structural and operational robustness of them can be quantified and compared.

The study introduces a methodology that can be used for systematically manipulating railway networks not only on the infrastructure level but also on the level of other subsystems including *Energy* and *Control-command and Signalling* devices. This extends the current lack of knowledge about degraded operational states and the ability of railway networks to deal with severe perturbations. The derived information is essential for all stakeholders since it allows the identification of the most vulnerable network elements and a prioritization of protective and enhancing measures in railway networks.

The study aims to increase the financial and social preparedness in all points along the so-called *disaster timeline* (see Figure 1), as introduced in [WEF, 2011]:

- **Before a disastrous event (Preparation phase):** Increase the awareness of factors contributing to the resilience of railway networks, suggest improvements beneficial for the phases *Planning and Prevention* and *Risk transfer*, e.g. by prioritizing investments in the network topology and operational characteristics such as track capacities, identification of most critical network elements, important rerouting alternatives and systematic assessment of degraded operational states by network manipulation including a framework mapping the dispatching of public transport lines,

Figure 1 Phases along the *disaster timeline*



Source: [WEF, 2011]

- **During the impact of a disastrous event (Response phase and counteractions):** Improve the ability to counteract the impacts of occurring events by reducing the response time and the evaluation of optimal decisions where to locate emergency units or the anticipation of further hazard consequences during the spreading of failures within the system,

- **After a disastrous event occurred (Recovery):** Anticipation of damages and degraded operation states, data and information for rebuilding the networks in a robust way, identification of bottlenecks in degraded operation states and improve the processes of risk assessment, business continuity management and emergency planning.

The derived information is essential to reduce the operational implications of hazardous impacts including the costs [Helbing, 2007]. Information about the consequences of disastrous events on the distribution of flows within the topology is of high interest: Differences between the network elements are quantified such that the constituents whose removal causes severe deteriorations can be distinguished from those with only moderate importance for the distribution of flows within the networks. A ranking of nodes and links provides essential information to decision makers such as network administrators about where to focus efforts of maintenance and robustness improvements against unexpected disruptions. Since countermeasures may have uncertain results, the implemented simulation and visualization framework supports understanding the complex interdependencies in extreme situations.

In summary, the study provides useful information about the robustness of railway networks in the following way:

- Identification of the **most critical elements** in railway networks, not only from the structural point of view but considering railway operation
- Information about the **consequences of planned events** such as construction works on the robustness of railway networks
- Identification of **bottlenecks in degraded operation** and major rerouting alternatives
- Reduce **response and recovery times** by optimizing the protection efforts and the location of emergency units
- Improvements of **customer information** about degraded operation states, anticipation of secondary consequences in the response phase (capacity thresholds of rerouting alternatives may become exceeded such that further deteriorations occur)
- **Prioritization of investments** and calculate the benefits from robustness enhancements such as building new tracks or increase capacity thresholds of tracks

- **Systematic calculation** and visualisation of degraded operational states mimicking the real-world dispatching solutions

- Knowledge about the **factors influencing** the resilience of railway networks and their strengths, i.e. information about the resilience in case of multiple simultaneous or successive removals of entire stations

- Deeper information about the **resilience of complex networks** with line path restrictions instead of routings along shortest path connections

1.4 Outline

1.4.1 System analysis

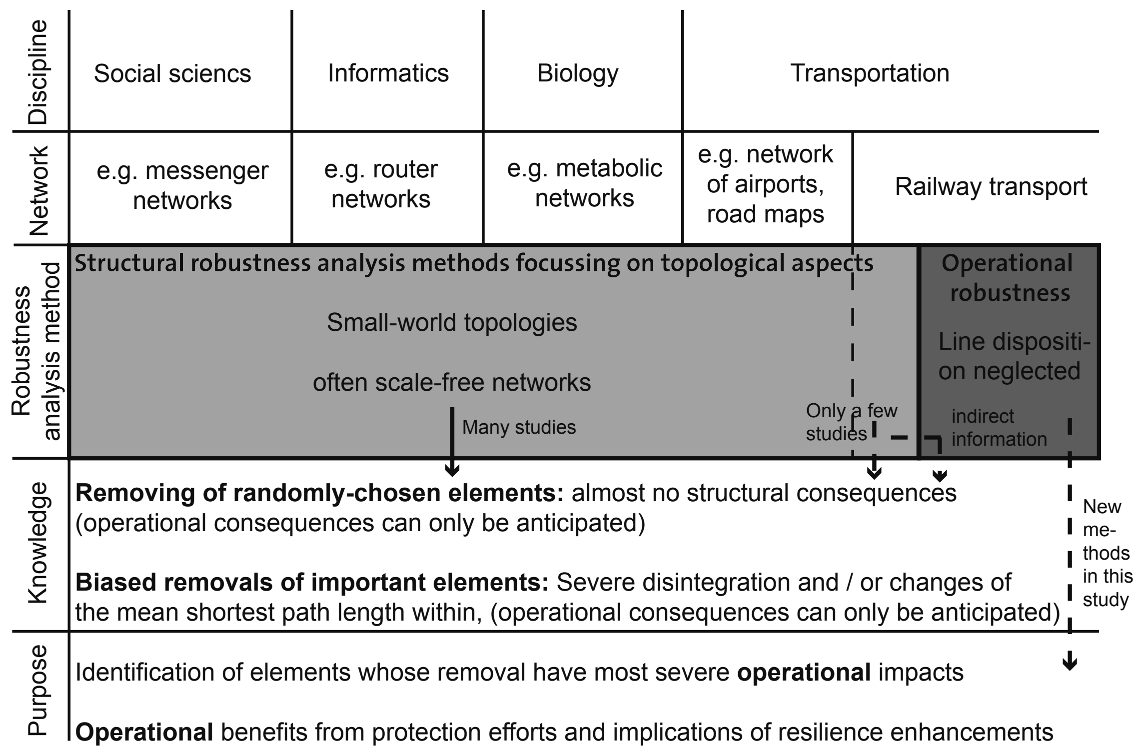
Analysing the robustness is of major importance for many large man-made systems, especially for critical infrastructures. Structural robustness information was enforced in various scientific disciplines including informatics, biology, engineering, medicine or social sciences. Though being the representations of very different systems, it was found that most analysed networks share the same topological features such that many of them belong to the set of scale-free networks. For networks of this type, much knowledge about the (structural) robustness is available. However, for railway networks operational aspects and requirements such as link capacities and line path restrictions have to be regarded such that a pure topology analysis of railway networks is not sufficient for entirely assessing their robustness. Instead of shortest path connections, trains travel along specific line paths and cannot always be arbitrarily rerouted. Instead, the original line path has to be maximally maintained in degraded operation and capacity thresholds of rerouting alternatives have to be considered.

Systems and networks with scale-free topologies were successfully shown to have to following structural robustness characteristics: On the one hand, these networks are highly robust against the removal of randomly chosen nodes. Non-biased removal strategies may for instance represent the impacts of natural hazards on the integrity of a network. Robust in this context means that the networks are likely to remain in a single large connected component such that the average shortest path lengths within it are almost not changed. The distribution of flows is not significantly affected and the performance of the analysed systems remains high even if many nodes are successively removed at choice.

On the other hand, biased removal strategies focussing on important nodes (for instance high-degree nodes or nodes that are contained in many shortest path connections) disintegrate scale-free networks very fast, i.e. even if only a very few nodes are removed. Biased node removals may mimic malicious behaviours such as terroristic attacks.

Chapter 2 introduces scale-free networks and shows how it can be determined that topologies belong to this network type. If railway networks are of scale-free nature, then at least some of the existing procedures and methods can be applied to approach the robustness of railway networks, i.e. the structural robustness can be assessed by existing methods. However, for simulating the consequences of threatening events on railway operation, new methods have to be developed that allow to calculate degraded operation states and to assess the operational robustness. Both, the structural and operational analysis results for railway networks are compared, which allows determining to which extent both coincide and in which cases they significantly deviate. It will be determined for which nodes it is sufficient to calculate the structural impacts, i.e. the consequences on network integrity such that the operational consequences can be anticipated. For instance, it may be possible to deduce whether primarily lines have to be truncated or rerouting is still possible. On the contrary, nodes are likely to exist whose removal has severe operational consequences but whose structural impacts are much less significant. The purpose of this study in the context of analysing systems respectively their network representations is illustrated in Figure 2.

Figure 2 Purpose of the study in the context of system analysis in various disciplines



1.4.2 Approach and steps

For assessing the robustness of railway networks, a simulation tool is evaluated and implemented that allows the manipulation of networks, i.e. removing nodes and links from the represented structures. These removals simulate the impacts of severe hazardous events that are in the scope of the study. Both, the structural and operational consequences of the removals are calculated and quantified in order to express the amount of impacts in a quantitative way. This means that degraded networks are calculated with existing procedures for the structural robustness and with new developed ones for determining degraded operation states that shall approximate the dispositive efforts in real-world situations.

On a general level, the study contains the following major working steps that are also illustrated in Figure 3:

Literature review: Existing resilience analysis methods are reviewed that are widely used for assessing the structural robustness of networks and critical infrastructures

Large amount of knowledge is available for simulating the ability of networks to withstand severe perturbations, but always focussing on the network structure. Flows are typically distributed along shortest path connections and the consequences of removing nodes and links on network integrity and the shortest path connections within the largest component are quantified. For assessing the impacts of threatening events on railway operation the existing methods are not sufficient since public transport lines do not necessarily follow shortest path connection but pre-defined specific line paths in both, planned and degraded operation.

Modelling phase: An appropriate representation of railway networks has to be evaluated that allows assessing the impacts of threatening events on railway operation. Beside the infrastructure topology other subsystems are included that may cause removals of stations and tracks, such as the failure of control or energy devices.

In reference to the European Directive 2008/57/EC [EU, 2008a], the following railway subsystems are represented and integrated in a multi-level representation of railway networks such that the robustness can be measured: the *Infrastructure* subsystem, the *Traffic Operation and Management* subsystem, the *Control-command and Signalling* subsystem and the *Energy* subsystem. In comparison with existing robustness studies of critical infrastructures, this study includes operational data such as line path restrictions and capacity limitations of the edges. Multiple two-dimensional networks are integrated into a multi-level representation of railway networks.

Evaluation, Implementation: A software tool is implemented that is suitable to calculate the structural and operational robustness of railway networks. The main steps are the formalisation of dispositive actions that are taken for establishing degraded operation states (truncation of lines or rerouting) and a method to quantify the amount of the degradation of railway operation due to node and link removals.

A robustness analysis tool is implemented in the *R* software environment [Crawley, 2008] that allows the manipulation of railway networks and to calculate the structural and operational impacts by rerouting or truncating lines traversing failing infrastructure elements. Robustness analysis methods are included that allow to quantify the amount of degradation of specific single or multiple removals. This means that multiple scenarios can be simulated and compared such that it is possible to identify the most critical elements within railway networks and to find bottlenecks in degraded operation offering essential rerouting alternatives. The tool provides information about the impacts of threatening events and visualises the calculated results.

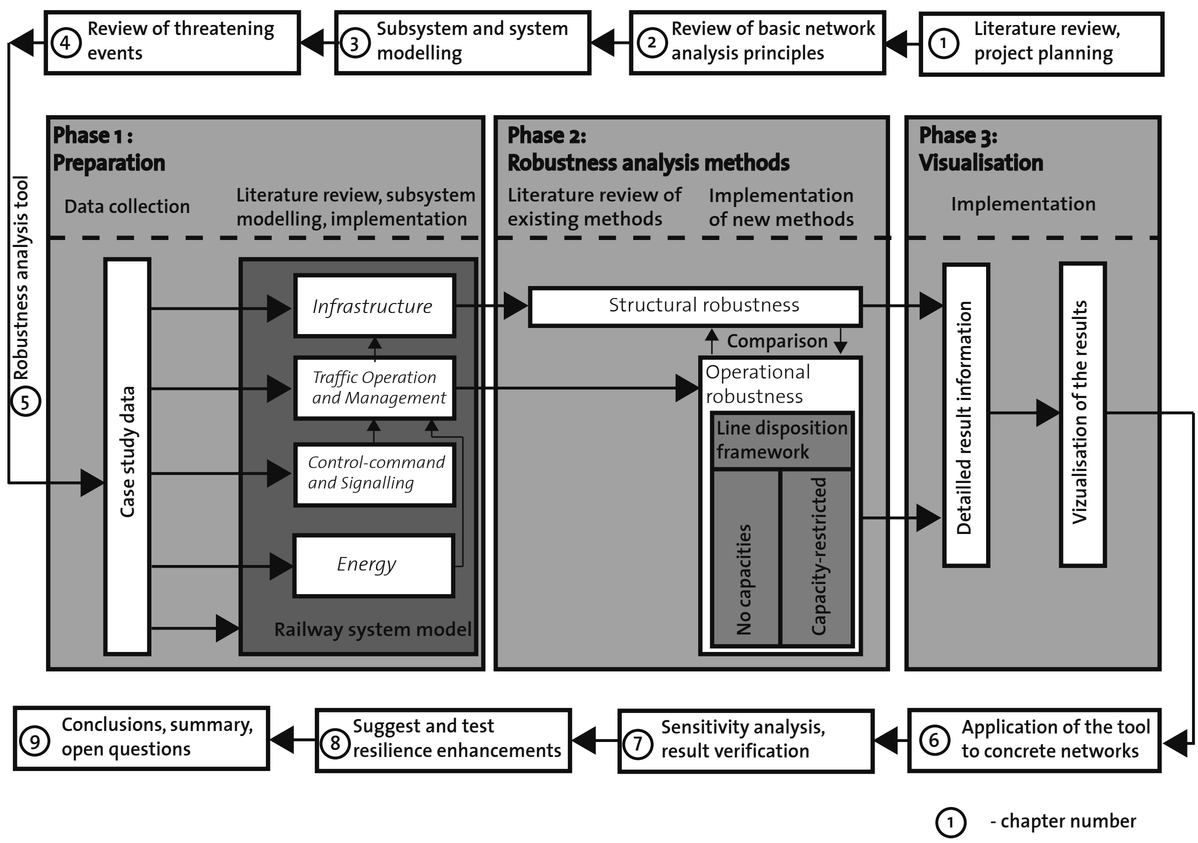
Application, Calculation: The structural and operational robustness of concrete railway networks is analysed. This illustrates the application areas and functionalities of the tool and supports a deeper understanding of the robustness of railway networks.

The implemented tool is applied to several railway networks, i.e. the Swiss railway network (standard gauge) and the Zurich tramway network in the years 2006 and 2025. The structural and operational robustness of these networks are calculated and the results are compared. Concrete case studies are included in a sensitivity analysis showing how the tool calculates degraded operational states. The simulation results are compared with real-world dispatching solutions of the transport operators to verify the model.

Interpretation and summary of the results: The main results of assessing the structural and operational robustness of railway networks are summarized that are provided by applying the implemented simulation tool. The results for the structural robustness of railway networks provided by existing methods and those gained by the developed new procedures for the operational robustness are compared to determine how the position of a removed node in the topology influences the kind and the amount of dispositive actions.

The main insights gained by applying the implemented simulation tool are summarized such that statements about the resilience of railway systems as critical infrastructures can be formulated. The contributions of the developed procedures to extending the current knowledge are highlighted and the strengths and limitations of the evaluated methodology are described.

Figure 3 Illustration of proceedings, contents and applied methods of the study



1.4.3 Contents

The document is organized as shown in Table 1 following the proceedings as displayed in Figure 3: Chapter 1 summarizes the motivation, the hypotheses, the goals of the study and the applied methods and gives an introduction to the study. Chapters 2 – 5 describe the fundamentals for the evaluation of the developed methodology, starting with introducing basic concepts from the field of network theory (chapter 2). A suitable way for sub-dividing the railway system according to European Directive 2008/57/EC [EU, 2008a] is presented in chapter 3. For each considered subsystem, is described how it can be represented. Chapter 4 summarizes natural, technical or social hazards and lists other events threatening railway systems. This means that the events are identified that may cause the removal of nodes and links as simulated in the robustness analysis tool.

Chapter 5 describes how to quantitatively assess the impacts of threatening events in a robustness analysis tool that is implemented in *R*. This tool is used for quantifying the structural and operational consequences of network manipulations and calculates degraded operation states mimicking real-world dispositive efforts. In chapter 6 the tool is applied to three case study networks, representing the *Swiss railway* network (standard gauge), the *Zurich tramway 2006* network and the *Zurich tramway 2025* network.

Chapter 7 contains a sensitivity analysis of the results and shows in detail how the tool calculates degraded operation states. For concrete cases, the calculated results are compared with real-world dispatching solutions. Chapter 8 shows how the robustness of railway networks can be improved and quantifies the benefits of three concrete measures applied to the analysed networks. Chapter 9 summarizes the results and shows the limitations of the evaluated methodology and states how the tool can be extended in further research projects.

Table 1 Structure of the document

Step	Contents	Comments	Chapter
Introduction	Motivation, hypotheses, goals, methods, contents	Introduction to goals, applied methods and purpose of the study	1
Fundamentals	Network theory basics	Introduction of basic topology measures for assessing the structure of networks, introduction of different network types	2
	Railway subsystems	Sub-division of railway systems, their representation and integration into a multi-level network of railway systems	3
	Events threatening railway networks	Collection of natural, technical, social and other events threatening railway networks, i.e. events simulated by removing network elements	4
	Modelling fundamentals	Description of the evaluated methodology and its implementation in *R*	5
Application	Robustness analysis results for concrete networks	Application of the methodology to several railway networks, calculation and comparison of results	6
Sensitivity analysis and model verification	Model verification and case scenarios	Sensitivity analysis and verification of the applicability of the tool, comparison of the solutions with real-world dispositive actions	7
Robustness enhancements	Suggest and test measures for robustness improvements	Collection of potential robustness enhancements, quantify the benefits gained for concrete cases, verify that the tool can be used to prioritize investment and enhancement efforts	8
Conclusions and summary	Conclusions	Summary, possible adapatations, extensions and limitations of the methodology, SWOT analysis	9
Bibliography			10
Glossary			11
Appendix			12

2 Network theory basics

2.1 Overview

2.1.1 Introduction

Contents of this chapter

«The vulnerability of modern infrastructures stems from their network structure […]» [Schneider et al., 2011]. The analysis of networks hence is an interdisciplinary field relevant in many scientific disciplines including biology, sociology, medicine, informatics and mathematics. Network theory gives powerful tools for systematically analysing network structures and the routing of units within it. Networks can be manipulated and the consequences can be measured giving useful information about the resiliencies of networks. This chapter introduces basic network analysis methods, as needed in this study. There are various introducing books including [Newman, 2010], which was extensively used for this study. Table 2 shows how this chapter is structured.

Table 2 Structure and contents of chapter 2

Section	Contents	Purpose
2.1	Overview	Network examples, introduction to network analysis
2.2	Representation of systems and subsystems	Representing topologies and flows within transport networks
2.3	Structural measures for network analysis	Basic topology measures for analysing topologies, basis for assessing the robustness of networks as performed in this study
2.4	Two-dimensional network models	Introduction of commonly-used two-dimensional network models for representing real-world systems and their robustness characteristics
2.5	Multi-level networks	Integrating multiple two-dimensional network models into multi-level networks, *system-of-systems* architecture
2.6	Summary	Conclusions

Real-world systems and graph theory

According to [Newman, 2010], *«a network is a simplified representation that reduces a system to an abstract structure capturing only the basics of connection patterns and little else. […] This certainly has its disadvantages but it has advantages as well.»* Network theory gives useful methods for systematically analysing the topological structure of systems. Since often it is not possible to directly measure how critical infrastructures react if hazardous events occur, complex systems are represented as networks that can be manipulated for assessing and deducing its robustness. The networks contain a set of vertices that are connected if two nodes interact. In social networks two nodes interact if two individuals know each other. For railway networks, nodes typically represent stations that are connected if there are tracks between them. Further examples of networks representing complex systems are summarized in Table 3.

Table 3 Examples for network representing real-world systems

Network	Nodes	Edges
Citation network	Article, patent, legal case	Citation
Food web	Species	Predation
Friendship network	Individual	Friendship relation
Internet	Computer, router	Cable, W-LAN connection
Metabolic network	Metabolite	Metabolic reaction
Power grid	Power plant, substation	Transmission line
World-Wide Web	Web-page	Hyperlink
Railways	Station	Tracks between two adjacent stations

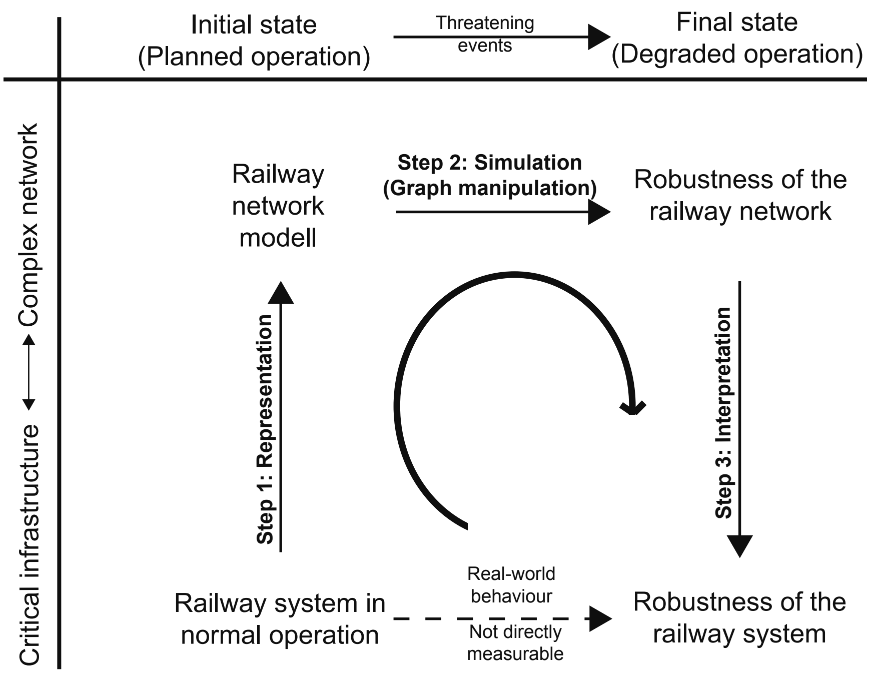
Source: [Newman, 2010]

Network theory provides powerful methods that *«can make mathematical predictions about processes taking place on networks»*. This study uses existing methods for analysing the structural robustness of railway networks and develops new ones integrating operational data and requirements. The connection between real-world systems and mathematical networks are schematically illustrated in Figure 4. Typically, measuring quantities such as the disaster robustness is not immediately possible:

«An experimental study of disasters under real world conditions is almost impossible, and therefore, mathematical and computer models are often very helpful tools to extend human knowledge.» [Buzna et al., 2008].

This is due to several reasons including the very long time it takes to record enough data. Hence, an appropriate representation of the analysed real-world system is modelled and implemented in the *modelling phase* or *representation phase*. In the *simulation phase*, specific calculations are performed suitable for assessing quantities of interest. In the *interpretation phase* the results are interpreted with respect to the analysed real-world system. This shall enable stakeholders to assess the impacts of events threatening railway transport, which is beneficial for instance for improving the preparedness of the system before such events occur.

Figure 4 General purpose of modelling complex systems



Since in the representation phase it is not possible to exactly model all aspects of a real-world system, simplifications have to be made. Table 4 describes those made in this study.

Table 4 Limitations of representing complex systems

Problem	Description	In this study
Structural complexity	Complex, tangled topologies	Limited network sizes
Network evolution	Topology can change over time	Topologies are assumed to be static and given, i.e. there is no network growth or edge rewiring, robustness enhancements can be tested
Connection diversity	Links can have different weights, directions and signs	Directions and signs are not considered. Links have different weights and capacities
Dynamical complexity	Nodes can be nonlinear dynamical systems	Binary states for all nodes and links: stations or tracks may either be blockaded or in service
Node diversity	Nodes can be of different type	Capacity restrictions, some stations offer turnaround alternatives
Meta-complication	Various complications can influence each other	Not considered
Level of detail	Microscopic or macroscopic modelling possible	Macroscopic graph representation

Source: based on [Strogatz, 2001]

Structural analysis results for transport networks

[Newman, 2010] gives a brief overview of the efforts of structurally analysing transportation networks. The author summarizes that only *«a moderate amount»* of network research has been done so far, primarily focussing on networks of road maps, airline routes and rail topologies. The author adds that the main task in the representation of railway networks is not the structure itself but the compilation of data *«may be laborious»*. Nodes most often represent the geographic locations of stations or road intersections that are linked by routes or roads.

The robustness of critical infrastructures and their network representations is a matter of great importance also for railway networks: most studies analyse the topological consequences of removing randomly or strategically chosen nodes, the latter ones focussing on the *most important stations*. Often, *important* nodes are those connected to many other nodes, i.e. high-degree ones. The robustness is measured by the ability of a graph to sustain in a large connected component, which mostly depends on the existence of cascading events [Amaral et al., 2004a].

One of the most important early transportation network research was published in [Kansky, 1963]. This study analysed the relation between transport network topologies and external conditions such as the economic developments. Much more research was done in the 1970s analysing airways, railways or road transport networks. All these studies focussed on the structure of a network rather than the distribution of flows within: Specific, pre-defined line paths and dispositive efforts in case of perturbations were not considered.

[Sen et al., 2003] proposed a model for analysing railway network operation focussing on the number of activities of changing lines when travelling in the network: A bipartite graph is drawn, containing two distinct node sets, on the one hand the stations and on the other one the lines operated in the network. Each station is connected to a line in which line path it is contained. The analysis of shortest path length for instance allows determining the number of different trains a customer uses for the journey (see also section 5.6).

[Murray-Tuite et al., 2004] presents a method for identifying the most vulnerable links within transport networks using O-D-matrices, cost-restricted flows and ideas from game theory. However, the vulnerability and disruption measures do not consider line dispatching.

2.2 Representation of systems

Real-world systems with non-trivial interactions between the system elements such as railways, power supply or social interactions are *complex systems. Complex networks* consisting of a finite set of network nodes and links represent them. The graphical representation (i.e. its visualisation) is usually referred to as *a graph*. Network theory aims to assess network characteristics by analysing the *structure of a network*, i.e. its layout or geometry. The consequences of events threatening railway networks can be assessed by manipulating these graphs, i.e. removing specific nodes and links and measuring the changes of specific parameters that are suitable for describing the network structure or the distribution of units within. This means, that for analysing the robustness of railway networks nodes representing stations or links representing tracks are removed and the changes of characteristic values such as the number of network in the largest connected component are measured. This quantity gives information about the number of stations that can still be reached in degraded state.

Representation of networks – Adjacency matrix

There are numerous ways of representing network structures in mathematical terms [Newman, 2010]. A graph can for instance be described by denoting the number of nodes present in the network combined with a complete list of all edges in the network, the *edge list.* Denoting the number of stations that is contained in the railway network and a complete list of all direct connections between any two stations can for instance represent the infrastructure of railway networks.

Another widely used method for representing networks is to use *adjacency matrices*. For each node, a row and a column is contained in the adjacency matrix. Its entries indicate for all potential pair of vertices whether they interact or not. For non-weighted networks, in which all nodes and links are equally important, the entries of the adjacency matrix are either zero, if two nodes do not interact (they are not connected), or one, if there is interaction between them. In the latter case, an edge connects the two corresponding nodes. Railway networks can be represented by adjacency matrices where a value of 1 denotes that two stations are connected by tracks and all other values are zero, i.e.:

$$A = \{a_{i,j}\} = \begin{cases} 1, if\ station\ i\ and\ station\ j\ are\ directly\ connected \\ 0, if\ there\ is\ no\ such\ direct\ connection \end{cases}$$

In some cases it is useful to consider tie strengths such that the entries of the adjacency matrix can take any non-negative value, depending on the quantity used for expressing the *amount of interaction* between a specific pair of nodes. In this study, various weights are considered such as the lengths of the tracks between two stations, the time needed for travelling along them or capacity utilizations or thresholds.

The following assumptions and simplifications are made for representing railway networks in this study, which in the vast majority of cases does not contradict the real-world situation:

- **Tracks always connect two different stations:** A node cannot be linked to itself, i.e. there are no *self-edges* present in the network. This implies that the entries of the adjacency matrix on its diagonal are always zero.

- **Tracks can be traversed in both directions:** All links are directionless and can be used in both directions. This implies that the adjacency matrix is symmetric.

- **The number of parallel tracks is considered in capacity limitations:** In this study, all stations are connected by a single link. *Multi-edges* are not considered. However, the number of parallel tracks is indirectly considered in the capacity limitations of links. Hence, for non-weighted railway networks, the adjacency matrix contains only binary values being either zero if there is no edge between two nodes or one in the other case. In the weighted case, the entry of the adjacency matrix may for instance denote the maximal number of trains that can travel along a link per day depending on the number of parallel tracks and various other factors.

Representation of networks – Paths and shortest path lengths

A *path* is *«any sequence of vertices such that every consecutive pair of vertices in the sequence is connected by an edge in the network»* [Newman, 2010]. For public transport networks, line paths determine sequences of stations successively served by a line. The *length of a path* either simply counts the number of traversed links or the sum of their weights, for instance their track lengths. A *circuit* is a path for which the first and the last node coincide. A graph without any circuit is called a *tree*. Railway networks may contain such circuits containing for instance dead-end stations. In this case, the calculation of the length of the path has to count the length of the link also multiple times. For the Swiss railway network, lines serving Lucerne for instance traverse the link between *Gütsch* and *Lucerne* multiple times.

A path between two vertices with minimal length is called *geodesic path* or *shortest path*. Shortest paths do not have to be unique; there may be multiple ones. Since only non-negative weights are assumed, geodesic paths are always non-intersecting, which means that no link is contained in the shortest path more than once. Hence, shortest path calculations will never consider passing dead-end stations contradicting the routing of trains in real-world situations. The length of geodesic paths is referred to as the *geodesic distance*, *shortest distance* or *shortest path length* and is defined as the sum of the weights of the included links. Depending on the considered weight, for railway networks, the shortest path length may for instance denote the number of intermediate stations, the sum of the track of all traversed links, the minimal time it takes to travel between two stations or the minimal number of times, a customer has to change lines on the journey (referring to [Sen et al., 2003]).

If there is no path between a specific pair of vertices, the geodesic distance is often considered to have infinite length. The mean value of geodesic lengths between any pair of nodes is called the *average shortest path length.* Basic structural measures relating to shortest paths are *diameter, closeness or eccentricity of a network* that are introduced in section 2.3.

2.2.2 Macroscopic graph representation

As [Caimi, 2009] states, *«the aggregated representation of a railway track topology by the macroscopic topology is not straightforward. The decision whether a certain part of the track topology should be represented by a node depends on the desired level of precision of the macroscopic level.»* In the evaluated methodology railway networks are represented such nodes represent stations and points, where trains can travel in different directions. Not necessarily all stations have to be modelled; stops of minor importance for railway operation are not modelled in a macroscopic model, but are included in the connection between major stations. In the macroscopic representation all stations are black boxes hiding the exact track topology within station areas.

2.3 Basic structural measures for network analysis

2.3.1 Introduction

The network topology has major impacts on the distribution of units within it and the robustness. Various measures are used for quantitatively assessing the topology of networks and for quantifying the impacts of removing nodes by comparing the pre-disaster values with those in degraded states. Table 5 provides an overview of the measures widely used in this study.

Table 5 Set of structural measures assessing the topological features of networks

Measures	Purpose	Application for transport networks
Size measures: Number of nodes and links, edge density	Description of the network size	Number of served stations, number of links, sum of all track lengths…
Connectivity measures: Connectivity, number of clusters, cluster size	Network integrity, number of nodes in the largest connected component	Can all stations be reached? Number of stations in largest connected component
Distance measures: Mean shortest path length, diameter, eccentricity	Average shortest path length between any pair of nodes, (mean) maximal shortest path length	Number of changing processes between two stations, trip duration, trip length in [km]…
Centrality measures: Degree, BC, closeness	Identification of most important elements	Stations contained in many shortest path connections or connected with many other ones
Regularity measures: Transitivity, Clustering coefficients	Measure for network density and transitivity (presence of triangles)	Availability of rerouting alternatives
Efficiency measures: Efficiency, costs	Measure for the density and efficiency of a network	Effectiveness of the distances in the network relative to direct tunnels between all pairs of stations

2.3.2 Size measures

For non-weighted networks, the size of a network is simply described by the number of nodes and links present in the network. Both quantities can be combined to determine the *edge density*, calculated as the mean number of edges that a node is connected with. These measures give first information about the size and the connectivity of a network. For weighted networks, the size of a network can also be expressed by the sum of all edge weights, for instance the total lengths of all available tracks. Size measures such as the number of nodes in the largest connected component in the degraded network play important roles for describing the dynamics of network integrity (for instance in [Schneider et al., 2011]).

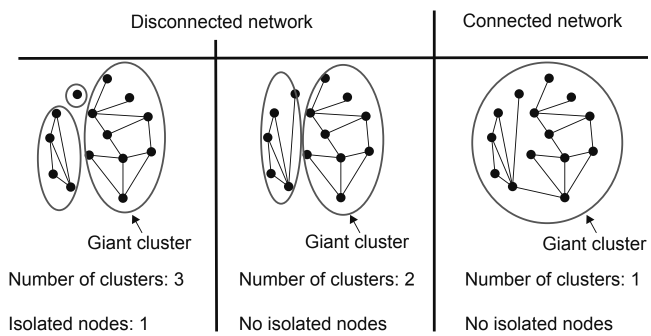
2.3.3 Connectivity measures

Connectivity measures analyse the integrity of a network, i.e. the number of connected clusters or the number of nodes connected in each of them. Networks with identical network size values can have very different connectivity.

Components, isolated nodes and clusters

A *component* in a network is a connected subset of nodes. Networks may contain multiple separated components. Single nodes that are not connected to any other network node are called *isolated nodes*. In Figure 5, the illustrated network initially consists of three components including an isolated node (example on the left side). Isolated nodes have zero degree and cannot be reached from any other node. For railway networks, isolated nodes are not traversed by any lines and hence not operated. The network on the right consists of a single component and is called *connected*. A *cluster* is a component in the degraded network, i.e. the network from where at least a single node or link is removed. The cluster containing the majority of nodes is referred to as the *giant cluster*.

Figure 5 Illustration of the connectedness of networks



Connectivity

A network is called *connected*, if it consists of a single component. Railway networks often are connected in regular operation such that all stations can be reached from one another. Hazardous events may affect network integrity such that the removal of a link or node causes the number of components to increase. The component containing the majority of network nodes is usually referred to as the *largest component* in planned state or *giant cluster* in degraded state. Removing a node or a link from the network can turn connected networks into disconnected ones, such that the number of components increases and the giant cluster size decreases. In this study, the relative size of the giant cluster compared with the number of nodes in the non-disturbed network is widely used for characterizing the impacts of threatening events on network integrity.

2.3.4 Distance measures

Shortest path length

A *path* is a sequence of subsequent nodes identifying how to get from a specific node to another one. There may be numerous paths between a pair of vertices, i.e. paths do not have to be unique. However, their lengths can significantly differ. The path with minimal length is called the *shortest path* or *geodesic path*. Its length is called *shortest path length* or *geodesic distance*. Also the shortest path not necessarily has to be unique. In non-weighted networks, the shortest path length simply counts the number of hops between two nodes. In weighted ones, the shortest path length can for instance measure the minimal travel time between two stations. The *average shortest path length* denotes the mean value of all shortest path lengths between any pair of nodes. Shortest path lengths can be useful for determining how fast flows can be routed through a network [Newman, 2001]. Many networks show surprisingly small values of the average shortest path length, even if they contain a many nodes.

For disconnected networks, not all the geodesic paths actually exist. By convention, one often says that the shortest path lengths between vertices in different components are of infinite length [Newman, 2010]. This implies that also the average shortest paths length becomes infinite, which is not very handsome for calculating distance parameters in network fragmentation processes. Then it might be helpful to follow a different approach: For all node pairs within a connected component, geodesic paths exist such that the average shortest path length is finite. For disconnected networks, sometimes the average shortest path lengths of all components are averaged, weighted according to the number of nodes within a component.

For characterizing the consequences of removing nodes or elements from railway networks, measuring the changes of the average shortest path lengths within the giant cluster compared to pre-disaster level gives valuable information about the degradation of routing flows.

Diameter

The *diameter* of a network is the largest shortest path distance between any two nodes in the network [Kooij et al., 2009]. For disconnected networks, only the paths that actually exist may be considered. The diameter is a less informative value than the average shortest path length since the diameter only expresses the shortest path length for a single pair of nodes lying far away from each other.

Eccentricity

The *eccentricity of a single node* is defined as the largest shortest path length to any other network node [Kooij et al., 2009]. The *network eccentricity* is the mean value of all node eccentricities. Eccentricity values can be used for identifying the most central nodes in a network, the nodes with small eccentricity values.

2.3.5 Centrality measures

Overview

In network analysis, much effort was made analysing the relations between the importance of vertices and their network position. There are various ways of defining the importance of a node including the degree centrality, eigenvector centrality, PageRank, closeness centrality and the betweenness [Newman, 2010]. This study focuses on degree centrality, closeness centrality and the betweenness as defined in [Jansen, 1999]:

- The degree centrality assumes that those nodes are highly central and thus important, who are linked to a large number of other nodes.
- The closeness centrality assumes that nodes with small distances to all other network nodes are more important than nodes with longer distances to all other network nodes.
- The betweenness centrality states that the most important nodes are contained in the majority of shortest geodesic paths in the network.

Node-degrees and their distribution

The *degree* of a vertex is a basic, widely used centrality measure. It is defined as the number of links that a node is incident with. Node degrees larger than two are observed for stations where lines cross. Node having degree 2 are typically traversed stations, i.e. stations with one incoming and one outgoing link. Nodes with degree 1 represent stations serving as endpoints of lines not intersecting with other routes. Formally, the degree of a node is defined as:

$$Degree(i) = \sum_{j \in V} a_{i,j} \text{ where } a_{i,j} \text{ are the entries of the adjacency matrix}$$

The *node-degree distribution function* P(k) *«gives the probability that a randomly selected node has exactly k edges»* [Albert et al., 2002]. The curve of the node degree distribution function significantly varies between different network types. There are networks where all nodes have the same degree (*regular networks*), while in others the degree of the network nodes has a large range. *The density function (or just distribution) of node degrees* measures the fraction of nodes with a certain degree. For transport networks, node-degree distributions sharply peak at degree 2, reflecting sequential structures [Zio et al., 2008]. For many real-world systems it was found that high-degree nodes are likely to exist with positive probability, even if the vast majority of them is of very low degree. The degree-distribution of many real-world networks was found to decay as a straight line in a doubly logarithmically scaled plot indicating a power-law, which has immediate consequences on the robustness of a network as described in section 2.4. Scale-free networks have a degree distribution of the following form:

$$P(k) \sim k^{-\gamma}$$

The shape of the degree-distribution function gives information about the type of the network, for instance whether a network belongs to the set of scale-free networks. For several network types, information about the robustness is available.

Closeness

The *closeness value* is measured as the average distance of a node to all other nodes. The node with the minimal closeness value is called the *most central node*. Nodes with low closeness values have short mean distances to all other nodes and might have more influence on other nodes [Newman, 2010]. Closeness centrality plays an important for the analysis of social networks. The main disadvantage is that in most cases the range of closeness value is small, scaling logarithmically with the number of nodes present in the network. As a consequence, the order of node importance can significantly change when the topology is changed.

Another drawback also mentioned in [Newman, 2010]: In networks containing multiple components, the closeness value becomes infinite. As for the average shortest path lengths, calculating the closeness values for the different components and combine these values is an appropriate way for getting finite values. However, this induces further problems since the nodes within small components then get smaller closeness values. A better solution hence often is to define closeness as the average of the inverse distances.

Betweenness centrality (BC)

While the degree centrality and closeness centrality analyse the node's connectivity, the betweenness measures *«how much falls "between" others»* [Newman, 2010]. Nodes with small degree centrality can have high betweenness centrality values. The concept of betweenness centrality was introduced in [Anthonisse, 1971] and [Freeman, 1977]. *«The BC counts the fraction of shortest paths between any two nodes that go through a node»* [Barthélemy, 2004]. The betweenness can be calculated for both nodes and edges and gives information about the influence of a node over the flows in the network. The BC values of nodes are typically widely ranged and scale linearly with the number of network nodes.

If the shortest path between two nodes is not unique, each path gets the inverse of the number of these paths. High BC-values indicate that a node is contained in many shortest paths. The removal of a node with high betweenness will severely lengthen the average shortest path length in the network [Barthélemy, 2004] and supports the network defragmentation.

Beside the absolute BC-value of a node, the relative betweenness can be calculated, i.e. the fraction of shortest paths in which a node (or link) is contained:

$$Relative\ BC\ (node) = \frac{BC(node)}{\frac{n(n-1)}{2}}$$

2.3.6 Regularity measures

Transitivity

The transitivity measures the regularity of a network: High values indicate that two neighbours of a node have a high probability of being connected themselves. Transitivity often is measured by the so-called *clustering coefficient* with values ranged between zero (two neighbouring nodes of a node are never connected) and one (all nodes are adjacent).

Two different definitions of the clustering coefficient are commonly used (see Figure 6 for an example). One common way of defining the clustering coefficient is to count the number of triangles in a graph (multiplied by 3 since each triangle is counted three times) divided by the number of all connected triples in the network [Newman, 2010], i.e.

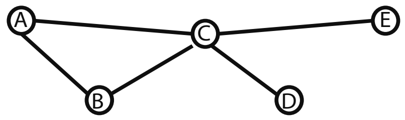
$$C^1(network) = \frac{3 * Number\ of\ triangles}{Number\ of\ connected\ node\ triples}$$

Another possibility is to define the *local clustering coefficient* denoted C^2 was defined in [Watts et al., 1998]. When quantifying the transitivity in this study, the following formula is used:

$$C^2(node) = \frac{Number\ of\ links\ between\ neighbours\ of\ a\ node}{Number\ of\ potential\ edges\ between\ them}$$

The clustering coefficient for the whole network is then defined as the average value of the local clustering coefficients of all network nodes.

Figure 6 Example for quantifying the transitivity of networks



Clustering Coefficient 1 = 3x1/8 = 3/8 = 0.375
Clustering Coefficient 2 = 1/5 x (1+1+1/6+0+0) = 0.433

Source: based on [Ziegler, 2010]

Transitivity is a local property expressing the probability of local rerouting possibilities. A high clustering coefficient is a common feature of many real-world networks: Many real networks form cliques, i.e. elements in which all the nodes are connected with each other and have hidden orders and hierarchies [Caldarelli et al., 2004], especially in social networks.

According to [Newman, 2010], the clustering coefficient for social networks is often ranged between 0.1 and 0.2, but also values of about 0.6 are possible for dense networks. For biological and technological networks, the transitivity value is often significantly smaller (≈0.01).

Assortative mixing by degree

The concept of *assortative mixing* analyses the tendency of vertices to connect to similar others and measures for instance the correlation of the degrees of adjacent vertices. The assortative mixing of network vertices is measured by the *assortative coefficient*. *Disassortative* mixing quantifies to which extent nodes connect to others with different characteristics.

Assortative mixing can be quantified using a covariance measure as described in [Newman, 2010]. The measure gives positive values in case of assortative mixing and negative for disassortative ones. The calculated values lie in the range between -1 and +1 and take value 0 if the endpoints of an edge are not correlated with the respect to the quantity of interest. Networks with high values of assortative mixing are called *assortative networks*; those with values close to -1 are referred to as *disassortative networks.*

A widely used concept in the field of network analysis is the *assortative mixing by degree* measuring whether and to which extent the degree of adjacent nodes correlate. The value of the assortative mixing by degree gives information about the network structure: In assortative networks both, high-degree nodes and low-degree ones tend to stick together such that a dense core region is likely to exist surrounded by a periphery [Newman, 2010]. This is often observed for social networks (see also Table 7). Networks with small disassortativity by degree indicate star-like topologies. Formally, the assortativity mixing by degree r is quantified by

$$r = \frac{\sum_{i,j}\left(a_{i,j} - {k_i k_j}/{2m}\right) * k_i k_j}{\sum_{i,j}\left(k_i \delta_{i,j} - {k_i k_j}/{2m}\right) * k_i k_j}$$

, where:

$a_{i,j} - entry\ of\ the\ adjacency\ matrix\ (either\ 0\ or\ 1)$

$k_i - degree\ of\ vertex\ i$

$m - Number\ of\ edges\ in\ the\ network$

$\delta_{i,j} - Kronecker\ delta, i.e.\ \delta_{i,j} = \begin{cases} 1, if\ i = j \\ 0, if\ i \neq j \end{cases}$

The authors of [Sen et al., 2003] states: *«It has been observed that social networks are assortative and technological and biological networks are disassortative.»* They calculated the assortative mixing by degree for the Indian railway network, finding a value of -0.033.

2.3.7 Efficiency measures

Global and local efficiency

The concept of network efficiency was introduced in [Latora et al., 2001] and applied to Boston's metro system in [Latora et al., 2002]. Network efficiency measures how effective information is passed in the network by comparing the airline distances between two stations with the average shortest path lengths within the network. The efficiency of a network is defined for both weighted and non-weighted networks. Efficiency accounts for the physical properties of systems and complements classical topology measures [Zio et al., 2008]. The global efficiency can be calculated according to the following formula:

$$E_{global}(network) = {\frac{1}{n*(n-1)} * \sum_{i \neq j} \frac{1}{d_{i,j}}} \Big/ {\frac{1}{n*(n-1)} * \sum_{i \neq j} \frac{1}{l_{i,j}}}$$

, where:

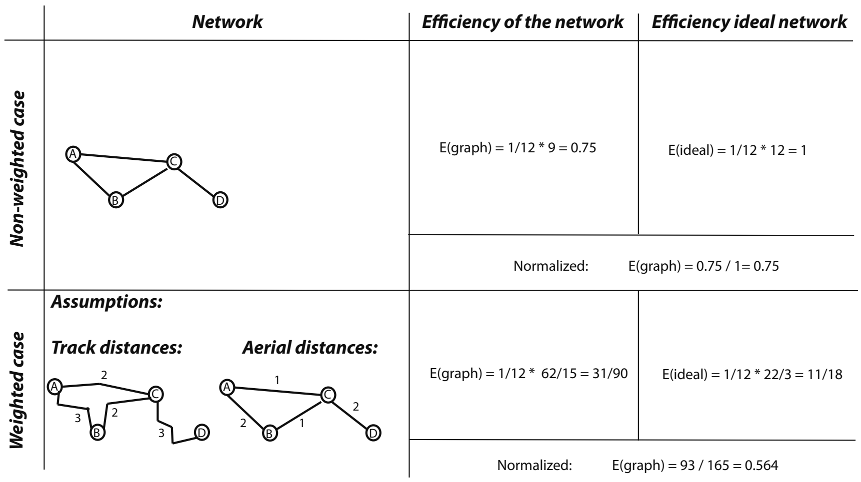
$n - Number\ of\ nodes\ in\ the\ network,$

$d_{i,j} - shortest\ path\ length\ between\ nodes\ i\ and\ j\ (may\ be\ infinite)$

$l_{i,j} - aerial\ distance\ between\ nodes\ i\ and\ j$

The first term denotes the network efficiency that is normalized by the second term, i.e. the network efficiency in an ideal network. Ideal in this context means that there are direct tunnels between any pair of stations. This normalization guarantees that the efficiency of the network is ranged in the interval [0;1] while large values are measured for highly efficient and dense networks. Figure 7 presents an example for which the network efficiency is calculated.

Figure 7 Example for quantifying the efficiency of networks



The local efficiency, i.e. the efficiency of a single vertex can be determined by applying the formula to the subgraph of the neighbouring nodes of it. For single vertices, a high value of the local efficiency indicates a high failure tolerance while small values indicate a poor local efficiency [Latora et al., 2002]. The authors found that many real-world networks including the Boston metro network and other underground networks are very efficient on the global level but poorly efficient on the local one. This implies that the networks are efficiently connected, but are not fault-tolerant on the local level such that the removal of single nodes drastically affects network integrity and the routing of trains.

Costs

The concept of *costs* is based on the idea that the efficiency of a network increases with an increasing number of network links [Latora et al., 2002]. For transport systems, adding new links induce immense costs such that the number of links is comparatively low, for instance in comparison with the density of social networks. Costs are quantified as follows:

$$Costs = \frac{\sum_{i \neq j} a_{i,j} l_{i,j}}{\sum_{i \neq j} l_{i,j}}$$

, where:

$$a_{i,j} - entry\ of\ the\ adjacency\ matrix\ (either\ 0\ or\ 1)$$
$$l_{i,j} - aerial\ distance\ between\ nodes\ i\ and\ j$$

For many transportation networks, even for small cost values high efficiency values are reached indicating that high global efficiencies are realized with low-cost network designs [Latora et al., 2002]. Table 6 shows the results of quantifying the efficiency and costs of transport networks. In the example illustrated in Figure 7, the value of the costs is 0.75 for the non-weighted network and 0.4 for the weighted case.

Table 6 Efficiency and cost values of real-world networks presented in [Latora et al., 2002]

Network	Network efficiency	Local efficiency	Costs
Boston underground metro	0.63	0.03	0.002
Boston underground metro and bus service	0.72	0.46	0.004

2.3.8 Structural properties of other real-world networks

[Newman, 2010] presents an overview of topological key values measured for various networks (Table 7). For all networks, the mean average geodesic distance is small relative to the size of the networks. Simultaneously, most networks have high clustering coefficients indicating small-world characters of the networks; a feature observed for many real-world networks.

While social networks often are assortative networks, the technological and biological networks are disassortatively mixed, such that high-degree nodes tend to connect to low-degree ones and vice versa. This verifies the results gained in [Sen et al., 2003] and indicates star-like topologies [Newman, 2010] without a sharp demarcation of a core and periphery region. On the contrary, social networks may be assortative networks with a core region that can be distinguished from the periphery. The core region contains high-degree nodes that tend to connect to others while the periphery contains the majority of low-degree vertices.

Table 7 Topological key parameters for real-world networks from [Newman, 2010]

	Network	Nodes	Links	Mean degree	Mean distance	Exponent γ	C^1	C^2	Assortative mixing by degree
Social	Film actors[2]	449’913	25’516’482	113.43	3.48	2.3	0.2	0.78	0.208
	Company directors[3]	7’673	55’392	14.44	4.6	-	0.59	0.88	0.276
	Email messages[4]	59’812	86’300	1.44	4.95	1.5 / 2.0	-	0.16	-
	Student dating[5]	573	477	1.66	16.01	-	0.005	0.001	-0.029
Technological	Power grid[6]	4’941	6’594	2.67	18.99	-	0.10	0.08	-0.003
	Train routes[7]	587	19’603	66.79	2.16	-	-	0.69	-0.033
	Software packages[8]	1’439	1’723	1.20	2.42	1.6 / 1.4	0.070	0.082	-0.016
	Electronic circuits[9]	24’097	53’248	4.34	11.05	3.0	0.010	0.030	-0.154
Biological	Metabolic network[10]	765	3’686	9.64	2.56	2.2	0.090	0.67	-0.240
	Protein interactions[11]	2’115	2’240	2.12	6.80	2.4	0.072	0.071	-0.156
	Marine food web[12]	134	598	4.46	2.05	-	0.16	0.23	-0.263
	Freshwater food web[13]	92	997	10.84	1.90	-	0.20	0.087	-0.326

[2] Reference: [Amaral et al., 2000], [Watts et al., 1998], degree distribution follows a power law

[3] Reference: [Davis et al., 2003], [Newman et al., 2001]

[4] Reference: [Ebel et al., 2002], degree distribution follows a power law, in and out-degree are distinguished

[5] Reference: [Bearman et al., 2004]

[6] Reference: [Watts et al., 1998]

[7] Reference: [Sen et al., 2003]

[8] Reference: [Newman, 2003], degree distribution follows a power law, in and out-degree are distinguished

[9] Reference: [Ferrer i Cancho et al., 2001], degree distribution follows a power law

[10] Reference: [Jeong et al., 2000], degree distribution follows a power law

[11] Reference: [Jeong et al., 2001], degree distribution follows a power law

[12] Reference: [Huxham et al., 1996]

[13] Reference: [Martinez, 1991]

2.4 Two-dimensional network models

2.4.1 Introduction

The section introduces basic networks types sharing some of the topological features of real-world networks, such that the simulation and analysis results are suitable to explain and predict the consequences of node or link removals on the topologies.

Representing real world systems is one of the main subjects of graph theory and has its origins in the 18th century with Leonhard Euler analysing small graphs with regular structures and limited network sizes. In times without the availability of large databases and in which analysis could not yet performed with computers, real-world systems were typically modelled as *simple networks,* i.e. networks with very regular structures. The set of simple networks includes regular lattices, stars, ring structures and full graphs. Regular networks and their topological characteristics are explained in Section 2.4.2

With the availability of computing machines in the last century, graph theory has become more statistical and algorithmic [Albert et al., 2002]. Since many complex systems at first glance seem to have a completely random structure, real-world systems were often represented as *random* graphs. These are networks with randomly placed edges between the nodes. The study of random graphs was enforced between 1950 and 1960 with the influential work of Erdös and Rényi. Since then, studying random graphs has developed into *«one of the mainstays of modern discrete mathematics, and has produced a prodigious number of results, many of them highly ingenious, describing statistical properties of graphs, such as distributions of component sizes, existence and size of a giant component, and typical vertex-vertex distances.»* [Newman et al, 2001].

With the computerization of data acquisition, i.e. the availability of large databases and other incitements such as increased computing power, the boundaries between different scientific disciplines broke down. It became more important to understand the behaviours of systems as a whole. The analysis of the real-world systems revealed that neither simple networks nor random networks sufficiently represent the structure of many real-world systems, in which some nodes were found to attract much more edges than others. This means that dominating nodes are present. In fact, real-world systems have topologies with characteristics lying between those of completely regular and random networks:

- Heavy-tail in node-degree distribution (i.e. non-peaked degree distributions)
- High clustering coefficients (i.e. high degree of interconnectedness)

- Hierarchical structure (like in tree graphs for instance)
- Community structures are present (i.e. highly interconnected clusters with only very few edges between different clusters)

Small-world networks are in the focus of recent interest because they appear to circumvent many of the limitations of either random networks or regular lattices when representing complex systems [Amaral et al., 2000]. Many small-worlds were found to have node-degree distribution functions and hence belong to the set of scale-free networks (section 2.4.4).

2.4.2 Regular networks

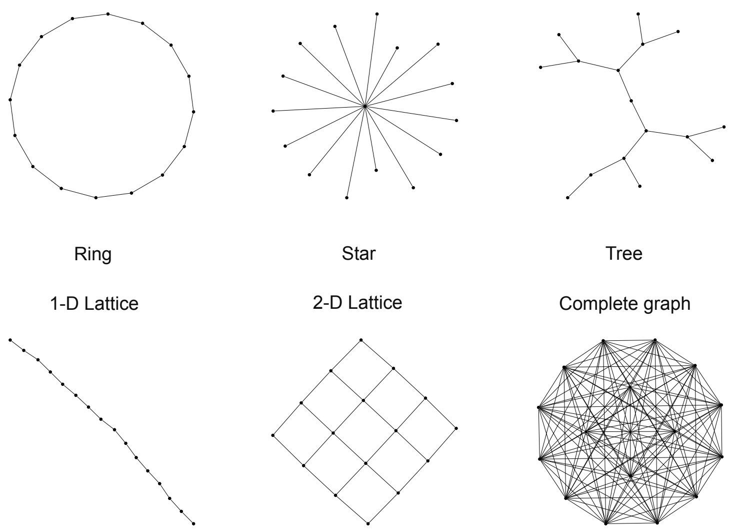
Regular networks are basic network types that were firstly used for modelling systems of small size. They have regular structures such that all parts of a network approximately share the same topological features. The set of regular networks contains ring structures, lattices, star topologies or full graphs (see Figure 8). In ring structures, each node is connected to its nearest neighbours. In star networks, all nodes are linked with a central node. In complete graphs or full networks every node is connected with every other node. These networks are maximally efficient on both, the local and network level. However, high costs are induced which is not realistic for modelling railway systems since each connection induces immense financial costs. Obviously, every type of regular network has specific robustness characteristics. In star topologies for instance, the removal of the central node totally disintegrates the network such that all remaining nodes become isolated and no units can be routed through the topology. Hence, these networks are maximally sensitive towards the deletion of this central node. Biased removal strategies focussing on the most important node promptly disintegrate the network structure. If all nodes are likely to be removed with equal probability, however, is likely to delete another node than the central one; the integrity of the remaining network is almost not affected such that the system can still be operated using the remaining nodes.

Even though regular networks are not suitable for representing entire transport systems it was found that at least on the local level regular structures may be present (Table 8).

Table 8 Types of regular networks and their applicability for representing transport systems

Network	Transport system
Ring	Isolated ring lines, e.g. for metro systems
Star	Regional airport networks or high-speed railway system in France (TGV)
Tree	Suitable for many urban railway systems
1-D lattice	Single transit lines
2-D lattice	Very dense transportation systems with changing possibilities at each station, for instance parts of Manhattan road map, Mainz bus systems, roads in the city centre of Mannheim
Complete graph	Only for cab systems and individual transport, very cost intensive

Figure 8 Examples of regular networks



2.4.3 Random networks

At first glance, many complex networks seem to be randomly connected. For this reason random graph theory is regularly used for studying complex networks [Albert et al., 2002]. Even though random networks are too random to describe the topological features of real complex systems [Goh et al., 2001], analysing their structural properties increases the understanding of processes and dynamics observed in complex real-world systems [Newman, 2010].

Random graph theory studies typical properties of random graphs that hold with high probability for graphs drawn from a certain distribution. There can be various different possible network realizations that are generated according to the following algorithms:

→ **Probability space:** Random graphs consisting of a specific number of nodes and randomly placed links can be derived by randomly choosing one realization among all the graphs containing exactly the specific number of nodes and links. The set of all these networks forms a probability space in which each realization is equally probable.

→ **Binomial model:** In a random graph consisting of a fixed number of nodes each node pair can be connected according to some specified connectivity probability.

The degree distribution of random graphs usually follows a Poisson distribution and is strongly peaked at the average node degree [Albert et al., 2002]. The average shortest path lengths of random networks are typically small (if the probability of randomly placing an edge is not too small) since long-range connections emerge. If the clustering coefficient is measured as the probability that two neighbours of a specified node are connected as well, this value equals the probability of randomly placing an edge between them. [Newman, 2010] states that the transitivity values for random networks differ sharply from those of real networks.

Error and attack tolerance

[Albert et al., 2002] analysed the structural consequences of removing multiple nodes from random networks according to either biased or non-biased strategies (left side of Figure 10). If nodes are removed randomly, i.e. all nodes have the same probability of being removed the giant cluster size decreases almost linearly (field a) approximating the x-axis. On the contrary, for the strategic node removals focussing on the high degree nodes a threshold value for the number of node removals exists, below which the curve follows those for the non-biased strategy. If the critical fraction is exceeded, the giant cluster size promptly drops down to zero. Also the average shortest path length within the giant cluster promptly drops down at the critical threshold (field c). For non-biased strategies, the average shortest path lengths in the giant cluster remains almost constant even for very large numbers of node removals.

In summarization, for small fractions of removed nodes, random networks remain in a large connected component. However, a critical fraction exists, above which the network promptly disintegrates if node are strategically removed (see also Figure 11).

2.4.4 Small-world networks

Motivation

Small-world networks recently are in the focus of interest because they circumvent many of the limitations of completely regular or random networks when representing real-world systems [Amaral et al., 2000], which have intermediate characteristics that lie between them:

Real-world networks have comparatively small average shortest path lengths (like random graphs) but with significantly larger clustering coefficients, indicating regular structures. Also the node-degree distribution of many real-world networks differs from those of regular or random graphs since *«for a large number of networks [...], the degree distribution has a power-law tail»* [Albert et al., 2002].

A network is called a *small-world network* by analogy of the small-world phenomenon that is popularly known as the six degrees of separation. The term *six degrees of separation* relates to an experiment conducted by Stanley Milgram examining the average shortest path length for social networks of people in the USA revealing that social contact networks have surprisingly small average shortest path lengths of about 6 persons [Milgram, 1967]. Modern studies of the small-world phenomenon confirmed these results. [Leskovec et al., 2007] analysed the social networks by statistically evaluating 30 Mia. Microsoft Messenger messages and concluded that the mean distance between two Internet users is 6.6 persons.

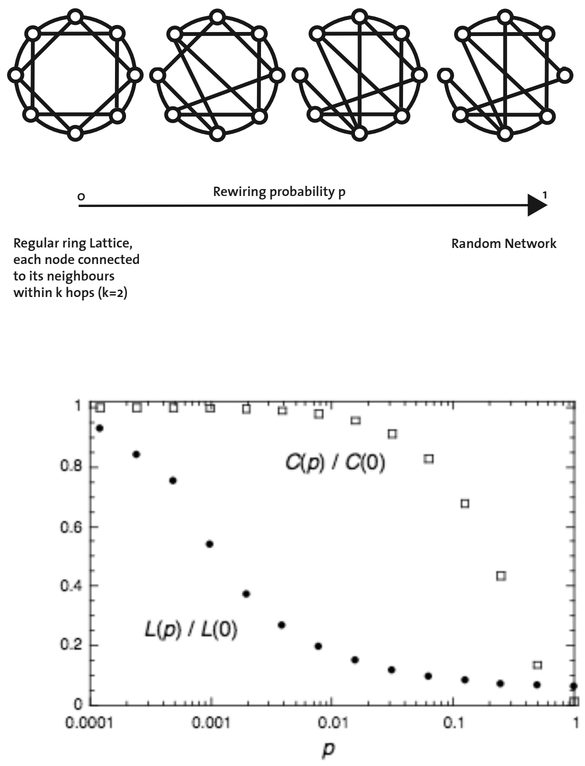
Watts – Strogatz model

The first successful attempt to generate graphs with high clustering coefficient and small average shortest path lengths was developed in 1998 by Duncan J. Watts and Steven Strogatz [Watts et al., 1998]. The authors introduced a method interpolating between random graphs and regular lattices by randomly rewiring some edges of a ring. Self-connections are not considered, neither are multi-edges. This rewiring transforms regular graphs into *small-worlds* in which the mean shortest path length is small (since long-range connection are likely to occur) and the clustering coefficient is high (due to the ring structure). The rewiring process is illustrated in Figure 9.

The upper part schematically shows how the regular ring structure turns into a network with complete random structure if the value of the rewiring probability p increases. The lower part of Figure 9 shows the corresponding dynamics of the average shortest path length in the present network L(p) relative to the initial shortest path length in the ring structure L(0). Also the values of the clustering coefficients of the rewired structure C(p) are shown for increasing rewiring probabilities relative to the ring structure C(0).

If the probability of rewiring edges increases, a transition phase occurs for which the clustering coefficient remains high (as in the ring structure) while the average shortest path length decreases significantly (as in random networks). This behaviour is due to the emergence of long-range connections. Both characteristics, small values of the average shortest path lengths and high clustering coefficients are typical for small-world networks. The diameter of small-world networks scales logarithmically with the number of nodes in the network [Amaral et al., 2000].

Figure 9 Construction of small-world networks according to Watts-Strogatz



Source: [Watts et al., 1998], p – rewiring probability, L(p) – average shortest path length for the family of randomly rewired graphs, C(p) – clustering coefficient for the family of randomly rewired graphs, L(0) - average shortest path length for the regular lattice, C(0) – clustering coefficient for the regular lattice

Even though the Watts-Strogatz model allows generating networks mimicking small average shortest path lengths and high transitivity values, the graphs still have node-degree distributions following a Poisson distribution, which does not hold for most real-world networks.

[Newman, 2010] states that the degree distribution *«has an unusual peaked shape with a lower cut-off, quite unlike the degree distribution (...) for real networks. In this respect, therefore, the small-world model does not mimic well the structure of networks in the real world.»*

Other disadvantages are the constant network sizes and the fact that the networks may become disconnected. [Newman et al., 1999] presented a modification of the Watts-Strogatz model by keeping the original edges and allowing self-connections which guarantees the connectivity. Constant network sizes means that it is not possible to model growth processes, i.e. the birth of new nodes such as the construction of new stations or additional tracks. However, many real-world systems have dynamic network sizes such that the number of nodes and links is constantly changing.

Barabasi-Albert model

These disadvantages were circumvented in the Barabasi-Albert model for generating small-world networks. In order to mimic the distribution of node-degrees observed for many real-world networks, [Barabasi et al., 1999] found two essential ingredients, network growth and *preferential attachment*. The latter one describes that during network growth processes, high-degree nodes are more likely to connect to new nodes than low-degree ones. This is also called the *rich-get-richer* principle. The result of a network generated according to the Watts-Strogatz model is a network with a node-degree distribution decaying as a power-law, i.e.

$$P(k) \sim k^{-\gamma} \; with \; \gamma = 3$$

The average shortest path length of networks generated according to the Barabasi-Albert model increases approximately logarithmically with the number of network nodes. Later generation models aim to circumvent the fixed value $\gamma = 3$, since for most real networks, the parameter was found to be between 1 and 4 (see Table 7). Other models also consider preferential attachment, but of a non-linear fashion. This generates small-world networks with scaling exponent γ larger than two. Another improvement in the modelling process is the consideration of an initial attractiveness, i.e. a positive probability of a new node to connect with an isolated node. Further extensions of the model consider adding new edges between existing nodes, edge rewiring, removal of existing edges or nodes and competition between the nodes, where each node has an intrinsic ability to compete for edges.

Copy model

Another generation model for small-worlds is the *copy model*, where a new node randomly selects an existing node and copies all of its edges. This also gives a small-world network with a degree distribution decaying as a power-law with $\gamma = 3$ [Goh et al., 2001].

2.4.5 Scale-free networks

Scale-free networks are small-world networks and have a node degree distribution following a power law, i.e. networks generated according to the Barabasi-Albert model. This is detected by straight lines when plotting the degree distributions using logarithmic scales and was observed in *«quite a few different networks»* [Newman, 2010], as shown in Table 7. The author adds that *«values in the range* $2 \leq \gamma \leq 3$ *are typical, although values slightly outside this range are possible and observed occasionally»*. While a true power law regime implies a straight line even for large node degrees, for many real-world network small fluctuations and deviations for very large node degrees. There are many reasons, while many real-world networks typically do not follow a straight line only for large degrees [Amaral et al., 2003]:

→ **Vertex aging:** Nodes can reduce activity and attract fewer edges than in younger ages.

→ **Consideration of costs for adding links and capacity limitations for additional nodes:** Considering costs for adding links and the capacity of a node limit the number of possible links to a certain node. In railway networks, the maximal number of links is small since all stations have limited spatial capacities such as the number of platforms or urban areas and new tracks and connections imply high financial costs.

→ **Limited information and access:** Even if adding links is free of costs, there may be constraints preventing the inclusion of edges [Amaral et al., 2004a]. Nodes may be divided into active and inactive ones. Active means still attract new nodes, while inactive ones do not.

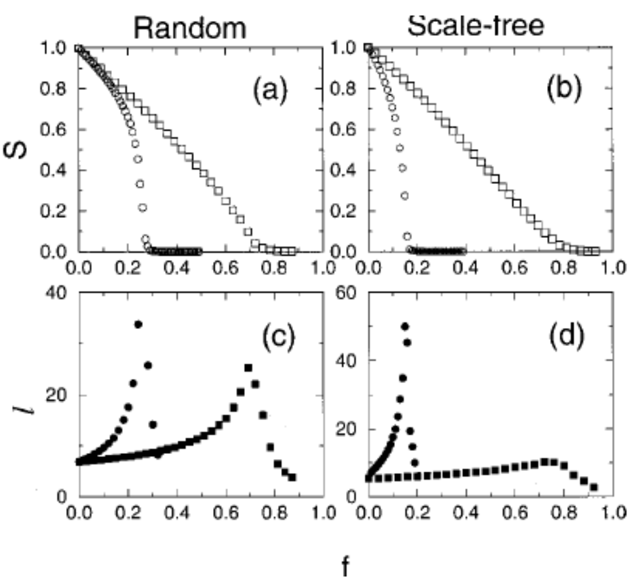
Nevertheless these networks are often referred to as scale-free networks. Deviations from the power law regime may also occur for small node degrees due to cut-off restrictions: In railway systems isolated nodes do not exist. Also the number of nodes with degree one, i.e. dead-end stations is not likely to be larger than traversed stations with two or more outgoing links.

Scale-free networks are further characterized by the statistical abundance of hub nodes, i.e. nodes that are connected with many others [EPJB, 2004]. Hub nodes play dominant roles in reducing the average shortest path distances between distant nodes [Goh et al., 2001] and are essential for efficient communication and navigability in network topologies. Obviously, removing the hub nodes strategically from the network has severe impacts on network integrity and the routing of flows within the structure.

«Scale-free networks are [...] paradoxically both, robust and fragile» [Newman, 2010] which was first found by [Albert et al., 2000]. The structural consequences of removing nodes from scale-free networks are shown in Figure 10 in the fields that are denoted field b and field d. If nodes are randomly removed (i.e. all nodes have equal probabilities of being removed), the giant cluster size decreases almost linearly indicating high robustness (field b). Even for very large fractions of removed nodes, the topology is likely to remain in a comparatively large connected component. This observation was also made for random networks (see field a). But removing the nodes following biased strategies focussing on the nodes having large degrees can totally disintegrate the network very fast, even for very small numbers of such removals. As for the random networks, a critical fraction of node removals exists, above which the network disintegrates into many small clusters of almost equivalent size. This critical fraction of node removals from scale-free networks is significantly below the critical fraction in random networks. Field d shows that the average shortest path lengths in the giant cluster remain almost constant for non-biased removal strategies. However, the average shortest path length increases very fast if the nodes having the largest degree are removed. In summarization, scale-free networks are highly robust against non-biased removal

strategies in which all nodes are removed with equal probability. Biased strategies remove the high degree nodes from the network, such that the network disintegrates very fast, even for a very small number of removed nodes. Scale-free networks are *«highly robust networks that can survive the failure of any number of their vertices»* [Newman, 2010].

Figure 10 Structural robustness of different network types against biased and non-biased removals of multiple nodes



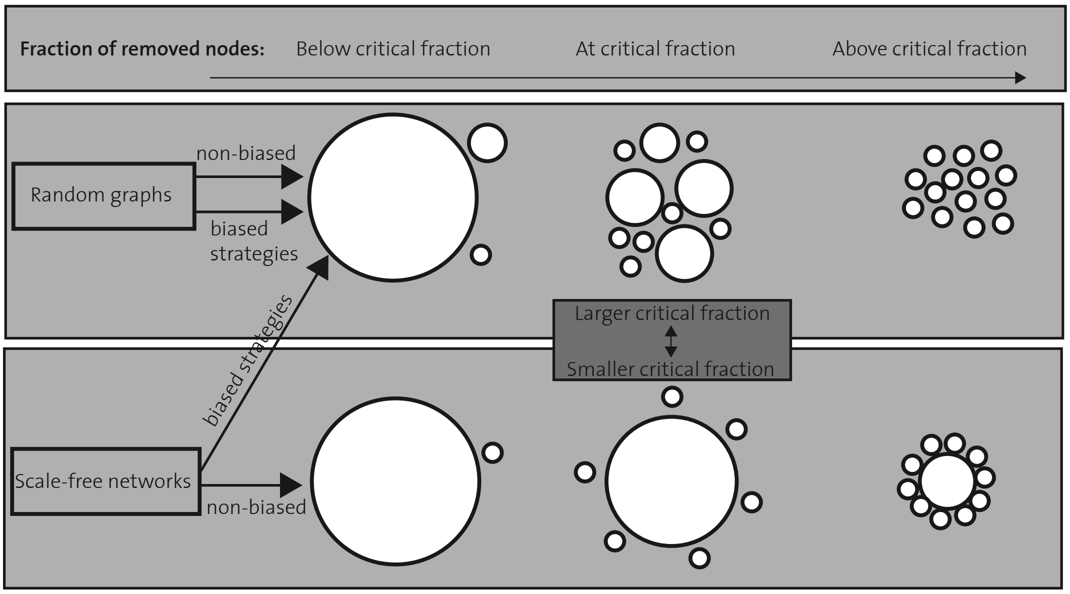
Source: [Albert et al., 2002], Boxes indicate removal of randomly chosen network nodes, Circles indicate that high-degree nodes are deleted from the network, S – Size of the largest connected component, l – Average shortest path length in the largest connected component, f – Fraction of removed network nodes

[Cohen et al., 2000] confirms these findings stating that the critical fraction of node removals from scale-free networks is significantly lower than those for random networks and depends on the scaling exponent: With higher values, the critical fraction of node deletions decreases.

The robustness of scale-free networks implies both, advantages and disadvantages: On the one hand, eliminating high-degree nodes promptly disintegrates the networks such that the system performance is significantly reduced. On the other hand, it is possible to remove only a small fraction of high-degree nodes to prevent failures from spreading within the entire topology: In social networks, passing a vaccination to only a very small number of individuals can eradicate viruses. Finding high-degree nodes, however, can be a difficult task (for instance in social networks) [Newman, 2010].

Figure 11 illustrates the fragmentation process for both, random graphs and scale-free networks: For random networks the biased and non-biased removal of nodes decompose the networks quite fast into small components. For scale-free networks, removing high-degree nodes shows quite similar characteristics. The critical threshold values are different, however. For non-biased removal strategies, successive break-offs of small components occur such that the giant cluster still comprises the majority of nodes.

Figure 11 Fragmentation process in random networks and scale-free networks



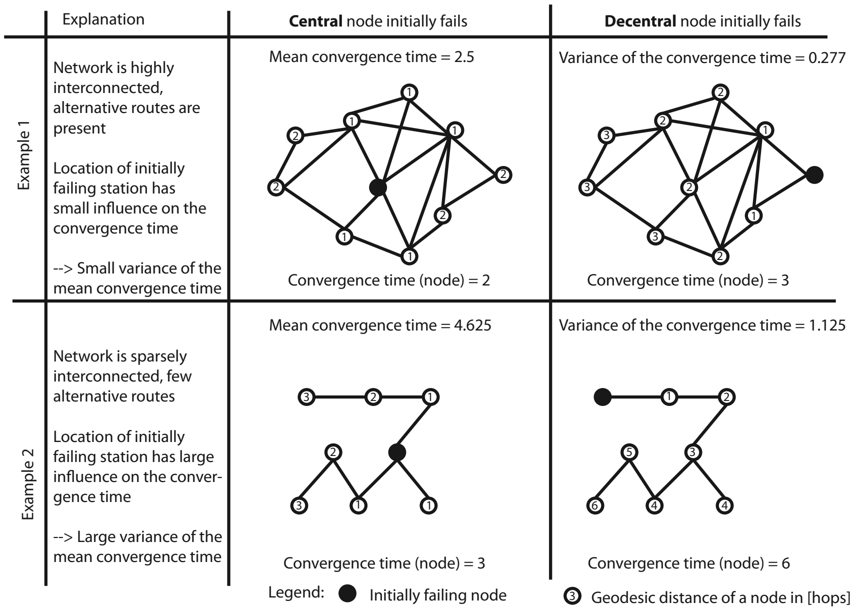
Source: relates to [Albert et al., 2000]

2.4.6 Application of epidemiological models

Epidemiological models are widely used for analysing the spreading of agents in social networks, for instance for simulating the spreading of rumours or viruses within populations. In virus dissemination models nodes are not removed, but are either *susceptible* or *infected* state. The latter one mimics situations, where nodes are cannot serve their intended function, while the first state refers to non-affected states. Each *infected* node can turn incident *susceptible* ones into *infected* state according to a specific infection probability, mimicking the spreading of failures or diseases. A wide variety of different models is available that provided much information about the spreading of viruses in populations and effective immunization strategies.

In this study, epidemiological models play a minor role: Setting the probability of infecting adjacent susceptible nodes to 1 is suitable for a detailed analysis of the network structure in the following way: The number of iterations until all nodes become infected is referred to as the *convergence time* and equals the eccentricity of the node. In this study, the convergence time is used for determining how the network position of the initially infected node by analysing and comparing the variance of the mean convergence time for different networks. Nodes with small convergence times have central positions in the network structure. Small variances of the convergence times indicate high regularities of the topology such that the location of the initially infected node has small influences on propagations (see Figure 12 for an example).

Figure 12 Illustration of applying virus dissemination models and the calculation of the convergence time



With exception of full networks (all nodes are connected to all other nodes), the position of the removed node in the network topology influences the *convergence time* (see Figure 12). The dependence of the mean convergence time on the position of the initially failing node can be assessed by comparing the variation coefficients, suitable to compare variances with different means. It is calculated as follows:

$$Coefficient\ of\ variation\ (Convergence\ time) = \frac{\sqrt[2]{Variance\ (Convergence\ time)}}{Mean\ (Convergence\ time)}$$

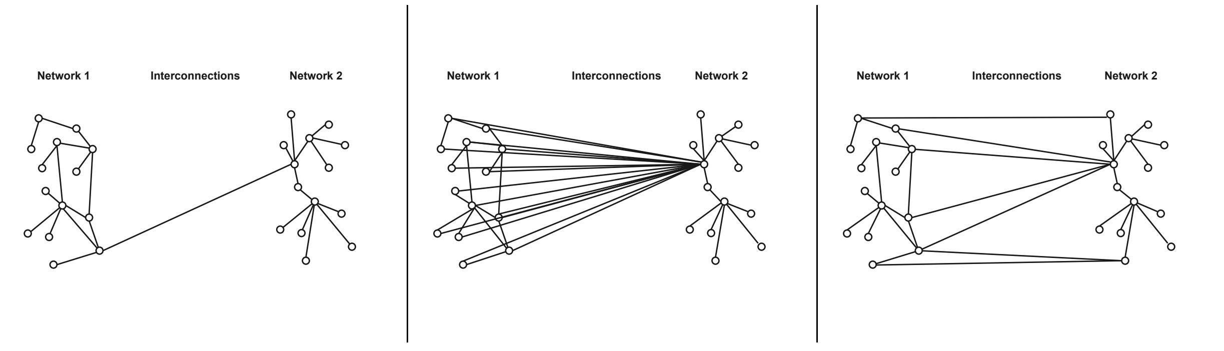
2.5 Multi-level networks

In this study, the railway infrastructure is modelled as a two-dimensional network that is assumed to have a scale-free topology. For this network, operational data is specified such as the routing of lines and the capacity thresholds of links, depending on the number of parallel tracks. This network is connected with other railway subsystems, i.e. the *Energy* subsystem and the *Control-command and Signalling* subsystem such that the failure of control devices and traction current units can be simulated. Hence, a multi-level representation of railway systems is built as described in chapter 3. This section gives a brief introduction about the structural characteristics of multi-level networks comprising several two-dimensional ones that are integrated. With other words, a very brief introduction shall be given about the structural characteristics of multi-level architectures if such information is available for the two-dimensional sub networks as schematically illustrated in Figure 13. If random networks are randomly connected, the overall network is still of random nature. Obviously, if the size of one of the interconnected subsystems is dominating those of the other ones, then the multi-level network approximately shares the topological features of the dominating sub-network (provided that the number of interconnections is not too large). If there is no dominating subsystem (in the number of network nodes an edges) the topological feature of the multi-level network needs further analysis as done in this study for the analysis of railway networks.

Generally, linking two nodes of separate sub-networks connects them. The main challenge for representing *systems of systems* is to determine the kind of interactions between the subsystems, i.e. to find the interacting nodes. Verifying that all interconnections are found and modelled is the most difficult task since they often are either not visible or not completely understood. Three types of interconnections can generally be distinguished:

- There are only two nodes interacting with each other. There is exactly one edge connects the two sub-networks (left part of Figure 13).
- A single node of a sub-network is connected with all others in the other sub-network. A failure of this node separates the interacting sub-networks (middle of Figure 13)
- There are at least two different nodes in each subsystem that interact with each other. Removing nodes or edges does not necessarily separate the connected subsystems (right part of Figure 13). In this study, this type of interconnection is considered.

Figure 13 Connecting two-dimensional networks into multi-level networks



3 Railway subsystems and their representation

3.1 Overview

This chapter shows how railway networks are modelled as multi-level architectures comprising multiple different railway subsystems. The subsystems are introduced and the modelling fundamentals are explained. Table 9 shows the structure of this chapter.

Table 9 Structure and contents of chapter 3

Section	Contents	Purpose
3.1	Overview	Contents of the chapter
3.2	Sub-division of the railway system	Introduction of railway subsystems, statements about the represented subsystems
3.3	*Infrastructure* subsystem	Definition and functions of the subsystem, its representation and data needed for the modelling process, representation example
3.4	*Traffic Operation and Management* subsystem	Definition and functions of the subsystem, its representation and data needed for the modelling process, representation example
3.5	*Control-command and Signalling* subsystem	Definition and functions of the subsystem, its representation and data needed for the modelling process, representation example
3.6	*Energy* subsystem	Definition and functions of the subsystem, its representation and data needed for the modelling process, representation example
3.7	Subsystem integration	Integration of the subsystem for assessing the robustness of railway networks, representation example

In this study, five steps can be distinguished for modelling railway networks (see Figure 14).

Step 1

Representation of the Infrastructure topology, manipulations of the infrastructure network for assessing the structural robustness, comparison of the results with other networks

The infrastructure topology is modelled, i.e. the track topology on a macroscopic level, where the nodes represent larger stations that are linked if there is a direct connection between them. The infrastructure is manipulated by removing nodes and the consequences on network integrity are measured, which allows an assessment of the structural robustness of railway networks. The results for the analysed railway networks (chapter 6) can be compared with the results gained for other networks displayed in Table 7.

For the analysed networks is checked whether the networks have scale-free topologies. If this can be verified, first information about the integrity dynamics in case of multiple node removals is available (see for instance Figure 11). This knowledge can be used for deducing for information about the impacts of node removals on railway operation: If nodes are removed randomly, the network sustains in a large giant cluster comprising the majority of nodes. Lines are likely to be truncated or rerouted but many stations are still operated. In case of biased removal strategies, it can be deduced that even for small numbers of node removals, the network disintegrates very fast into many very small clusters. Hence, it can be assumed that many lines are truncated or entirely put out of service. Railway operation is severely reduced and additional modes of transport have to be organized, such as bus shuttles in order to connect the isolated components.

Step 2

Specification of operational data for the utilization of the infrastructure network such as line paths, line frequencies, link capacities and turnaround alternatives in tramway networks → Operational robustness information is calculated that can be compared with the analysis results of the structural resiliencies

For the infrastructure network of the railway system, operational data is specified for simulating the operational consequences of node removals. The calculated results such as the identification of the nodes whose removals has the most severe impacts on railway operation may not necessarily coincide with the structural ones. With other words, it is assumed that nodes exists, whose removal has only slight impacts on network integrity but induces severe influence on railway operation. It may for instance happen that rerouting is not possible due to capacity limitations of the rerouting edges such that the network remains structurally connected but operationally disintegrates. For such analysis a method needs to be evaluated and implemented that is able to display the dispositive decisions of the operators, i.e. to calculate degraded operation states mimicking those in real-world situations (described in chapter 5).

Step 3

Display failures of control devices, add the level of Control-command and Signalling devices and simulate consequences of failures of signal boxes for railway operation

The failure of single or multiple control devices (signal boxes) can induce the non-availability of multiple stations and connections that are remotely controlled from it. This means that the removal of a signal box can cause the simultaneous removal of multiple infrastructure nodes and links that are controlled by this device. An additional level is added to the infrastructure network by specifying for each infrastructure element the controlling signal box.

Step 4

Display failures of traction current areas and power supplying substations, add the level of Energy devices and simulate failures of energy substations in railway networks

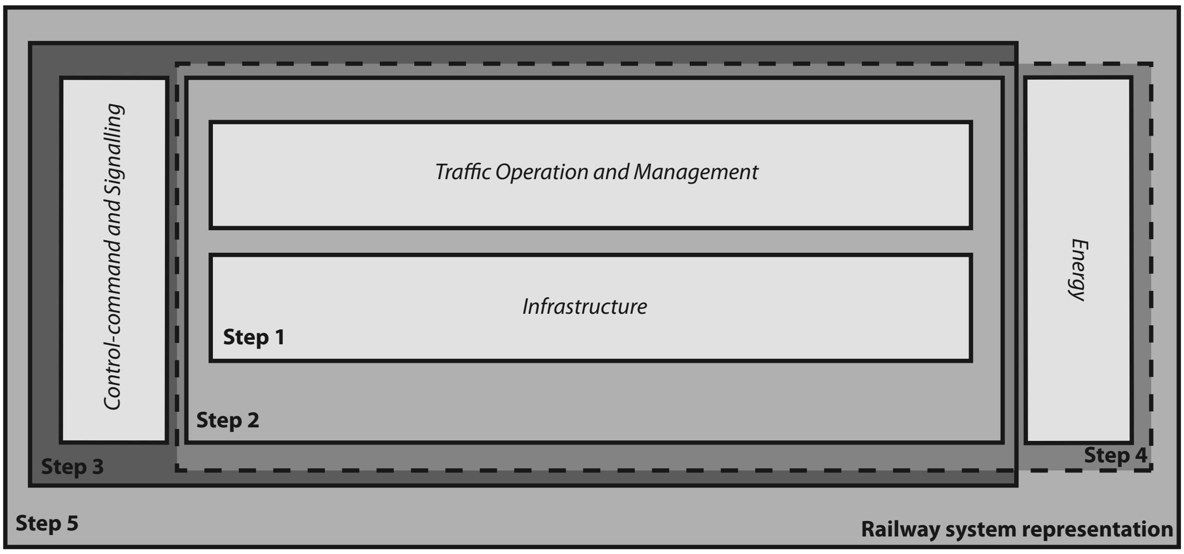
For each infrastructure element is specified from where traction energy is supplied. This allows the simulation of traction current area eliminations, i.e. the simultaneous removal of all infrastructure nodes and links that cannot longer be used for operation since no traction energy can be supplied. Degraded operation states are calculated and the impacts of such removals are quantified.

Step 5

Integral model of railway systems forming a multi-level representation of transport processes (train movements) that allows to simulate the failures of single or multiple topology elements, control boxes and traction current areas

Railway networks have a multi-level architecture that allows calculating degraded operational states if single or multiple infrastructure elements are removed. These removals can mimic the non-availability of single stations and tracks due to the occurrence of threatening events or multiple simultaneous ones, for instance the elements that are remotely controlled from a specific control device or that belong to a failing traction current area.

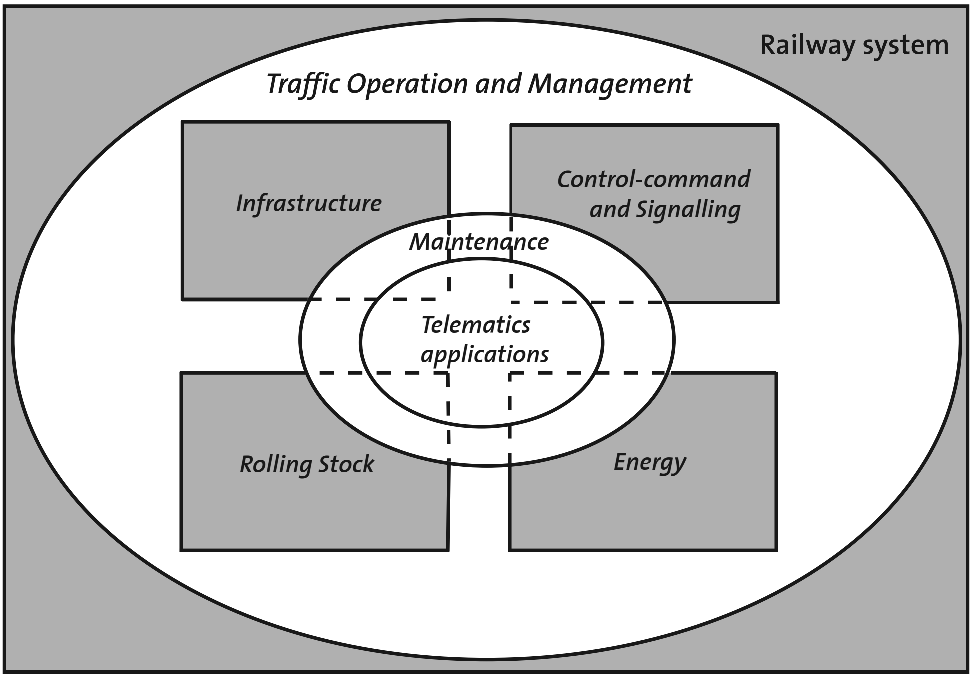
Figure 14 Major steps when representing railway networks as multi-level architectures



3.2 Subdivision of the railway system

Information about railway system architecture is for instance provided in official documents such as the European Directive on the interoperability of railway transport [EU, 2008a], according to which the system contains multiple subsystems with structural and functional importance (see Figure 15). Structural subsystems are illustrated as boxes, while circles indicate operational ones. The operational subsystems are connected with all structural ones since there are overlapping areas with all of them: All structural subsystems and the subsystem *Telematic applications* have to be maintained for instance.

Figure 15 Structural and operational subsystems of railway networks



Boxes show structural areas, circles represent functional ones

While *Infrastructure, Traffic Operation and Management, Control-command and Signalling, Rolling stock* and *Energy* are necessary requirements for providing railway transport, *Maintenance* and *Telematics applications* can be assumed to define transport quality, but do not threat its operability – at least in short-terms. Table 10 shows which subsystems are represented in this study for assessing the structural and operational robustness of railway networks.

Table 10 Interpretation and effects of subsystem failures for railway transport

Subsystem	Impact of subsystem failure	Immediate consequence of hazardous events	Represented?
Infrastructure	Potentially system-wide	Blockaded tracks and stations	✔
Traffic Operation and Management	Potentially system-wide	Dispositive measures such as rerouting or truncation of line paths, degraded operational state	✔
Control-command and Signalling	Potentially system-wide	Blockaded stations up to entire regions	✔
Energy	Potentially system-wide	Blockaded tracks up to entire regions	✔
Rolling stock	Subsystem-blockade improbable	Trains may be substituted	✗
Maintenance	Long-term consequences	Especially long-term consequences	✗
Telematics applications	Long-term consequences	Reduces transport quality and induce delays	✗

For all represented subsystems, Table 16 shows which elements are represented. In the following sections of this chapter each of the modelled subsystems is formally defined and it is shown how they are represented and integrated in a multi-level representation of the railway system in this study.

Table 11 Subdivision of the railway system on the macroscopic level

System	Subsystem	Represented subsystem elements and relevant data
Railway network	*Infrastructure*	Stations and tracks between them, geo coordinates of the stations
	Traffic Operation and Management	Specification of operational key data such as line paths, frequencies of the lines, track capacities, locations of turnaround points, turnaround times
	Control-command and Signalling	Control boxes, information from where stations are remotely controlled or whether they are locally operated
	Energy	Energy substations, traction current units, specification from where energy is distributed for the represented Infrastructure elements

3.3 *Infrastructure* subsystem

The *Infrastructure* is a structural railway subsystem comprising *«the track, points, engineering structures (bridges, tunnels, etc.), associated station infrastructure (platforms, zones of access […]), safety and protective equipment»* [EU, 2008a]. «*The topological structure of a network provides critical information regarding network vulnerability»* [Nagurney et al., 2010]. The *Infrastructure* subsystem is the basic topology structure for enabling railway transport and in the railway network model in this study. Tracks are necessary for physically guiding vehicles and for allowing them to run safely, i.e. they provide safety against derailment. Several specifications are required such as for distances between track centres, railhead profiles, minimal curve radiuses or track resistances [EU, 2008c]. In this sense, the represented *Infrastructure* subsystem elements are shown in Table 12. On the macroscopic level, the set of larger stations is modelled connected by links if there are tracks between the stations. Smaller system parts such as the rails itself, rail fastening systems, track sleepers, switches or crossings are not modelled.

Table 12 Constituents of the *Infrastructure* subsystem

Represented elements	**Elements that are not modelled**
Large stations → Nodes	Small stations, platforms, single switches
Track system → Links	Single or multiple tracks on the microscopic level

Nodes represent larger stations that are linked if there are tracks in between without other intermediate stops. Table 13 provides further information about the representation.

Table 13 Representation of the *Infrastructure* subsystem in this study

	Nodes	**Links**
Representation	Stations and intersections	Tracks between stations
Example	Oerlikon, Berne, Basel SBB…	Zurich HB – Thalwil, Geneva Airport – Geneva …
Data source	Official maps (see appendix), GIS databases, [Wägli, 1998]	
Attributes	Geo coordinates	Track lengths in km, time needed for traversing the links
Comments	Stations are modelled on macroscopic level	Single edges that can generally be used in both directions (multiple parallel track are considered by edge capacities)

The interfaces and connections of the *Infrastructure* subsystem with the other modelled ones are shown in Table 14.

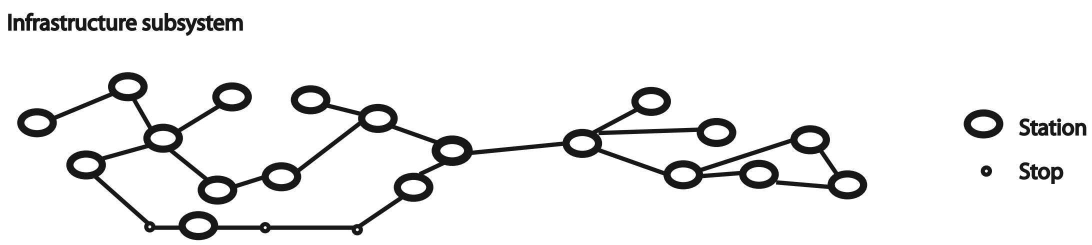
Table 14 Interfaces of the *Infrastructure* subsystem

Subsystem	Interfaces
Infrastructure	Switch, crossing, station, engineering structure (bridge, tunnel), distance between track centres
TOM	Documentations for the driver, documentation for degraded operation, detection equipment…
CCS	Use of electric or magnetic brakes, train detection systems…
Energy	Electrical tower, conductor rail, return circuit, vehicle and pantograph sway

Source: [EU, 2008c]

An illustration how to represent the *Infrastructure* subsystem is displayed in Figure 16. Small stops are not modelled here, but obviously, they easily could be integrated. For each station, its coordinates are specified in order to plot the modelled *Infrastructure* subsystems as two-dimensional maps as well as for calculating efficiency values as defined in section 2.3.7.

Figure 16 Representation of *Infrastructure* subsystems



Analysing the structural robustness of the *Infrastructure* subsystem does not consider operational aspects such as line routing and capacity restrictions of the links. However, removing nodes or edges decreases the giant cluster size and changes the average shortest path length within both providing hints about the induced operational consequences:

- **Network integrity:** Removing only a few nodes can reduce the giant cluster size drastically. Hence, the network disintegrates such that many stations cannot be reached any longer. In degraded operation, lines are likely to be truncated such that train paths are either split into distinct parts or line paths are shortened.

- **Network connectivity:** Even if the network sustains in a large giant cluster, the removal may significantly increase the average shortest path length within the giant cluster. In these cases train paths are likely to be rerouted if the rerouting alternative is not too long relative to the train path length in planned operation and has enough capacity left. This can significantly increase the train paths lengths such that additional vehicles are needed for maintaining the headway times of the corresponding line.

3.4 *Traffic Operation and Management* subsystem

According to [EU, 2008a], the *Traffic Operation and Management* subsystem contains *«the procedures and related equipment enabling a coherent operation of the different subsystems, both during normal and degraded operation»*. These procedures include for instance marshalling, train driving or traffic planning and management measures. The subsystem addresses to staff, trains and train operation principles and provides information about the routings of trains in both, spatial and temporal dimension, i.e. train paths [EU, 2008b]. *«Traffic Management must ensure the safe, efficient and punctual operation of the railway, including effective recovery from service disruption.»* [EU, 2006b]

For analysing the operational robustness of railway networks, train movements must also be represented together with the implemented infrastructure topology [Zhu, 2000]. The *Traffic Operation and Management* subsystem is strongly connected to the topology railway transport relies on. In this study, the subsystem is not represented as an additional, separate two-dimensional network but specifies all necessary information about the planned operational state of railway service and the conditions required for establishing a degraded one due to the occurrence of threatening events. In the implemented model the following information is used for representing railway networks:

- **Line paths:** For all represented lines, the line paths are specified denoting whether a line passes a station or not. Not necessarily all lines have to be represented if data is not available or their implementation takes much time and induces high costs. Increasing the number of represented lines also improves the quality of the calculated results.

- **Line frequencies:** For each represented line, the headway time between two courses is specified such that the capacity utilizations of nodes and links can be calculated.

- **Link capacities:** For each link, the maximal number of trains is specified that can use an element within a specific period of time depending for instance on the number of parallel tracks. Capacity utilization and threshold information are needed for determining whether rerouting alternatives have enough capacity left. In this study, the *theoretical capacity* and *operational capacity* are considered (introduced in [Anderhub et al., 2008]). The *theoretical capacity* denotes the maximal number of trains that can traverse an element per direction within a specific time interval. The *operational capacity* gives the corresponding reduced threshold value considering stability aspects and buffer times.

- **Turnaround alternatives:** Some stations offer turnaround possibilities in planned or degraded operation. For tramway networks, stations where vehicles may change the direction of travel such as turnaround loops are specified. For railways larger stations, i.e. the stops of long-distance trains are potential endpoints in degraded operation.

- **Turnaround times:** For each line the turnaround time at (potential) end points is specified, denoting the minimal time span for changing the direction of travel. This quantity is needed for calculating the turnaround time of a line and the number of vehicles needed for line service within the pre-defined frequency.

The interfaces of the *Traffic Operation and Management* subsystem with the other represented ones are shown in Table 15.

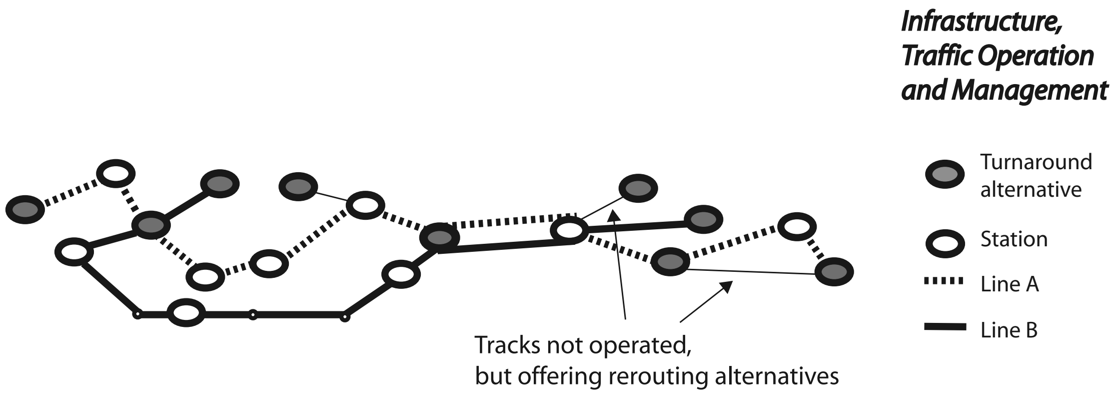
Table 15 Interfaces of the *Traffic Operation and Management* subsystem

Subsystem	Interfaces
Infra-structure	Documentations for the driver, documentation for degraded operation, detection equipment…
TOM	Data and operation management, data exchange, communication protocols…
CCS	Compatibility between recorded data, cryptographic keys for transmission, data transmission…
Energy	Control and supervision of the power network, electrical interference and harmonic emissions…

Source: [EU, 2006a], [EU, 2008c]

As already stated the *Traffic Operation and Management* subsystem is not a two-dimensional network itself, but is represented together with the *Infrastructure*. In the example illustrated in Figure 17 two lines run within the *Infrastructure* topology. There are links contained in both line paths and connections are present that are not traversed by the represented lines. These non-used tracks may be used in degraded operation for rerouting lines. Each potential turnaround station can be the endpoints of degraded line paths if lines have to be truncated.

Figure 17 Representation of *Traffic Operation and Management* subsystems



3.5 *Control-command and Signalling* subsystem

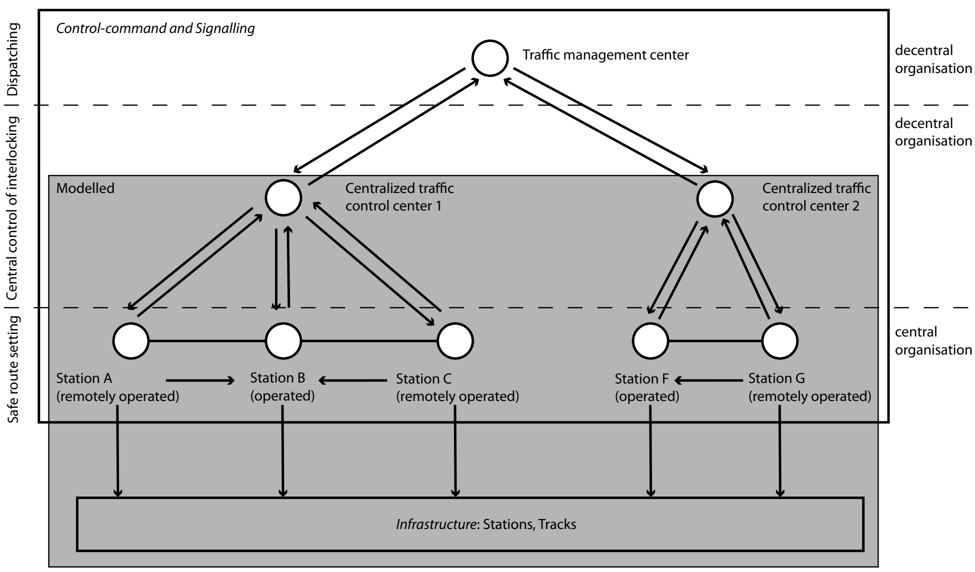
The *Control-command and Signalling* (CCS) subsystem contains the *«set of functions and their implementations which allow safe movement of trains»* [EU, 2006c]. These are the functions that are essential for the safe control of railway operation in normal and degraded operation state [EU, 2002]. The subsystem devices *«must enable trains to travel with a level of safety which corresponds to the objectives set for the network»* [EU, 2001a].

In order to fulfil its functions both trackside equipment and on-board devices are needed such as data transmissions to and from the trains, train detection and driver information regarding communication of commands and signalling information, automatic train-protection (selecting train-supervision mode, defining intervention function, setting train characteristics), train-integrity check, health monitoring and failure mode support and data exchange between on-board and trackside assemblies [EU, 2002].

The subsystem is essential for ensuring safe and efficient train movements [Germroth, 2009] and relies on new developments such as the information technology, which allow the automatic train-supervision and the integration of technological environments such as the distribution of information to the staff in the operation control centres [Weidmann, 2007]. Centralized surfaces for controlling large numbers of (remote) control boxes exist that secure all open-line installations such as signals, switches or level crossings [Germroth, 2009]. Within the last years, the centralization of CCS-devices allowed to automatize signalling and train supervision processes such that security, availability and efficiency of railway transport could be improved. The devices control for instance signals, switches and level crossings.

Three organizational CCS-levels can be distinguished (Figure 18), which are not all considered in the evaluated methodology: only the levels up to *Central control of interlocking* are represented. For each *Infrastructure* node is specified whether and from which station it is remotely controlled.

Figure 18 Represented elements for *Control-command and Signalling*



Source: [Weidmann, 2007]

In Switzerland, the *SBB* widely uses *ILTIS* for centrally controlling about 700 signal boxes from about 20 traffic control centres ([Achermann, 2009], [Germroth, 2009]). The organizational levels of the *Control-command and Signalling* subsystem are briefly described in Table 25. Only the operational and dispositive levels are implemented in this study.

Table 16 Organizational levels of the *Control-command and Signalling* subsystem

Level		Units	Number for SBB	Systems used by SBB	Tasks and functions
Operational level → Implemented	Local	Signal boxes	About 700	Integra-Signum, ETCS	Provide safe und punctual routes
Dispositive level → Implemented	Regions	Centralized traffic control centres	25 larger ones plus few others	RCS; Iltis	Automation of train traffic, central interlocking control, regional coordination of timetable-relevant decisions
Dispatching → Neglected	Entire network	Traffic management centres	5		Coordination of network-wide processes and decisions

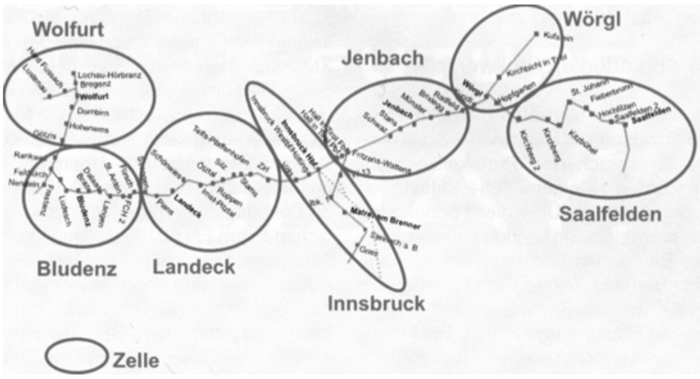
Source: [Germroth, 2009], [Achermann, 2009], [Leemann, 2005]

On the operational level, the control of signals and the position of switches are aggregated in *signal boxes* that ensure safe train movements. Signal boxes are the central elements of train operation safety systems. Decisions about routes, train speeds and distances between two vehicles are signalized and supervised in the signal boxes. Control centres provide visual and audio information to the travellers and train drivers and are essential for supervising, monitoring and guiding train movements in normal and degraded operation [Maier, 2010].

There are several different technologies used for operating signal boxes including mechanical, all-relay interlocking boxes, electro-mechanical signal boxes and electronic signal boxes. Electronic signal boxes allow centralizing the supervision of control-command and signalling processes in remotely controlled, centralized control centres. From 1924 electro-mechanical signal boxes continuously replaced mechanical ones, allowing a higher degree of centralization since with exception of the largest stations it now became possible to control entire stations from a single location. In 1956, the first all-relay interlocking was established in *Lyss* [Leemann, 2005]. This further increased the centralization dynamics. Since 1989 electronic signal boxes are widely used that are often controlled from centralized traffic control centres.

On the dispositive level, remote traffic centres allow to centrally coordinate and control the movement of trains in an efficient way, while in sparsely utilized areas, remote control centres are used for automatically operate crossings of trains or supervising shunting movements [Weidmann, 2007]. Figure 19 visualizes an example for integrating local control boxes into centralized traffic control centres in Austria.

Figure 19 Example for remote controlled stations in Austria



Source: [Valvoda et al., 2010]

On the level of network control centres, network-wide processes and decisions concerning the entire railway system are coordinated. In case of disastrous events causing system-wide blockades, network control centres coordinate the remote control centres and are responsible for railway operation within the railway network. In Switzerland, there are four network control centres situated in *Zurich*, *Olten*, *Lausanne* and *Bellinzona* as well as *Spiez*.

Table 17 Constituents of the *Control-command and Signalling* subsystem

Represented elements	**Elements that are not modelled**
Signal boxes controlling stations → Nodes	Traffic management centres, ETCS constituents…
Link indicating for each station from where it is controlled → Links	CCS interconnections, single cables …

Table 17 shows how the *Control-command and Signalling* subsystem is represented in this study. The concept of representing signal boxes remotely controlling others and locally operated ones are shown in Figure 20. *Control box 1* remotely controls *Station 1* and *Station 2*. It is assumed that the removal of the device *control box 1*, both stations are removed from the *Infrastructure* subsystem since they are (at least shortly after their failure) not longer operable. After some period of time, the failing stations are locally operated. *Station 3* is locally controlled. If *Control box 2* fails, the *Station 3* is removed from the *Infrastructure* subsystem and dispositive efforts become necessary for establishing degraded operation states.

The failure of a control centre is assumed to induce the removal of a specific set of stations (the stations that are controlled by the failing CCS-node), such that multiple stations are removed. This holds at least shortly after the occurrence of the failure.

Figure 20 Illustration of the concept of remotely controlled and locally operated stations

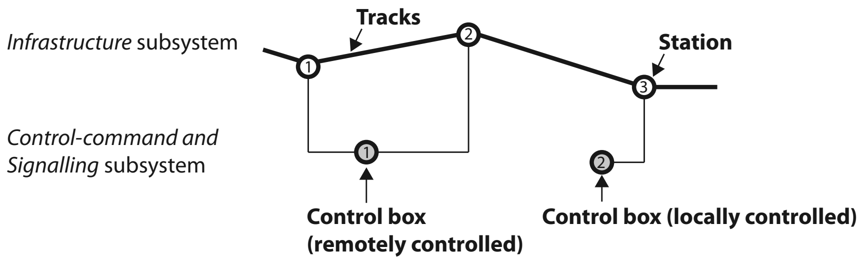
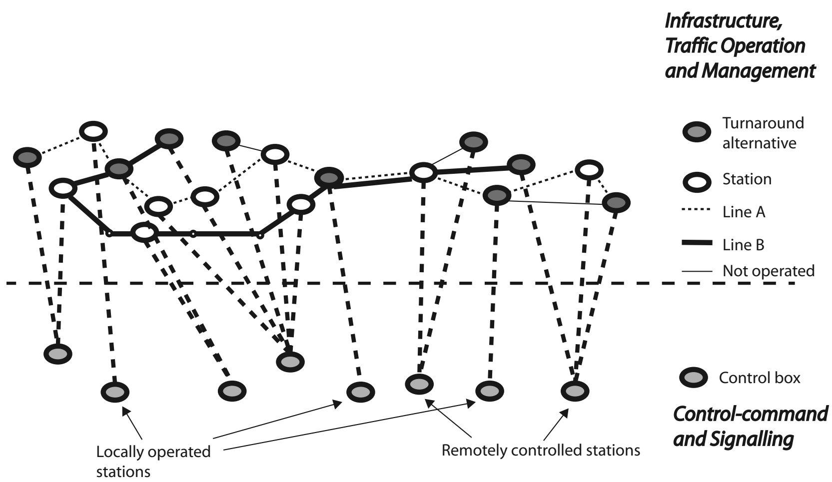


Figure 21 shows how *Control-command and Signalling* devices are connected with the networks representing the *Infrastructure* and *Traffic Operation and Management* subsystem in this study. All represented *Infrastructure* nodes are connected with exactly one control box that controls them. Stations can either be remotely controlled or locally operated.

Figure 21 Representation of *Control-command and Signalling* subsystems

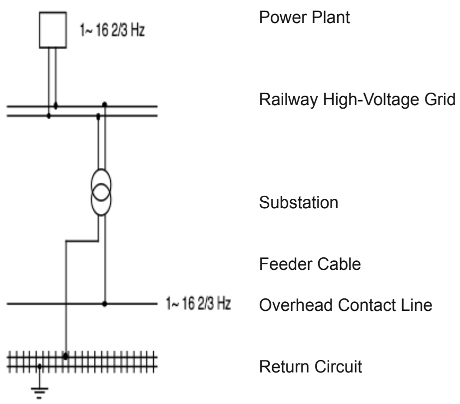


3.6 *Energy* subsystem

The *Energy* subsystem is defined as the *«electrification system, including overhead lines and on-board parts of the electric consumptions measuring equipment»* [EU, 2008a]. It consists of substations, sectioning locations, separation sections, the contact line system and return circuits [EU, 2011] and distributes electrical energy to trains (with 16.7 Hz in Switzerland) and railway network devices (with 50 Hz) in two different networks. This study focuses on the network supplying electrical current to trains and allows to simulate situations where traction current areas fails and a specific set of nodes and links fail (depending on the availability of redundancies).

The subsystem is designed such that every train is supplied with the needed power regarding line speed, minimal possible headway, maximum train current, power factor of trains, timetable and planned service and the mean useful voltage [EU, 2008d]. It consists of functional elements from its generation (power plants) to consumption (interface between overhead contact lines and pantograph) as shown in Figure 22.

Figure 22 Constituents of *Energy* subsystems as modelled in the study



Source: [Weidmann, 2009]

Energy production - Power plants → not modelled in this study: In power plants energy for the railway system is produced. There are several types of power plants including wind parks, hydroelectric / nuclear / solar / biomass and tidal power plants.

Energy from the public grid – Converter → not modelled in this study: Railway networks also receive power from public grids by converting voltages to compatible values.

Global distribution – High-voltage grid → not modelled in this study: Railway-specific high-voltage grids transmit electrical energy via long-distance traction current networks to substations.

Transformation – Substations → Represented in this study (Substations may fail): Substations link the high-voltage grid with the system of overhead contact lines. They are used to transform the high-voltage to a voltage that can be used for train movements.

Local distribution – Feeder cables and sectioning points → Represented in this study (Traction current areas may fail): Feeder cables locally distribute the power between the substations and the overhead contact lines. Sectioning points describe the set of electrical equipment between the supplying substations and the overhead contact lines providing protection, isolation and other auxiliary supplies [EU, 2008d].

Overhead contact lines – Pantograph → not modelled in this study: Overhead contact lines distribute electrical energy to trains travelling on the infrastructure. The interface between the overhead contact line and the vehicle is called pantograph. The network of overhead contact lines contains *«manually or remotely controlled disconnectors which are required to isolate sections or groups of the overhead contact lines according to operational necessity»* [EU, 2008d].

Return circuit → not modelled in this study: The return circuit consists of all conductors forming the intended path from the traction return current and the current under fault conditions [EU, 2008d].

In this study, the *Energy* subsystem is represented on the level of traction current entries and substations (Table 18). For each node and link in the *Infrastructure* subsystem is specified from where electrical current is provided. Redundancies are present since some stations or links are supplied with electrical current from multiple traction current areas.

Table 18 Constituents of the *Energy* subsystem

Represented elements	**Elements that are not modelled**
Substations → Nodes	Converter stations, power plants…
Current entry stating for each *Infrastructure* node and link from where electrical energy is supplied → Links	High-voltage grid, return circuits, overhead contact lines, interactions within *Energy* subsystem…

The *Energy* subsystem interacts with many other ones (see Table 19). The impacts of *Energy* subsystem blackouts in the 50 Hz network on critical infrastructures are extensively studied in [Petermann et al., 2011], stating that energy supply is essential for railway networks. They recently depend to a greater extent on the supply of electrical current supply due to extensively used information and communication devices that become essential ingredients for high-efficient and safe transport services.

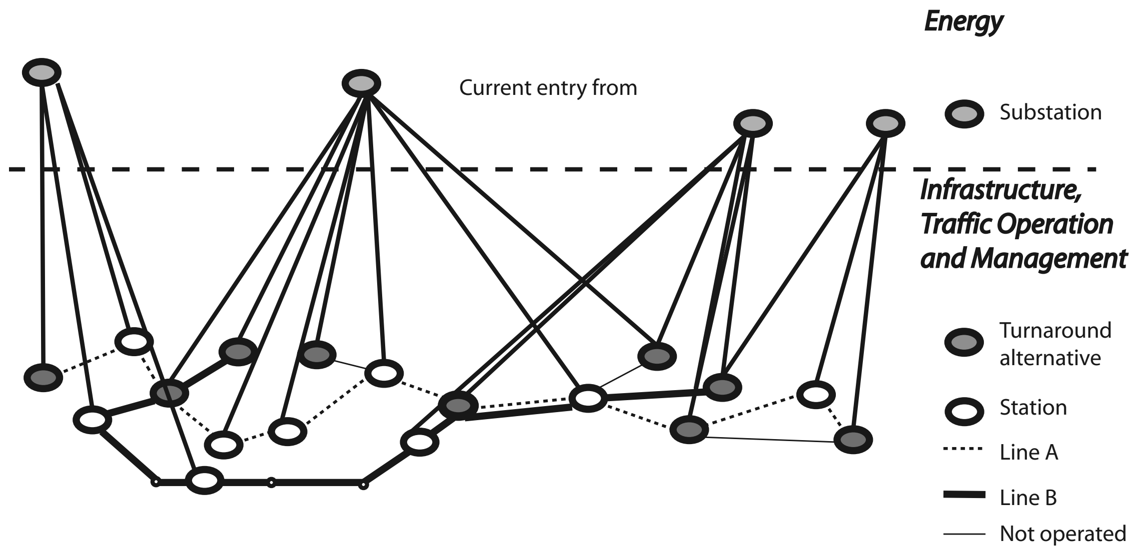
Table 19 Interfaces of the *Energy* subsystem

Subsystem	Interfaces
Infrastructure	Electrical tower, conductor rails, return circuits, contact wire height and gradient…
TOM	Supervision of railway power network, electrical interference and harmonic emissions
CCS	Control of train current, control lowering of pantographs, electromagnetic compatibility…
Energy	High-voltage cables, feeder cables

Source: from [EU, 2011], extended

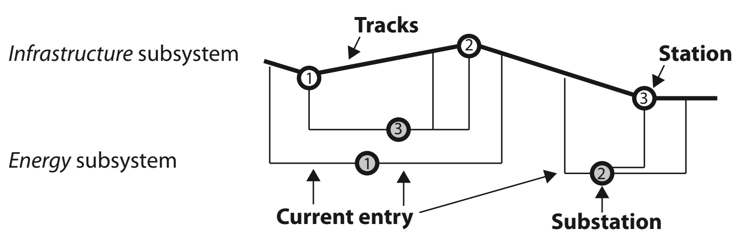
A visualisation of how the *Energy* subsystem is represented is shown in Figure 23.

Figure 23 Representation of *Energy* subsystems



For representing the *Energy* subsystem, information from the operators are needed that specifies for each *Infrastructure* element from which substations energy is supplied. There might be several substations providing energy to a link such that it only fails if either both supplying energy substations fail (due to redundancies) or if one of them fails in case that an edge is connected to multiple *Energy* nodes (see Figure 24). The link between *Station 2* and *Station 3* is removed only if both *Substation 2* and *Substation 3* fail. Both substations provide electrical current to the connection, such that the connection is only removed from the topology if both fail simultaneously. *Station 1* cannot be reached any longer if *Substation 3* fails.

Figure 24 Illustration of the concept of current entry and substations



3.7 Subsystem integration

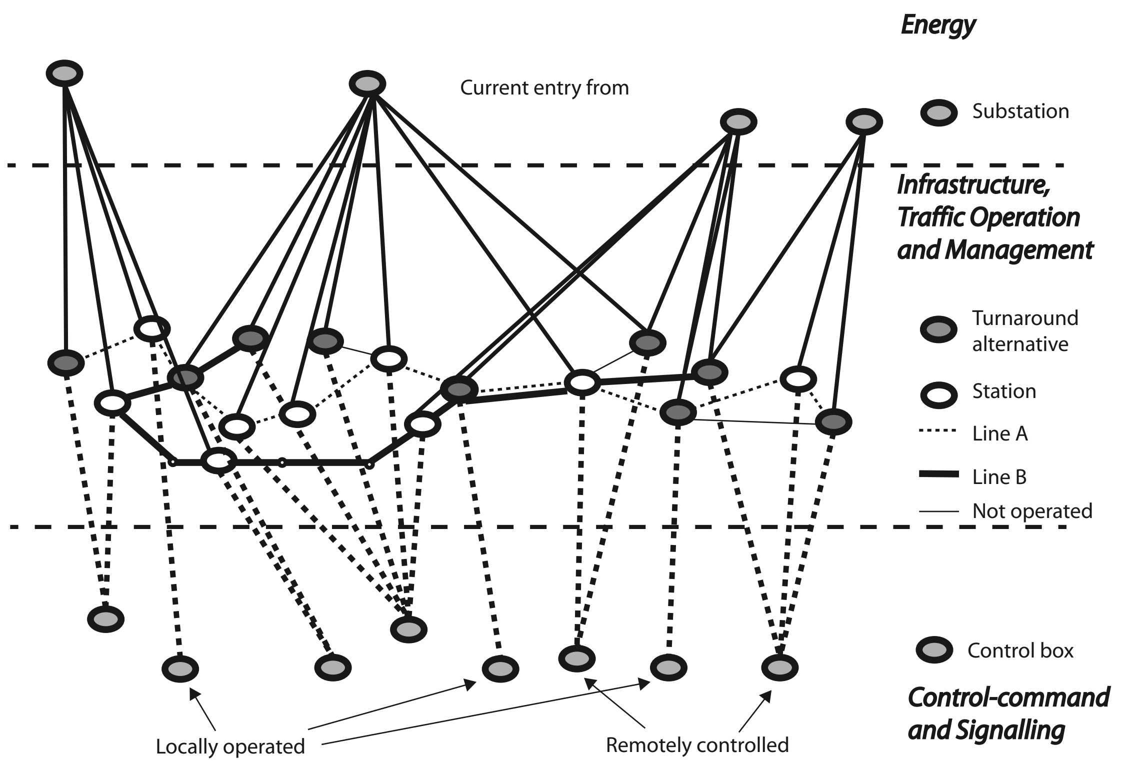
A brief overview about the modelled railway subsystems, their functions and their representations is given is given in Table 20.

Table 20 Summary of the modelled subsystems and their representation

Subsystem	Function	→ Nodes	→ Edges
Infrastructure	Track guidance	Stations	Connections between adjacent infrastructure nodes
TOM	Conditions for railway operation (line paths, capacity thresholds…)	Line paths within the infrastructure network in normal and degraded operation	
CCS	Safe and efficient train movements, coordination and dispatching	Centralized traffic control centres, signal boxes	Assignment from where an *Infrastructure* node is controlled
Energy	Power supply for the installations	Substations	Assignment of power supply to *Infrastructure* node and links

Figure 25 visualizes how the two-dimensional subsystem representation can be integrated into a multi-level representation of railway transportation. This figure also summarizes the basic principle of the evaluated methodology for assessing the robustness of railway networks. In contrast to existing studies, multiple subsystems are integrated and operational aspects are considered.

Figure 25 Multi-level representation of railway networks

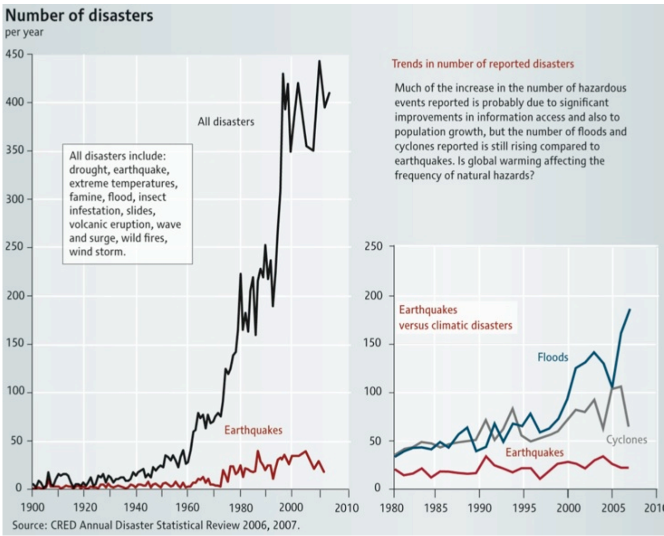


4 Events threatening railway transport

4.1 Overview

Critical infrastructures are threatened by hazardous events including failures of system components, human errors, natural hazards and malicious behaviours [Kröger, 2008]. The number of such disasters and their impacts seem to increase as Figure 26 shows and [Wittwer, 2010] for the situation in Switzerland. Also, railway systems are likely to be affected more often by disastrous events ([ARE, 2007], [Denzler, 2009]). It is assumed that due to the climate change (increasing rain falls), the number of disastrous events will increase for certain locations in Switzerland [Stutz, 2007]. Additional factors that may lead to increasing numbers of natural disasters are the dense area utilization and increasing complexities of railway installations.

Figure 26 Number of natural disasters per year after 1900



Source: [UNEP, 2009]

But not only hazardous events may induce severe operational consequences; also planned events such as construction works or demonstrations may cause blockades of stations or connections such that dispositive measures become necessary for stable degraded operation states. From the operational point of view, after the occurrence of a threatening event, finding the reason for or type of event is less important than identifying the stations and tracks that cannot be used any longer. Shortly after detecting failures in railway networks, the transport operator tries to calculate dispositive measures that are suitable to establish stable operation states. This section only gives a brief introduction about the threatening events that are represented by removing single or multiple links from the represented railway networks.

In most cases, hazardous events initially have locally limited impacts, usually only putting a few stations and tracks out of service. However, failures may spread and have the potential to blockade large system parts or even the entire railway network. This may be due to calculating rerouting alternatives such that the operational capacity threshold values of links are exceeded. Then, additional links may not be operable anymore.

Social hazards such as terroristic attacks are often biased towards specific network constituents. Non-biased failures are often referred to as *errors*, while biased ones are called *attack*s. Table 21 shows how threats can generally be distinguished.

Table 21 Scheme for distinguishing different kinds of threatening events

	Events originating inside the system	Events originating outside the system
Non-biased (*Errors*)	Accidents such as derailments or technical hazards → Approximately uniformly distributed among the nodes or links	Natural hazards, accidents at level crossings… → Approximately uniformly distributed among the nodes or links
Biased (*Attacks*)	Malevolence: revenge, sabotage, strikes → Non-uniformly distributed among the nodes or links, but focussed on *important* ones	Malevolence: terrorism, crime, cyber attacks → Non-uniformly distributed among the nodes or links, but focussed on *important* ones

The structure of this chapter is shown in Table 22.

Table 22 Structure and contents of chapter 4

Section	Contents	Purpose
4.1	Overview	Contents of the chapter
4.2	Event types	Collection of events threatening railway networks
4.3	Event classification scheme	Classification schemes of threatening events

4.2 Event types

4.2.1 Hazardous events threatening critical infrastructures

Many systems are threatened by events that are typically characterized by little lead-times such that enhancing measures typically comprise protection or recovery improvements. Counteractions during the response phase are difficult because the location and initial impact of such events cannot be anticipated and have severe consequences [Kröger et al., 2008]. A framework for systematically characterizing different hazard types is given in [KATARISK, 2009] for Switzerland. Aspects of malicious behaviours such as terrorisms or cyber attacks as well as crime are not considered, but are added to the contents of Table 23.

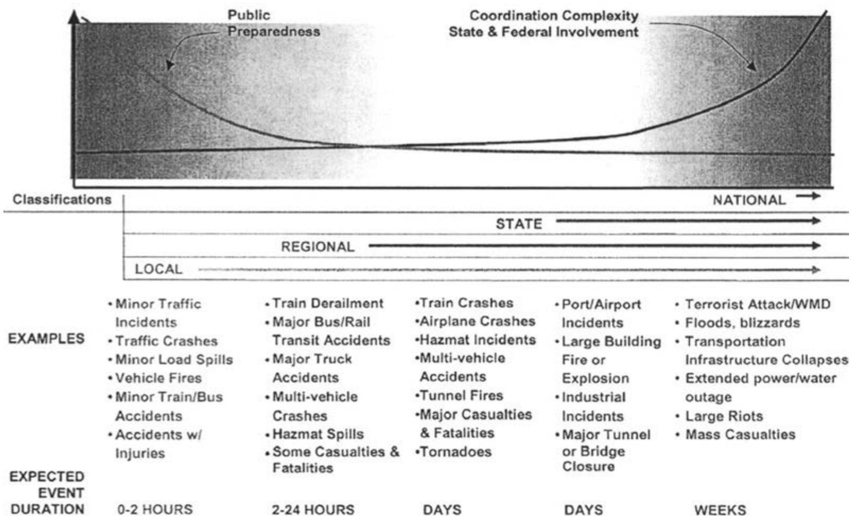
Table 23 Summary of hazardous events threatening critical infrastructures

Natural hazards	Technical hazards	Social hazards
Earthquake*,	Car accident*	Sport accident*
Ground shift*	Plane accident*	Non-work-related accident*
Avalanche*	Railway accident*	Accident at work*
Cold period*	Fire*	Migration*
Dry and hot weather*	Dam break*	Epidemic*
Floods*	Chemical accident*	War
Forest fire*	Radioactivity*	Economic hazards
Meteorite*		Agriculture and unsustainable resource management
Volcanoes		Crime
Animal epidemics or diseases		Terrorism
Storms* (Thunderstorm*, windstorm*, blizzard, sandstorm, hurricanes)		Cyber attacks
		Employer strikes
		Suicides

Source: * from [KATARISK, 2009]

For transportation systems, [TRB, 2009] provides an analysis of the spatial and temporal impacts of hazardous events threatening transport systems in the United States (see Figure 27).

Figure 27 Classification of hazardous events threatening transport systems from [TRB, 2009]



Source: [TRB, 2009]

The x-axis denotes the spatial dimension of hazardous events and distinguishes between local, regional, state and national hazard impacts. The y-axis expresses the value of public preparedness and the coordination complexity of such events if they occur. The expected event durations as indicators for the timescale impacts of hazards reaches from event that cause system crashes for weeks (national events) to timescale effects of less than two hours (local events). Local events include minor traffic and railway accidents and vehicle fires. Regional events have expected durations between 2 and 24 hours and include train derailment and major transit accidents.

4.2.2 Events threatening railway networks

Critical events threatening railway transport can be specified divided into operational hazards, infrastructural hazards and external hazards [SBB, 2010]:

Operational hazards:

- Production errors including errors of the train driver (handling errors, missing train driver), missing trains, train composition errors
- Rolling stock errors like tractive stock failures, wagon failures, axle breakages
- Logistic errors
- Customer service failures including missing train crews
- Others such as emergency brake misuse, health emergency case

Structural errors:

- Operation control errors like wrong dispositional measures
- Infrastructure unit failures including failures of signals, switches, barriers, clear track signalling systems, detection units, tracks (rail breakages) or contact lines
- Failures of *Energy*, *Control-command and Signalling* or *Traffic Operation and Management* devices including breakages of power supplying substations
- Explosions and fires [BAV, 2010]
- Larger technical failures caused by damaged units and parts of devices [BAV, 2010]

External hazards:

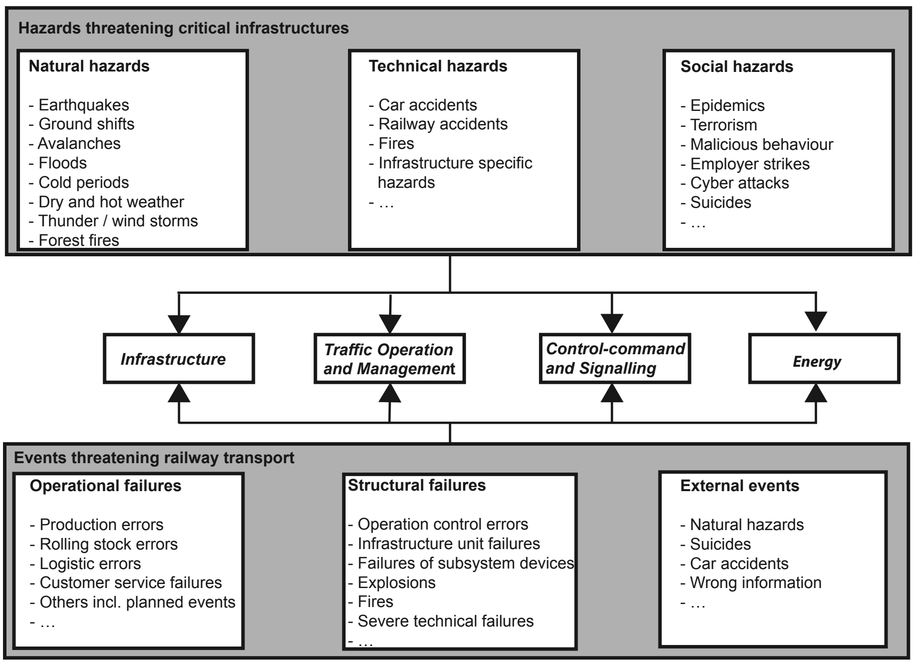
- Car accidents

- Suicides
- Natural hazards
- Maintenance measures
- Wrong information

Besides humans also animals play significant roles for external events [Keegan et al., 2000]. A collection of potential hazards threatening critical infrastructures in general and the operability of railway systems is illustrated in Figure 28. All these events may be the hazardous events simulated in the implemented disaster robustness analysis tool. For quantitatively assessing the consequences of failures in railway networks, the following measures may be used [Ahrens et al., 2009]:

- Duration in [minutes]
- Spatial expansion in [number of stations, fraction of stations or km^2]
- Number of persons concerned
- Delayed arrivals for each concerned person in [minutes per customer]
- Associated costs in [CHF]

Figure 28 Typology for hazards threatening railway (sub)systems



4.3 Event classification scheme

Hazards often are classified according to the impacts and the rate of occurrence. KATARISK provides a classification scheme for hazards using the indicators listed in Table 24. For a monetary quantification of the potential damages risk aversion is considered paying attention to the fact that a single large event with the same amount of damage is considered more catastrophic than many small events with totally the same amount of damage.

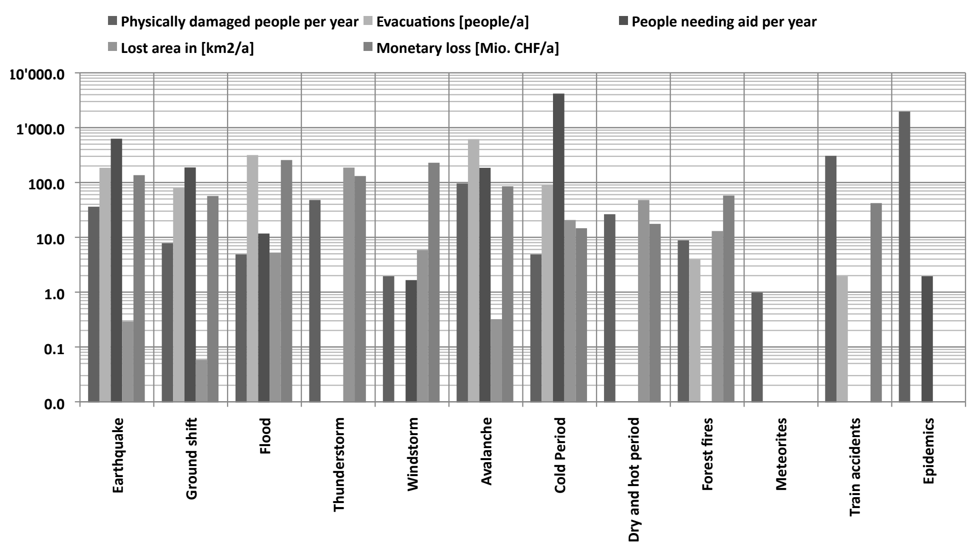
Table 24 Indicators for measuring disaster impacts in [KATARISK, 2009]

Indicator	Measure
Number of deaths or injuries due to hazards	[People/a], [Mio. CHF/a]
Number of evacuated people due to hazards	[Evacuations/a], [Mio. CHF/a]
Number of people that need support	[Support to people/a], [Mio. CHF/a]
Areal losses: damage to forests, areas used in agriculture and damages of areas serving for housing or economic purposes	[km^2/a], [Mio. CHF/a]
Financial losses: costs for reparation or recovery due to hazardous events	[Mio. CHF/a]

Source: [KATARISK, 2009]

[KATARISK, 2009] defines five different event categories (EK1 – EK5) considering aspects that include the spatial context and availability of emergency units. The events of categories EK2 – EK5 can induce damages that are represented and assessed in this study. The annual statistical damages expected for Switzerland are illustrated in Figure 29.

Figure 29 Statistical expected damages due to hazards for Switzerland (EK1 – EK5)



Source: Data from [KATARISK, 2009]

EK1: Events inducing damages that can usually be locally circumvented. EK1 events are not considered as catastrophic events and are supposed to occur several times a day.

EK2: Local catastrophic events that cannot be handled by local emergency units, inter-local support – i.e. support from other cities - is necessary. EK2 events happen rarely per year until once within a decade and are supposed to occur several times in the next 25 years.

EK3: Regional catastrophic events with damages that cannot be handled by regional emergency sources. Inter-local support is not sufficient. Inter-regional support becomes necessary. Events of category EK3 happen rarely within a decade until once within a century. They are expected to occur in Switzerland within the next 25 years only a few times.

EK4: Cantonal catastrophic events (i.e. on the level of the member states of the federal state) cause damages that need inter-cantonal or even federal help. Event of category EK4 are rare within a century. They are supposed to occur at least once in Switzerland within the next 25 years with a probability of 25 per cent.

EK5: National catastrophic events cannot be handled with national emergency units; international help is necessary. EK5 events are rare within a millennium until once within a period of 100’000 years. Events are expected to occur at least once in Switzerland within the next 25 years with a probability of 2 per cent.

Table 25 Definition on the event categories in [KATARISK, 2009]

	EK2	**EK3**	**EK4**	**EK5**
Spatial dimension	Urban	Regional	Cantonal	National
Inhabitants in Switzerland [*1’000]	2.5	90	300	7’200
Area [km^2]	15	150	1’500	41’000
Budget [Mio. CHF per year]	15	500	2’000	175’000
Physically damaged people [Tsd. people per event]	> 0.1	> 1	> 10	> 100
Evacuated people [Tsd. per event]	> 1	> 10	> 100	> 1’000
People needing support [Tsd. per event]	> 10	> 100	> 1’000	Impossible
Lost area [km^2 per event]	> 5	> 50	> 500	> 5’000
Monetary loss [Mio. CHF per event]	> 250	> 2’500	> 20’000	> 100’000

Source: [KATARISK, 2009]

Table 26 shows impact severity levels typically used for risk assessment analyses. Risk assessment categorizes risks according to the hazard impacts and their rates of occurrence.

Table 26 Hazard severity levels from [IEC, 2002] and event classification according to [KATARISK, 2009]

Category	Definition in [IEC, 2002]	Consequences	Event category in [KATARISK, 2009]
Insignificant	Possible minor injury	Minor damages	EK1
Marginal	Minor injury and / or significant threat to the environment	Severe system damages	EK2, EK3
Critical	Single fatality and / or severe injury and / or significant damage to the environment	System is blockaded to a large extent	EK3, EK4
Catastrophic	Fatalities and / or multiple severe injuries and / or major damage to the environment	System-wide blockade	EK5

Source: [IEC, 2002], last column was added

A classification scheme for the rate of occurrence is introduced in [IEC, 2002] distinguishing six categories of occurrence probabilities shown in Table 27.

Table 27 Categories of the frequency of occurrence of hazardous events in [IEC, 2002] and event classification in [KATARISK, 2009]

Category	Definition in [IEC, 2002]	Event category in [KATARISK, 2009]
Frequent	Likely to occur frequently. The hazard will continually be experienced.	EK1
Probable	Will occur several times. The hazard can be assumed to occur often.	EK1
Occasional	Likely to occur several times. The hazard can be expected to occur several times.	EK2
Remote	Likely to occur sometimes in system life cycle. Occurrence can reasonably be expected.	EK2
Improbable	Unlikely to occur but possible. Hazard may exceptionally occur.	EK3 - EK4
Incredible	Extremely unlikely to occur. It can be assumed that the hazard may not occur.	EK5

Source: [IEC, 2002], last column was added

5 Computation fundamentals

5.1 Overview

This chapter shows how the structural and operational resiliencies of railway networks are analysed and quantified in this study. Threatening events may cause the removals of single or multiple nodes or links from the represented subsystems as shown in chapter 3. This removal has impacts of the network structural, i.e. the values of the giant cluster size and the average shortest path lengths within the giant clusters. Deleting nodes and links also has impacts on railway operation such that all lines traversing the removed elements in planned operation have to be rerouted or truncated. This chapter introduces a method that is suitable to calculate degraded operation states and for quantifying the reductions of the system performance. This means that a measures is introduced that allows to quantify the degradation of railway operation such that the most critical network elements and bottleneck in degraded operation can be identified. The impacts of threatening events on the operation in the multi-level representations of railway systems are simulated in a robustness analysis tool that is implemented in the *R* software environment. This chapter introduces the implemented procedures and its contents are summarized in Table 28.

Table 28 Structure and contents of chapter 5

Section	Contents	Purpose
5.1	Overview	Contents of the chapter
5.2	The *R* software	Reasons for choosing *R* for robustness analysis
5.3	Representation of events threatening railway transport	Show how to represent threatening events in *R*
5.4	Measuring the system performance	Introducing the basic principles for assessing the robustness
5.5	Quantifying the structural robustness	Show framework for quantitatively assessing the structural consequences of events threatening railway systems
5.6	Quantifying the operational robustness	Show framework for quantitatively assessing the operational consequences of events threatening railway systems
5.7	Features of the implemented analysis tool	Explanation of the implemented modules for robustness analysis

The *R* software is briefly introduced in section 5.2 pointing out reasons for choosing it. Section 5.3 describes how to represent the impacts of the threatening events that were introduced in chapter 4. The basic principles for measuring the robustness of networks in a quantitative way are presented in section 5.4. Section 5.5 shows how to quantify the structural robustness of railway networks; the operational one is subject of section 5.6. Section 5.7 summarizes the features of the implemented robustness analysis tool.

5.2 The *R* software

[Nagurney et al., 2010] states that simulation tools are of major interest: *«Tools that enable the identification of which nodes and links really matter in [...] network systems and should, thus, be better maintained and/or enhanced to provide essential information to decision-makers from governmental employees and policymakers to planners, engineers, and scientists, to corporate and organizational leaders.»*

For analysing the stability of railway networks and for quantitatively assessing the structural and operational consequences of simulated threatening events the open source software *R* was found to be most suitable. *R* can be used in various ways as for instance for statistical computing, data analysis and graphics. *«It consists of a language plus a run-time environment with graphics, a debugger, access to certain system functions, and the ability to run programs stored in script files.»* [Hornik, 2011]. The free software runs on UNIX, Windows and MAC platforms and is continuously extended by additional packages containing method packages and data for specific detailed analysis. Its structure and the possibility to easily write new functions were additional reasons for choosing *R*. The number of scientists publishing their analysis results using this software continuously increases, and there are good documentations for using the software. [Crawley, 2008] gives a good introduction into the basic programming principles of *R*.

The additional package *igraph* [Csardi et al., 2006] allows to create and manipulate graphs and to perform efficient network analysis even for very large instances, i.e. networks consisting of a large number of nodes and links. It offers methods for analysing basic topological network features such as centrality and distance measures as introduced and defined in chapter 2. The *igraph* package is also suitable for visualising complex networks and the results calculated in this study, i.e. railway networks in planned and degraded operation. The package also allows to calculate basic parameters describing the structural properties of networks including most of the structural measures introduced in section 2.3.

R provides a large set of methods for assessing the robustness of networks, but always from a structural point of view. For this study the set of analysing methods are extended such that is possible to measure the impacts of single or multiple node or link removals on railway operation in a quantitative way. This means that specific paths are defined representing the train routes that have to be dispatched if the network is manipulated. The dispositive actions that are calculated mimic realistic and feasible dispatching solution decided by the railway operators. However, the robustness analysis tool is not an expert tool, but it provides powerful features for visualising degraded operation states and to suggest rerouting alternatives or truncation of line paths. The implemented tool is applied to multiple case study networks in chapter 6, but can also be applied for any other railway network if the relevant input data is specified.

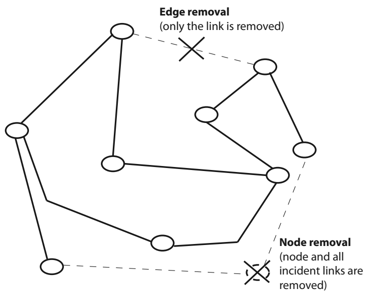
5.3 Representation statements and assumptions

5.3.1 Representing the impacts of events threatening railway transport

The events threatening railway systems as introduced in chapter 4 are represented by removing the nodes and links that are no longer available for railway transport. This is represented as follows (see also Figure 29 for an illustration):

- **Node removal:** The node and all the incident edges are removed from the network.
- **Edge removal:** A single link is removed from the network. Nodes may become isolated.

Figure 30 Impacts of events threatening railway transport on networks



5.3.2 Adaptations necessary when representing the *Infrastructure*

The study aims to assess both the structural and operational consequences on railway transport. First test runs of the implemented disposition framework showed that in some cases it is beneficial to modify the represented *Infrastructure* subsystem to achieve more realistic results for the calculated degraded operation states. Two kinds of functional adaptations of the *Infrastructure* subsystem are considered:

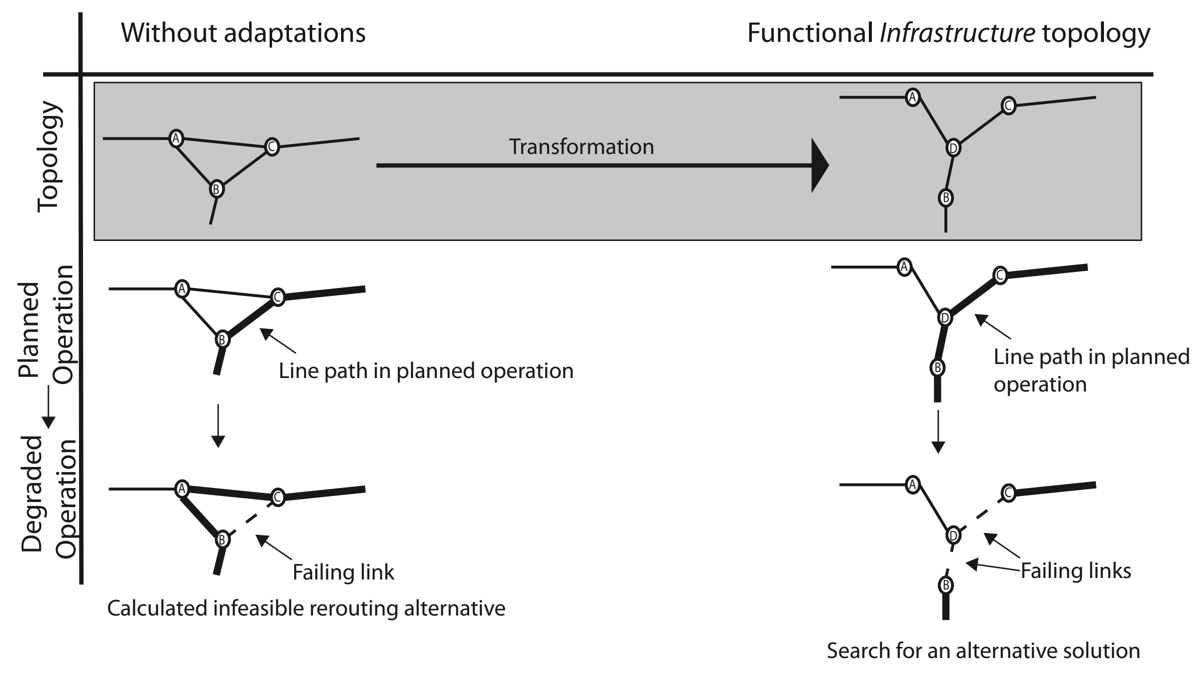
1. Elimination and transformation of track triangles,

2. Removal of edges in cargo areas.

The decisions for or against adaptations of the track topologies depend on the specific situation and the available rerouting possibilities for degraded operation. The first point addresses to a transformation of the topology in situations as shown in Figure 31: Track triangles in some cases are turned into tree structures depending on the possibilities of coping with edge and node removals: In Figure 31, if the link between *Node B* and *Node C* is removed, they are still connected via *Node A*. However, depending on the microscopic track topology, this alternative path may not be suitable or exist at all for rerouting lines in degraded operation. Substituting the triangles with tree structures may be feasible for improving the calculated solutions and quantifications of the degradations of railway operation.

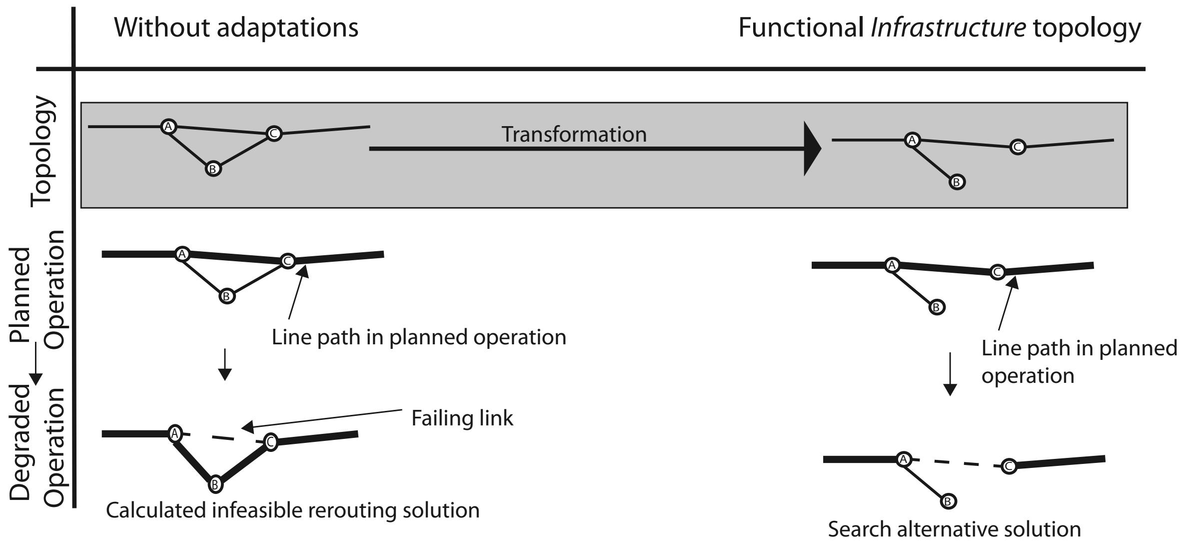
In the example, a new node is added, *Node D*. The number of edges remains constant. If now a link between *Node B* and *Node C* fails, rerouting the line via *Node A* is no longer possible and a new, more realistic solution has to be found. However, it may happen that the track triangle actually exists and is suitable for degraded operation. Then, the triangle is not transformed and remains in the network.

Figure 31 Adapting the *Infrastructure* subsystem: Transformation of track triangles



In some cases it may also be useful to eliminate some edges that physically exist in the *Infrastructure* topology but that do not rerouting alternatives. For instance, routing trains through cargo stations may not be feasible in all cases. In example is illustrated in Figure 32, *Node B* may represent a cargo station. If the link between *Node A* and *Node C* fails, a rerouting alternative via physically *Node B* exists and is likely to be calculated for rerouting lines. However, this rerouting solution may not always be suitable. Hence, the topology is adapted into functional *Infrastructure* topologies such that such solutions cannot be calculated anymore.

Figure 32 Adapting the *Infrastructure* subsystem: Transforming cargo stations



5.3.3 Further assumptions

Further assumptions are implicitly made when representing the railway networks:

- All paths in the topology can be driven in either planned or degraded operation state.
- Edges are directionless.
- Traversing edges induces the same amount of travel time for both directions.

5.4 Measuring the system performance

5.4.1 Introduction of the resilience concept

Definition of the resilience

This section introduces a method for quantitatively assessing the impacts of threatening events on railway systems, i.e. the consequences of removing single or multiple elements from railway networks. Removing infrastructure nodes or links may induce dispositive efforts for rerouting or truncating the lines traversing the deleted element. The introduced measure allows quantifying the amount of degradation of railway operation and makes it hence possible to compare different hazard scenarios.

In this study, the amount of degradation of railway operation is measured by quantifying the system performances in planned and degraded operation. If the difference between both values remains small even for hazards implying the removal of a large number of elements, the network is usually said to be highly robust and to have a high resilience.

The resilience of a network describes *«the ability of social units (e.g. organizations, communities) to mitigate hazards, to contain the effects of disaster when they occur and to carry out recovery activities in ways that minimize social disruption and mitigate the effects of future disasters»* [Bruneau et al., 2003]. A resilience concept is introduced in [Bruneau et al., 2003] and is adopted such that it can be applied for analysing the resilience of railway networks. All critical infrastructures should be designed in a robust way such that the system is able to withstand internal or external perturbations. This means they should easily be recoverable and have to be designed in a way such that the consequences of catastrophic failures are minimized [Harrald, 2007]. For railway transport this means for instance that rerouting alternatives are designed-in in railway networks such that is possible to locally drive around removed elements. [WEF, 2011] states that *«actions taken immediately before or during an event are crucial for limiting impact [...]. These actions include last minute resilience measures, early warning systems, evacuation plans and efficient response measures»*.

Structural and operational robustness

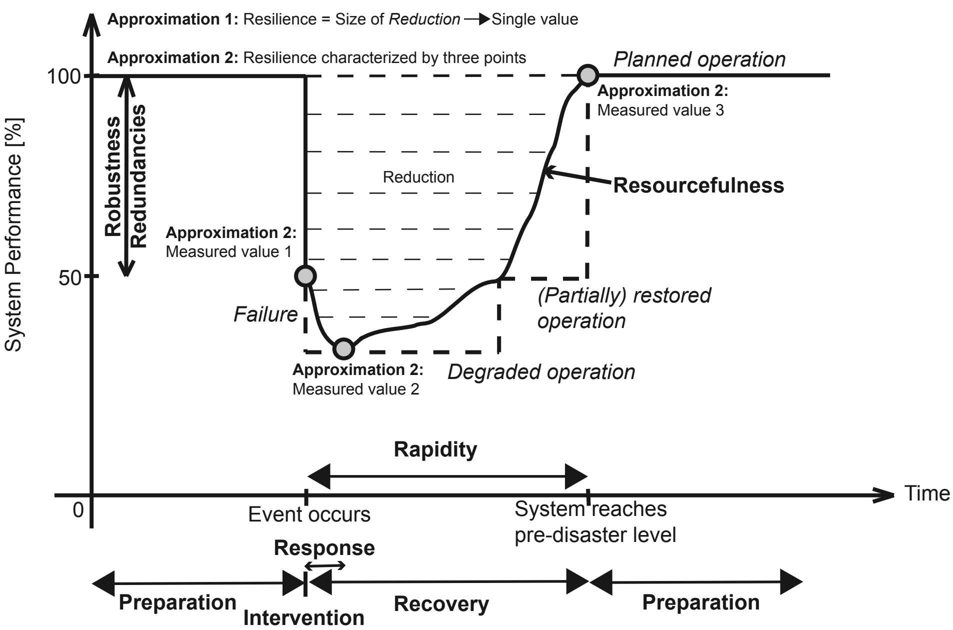
In this study, the impacts of removing nodes and links on railway networks are measured by two different resilience measures, the *structural* and the *operational robustness* of railway networks. The structural robustness measures the impacts of removing nodes and links from the *infrastructure* subsystem on network integrity. Various results for the structural robustness of many different real-world networks are available (see Table 7). Typically, it is quantified by either measuring the degradation of the integrity of networks, i.e. the giant cluster sizes or the network connectivity, i.e. the changes of the average shortest path length values. In this study both values are integrated into a single value for quantifying the structural robustness. Section 5.5 shows how the structural robustness is quantified in this study in more detail.

The operational robustness measures the impacts of failures originating in the entire multilevel network representation of railway system on railway operation. This is a new concept and includes multiple different measures such as the number of served stations and is described in section 5.6.

System performance curve

Figure 33 visualizes the impacts of hazardous events on the system performance during the disaster timeline and shows the resilience elements as introduced in [Tierney et al., 2007]: In planned operation state no elements are removed from the network such that the system performance is assumed to be 100 % or 1. When a threatening event occurs the removal of single or multiple elements induces usually the degradation of railway operation. Hence, with the occurrence of a threatening event, the system performance is promptly reduced.

Figure 33 Illustration of the system performance curve and the resilience concept



Source: Based on [Tierney et al., 2007], extended

After the occurrence of a hazard, the system performance may further decrease representing cases where failures spread such that initially non-affected system parts also fail. For railway transport a hazardous event may cause the removal of a single link, i.e. due to a tree falling on the tracks. It this situation it may be possible that all affected lines are rerouted such that capacity thresholds are exceeded and further edges are blockaded. This means that cascading effects may occur, if rerouting lines exceeds the capacity utilization thresholds such that the operation along them is not stable any longer. The system performance may hence further decrease until a minimal value is reached defining the level of degraded operation that can be operated in a stable way (see [Petermann et al., 2011]). The value may take value zero, if operation is not possible at all.

During the recovery phase, the system performance can be increased due to response and recovery measures. At some point of time, railway operation service may be partially restored such that the degraded operational level is increased. For instance, some of the tracks can be used again, potentially with decreased speed and reduced capacity utilization. After some time, the pre-disaster level of the system performance level is regained and the system returns to the planned operation state.

Resilience elements

The resilience concept introduced in [Tierney et al., 2007] distinguishes between four different aspects of how threatening events influence the system performance: robustness, redundancy, resourcefulness and rapidity. Though these elements were introduced for assessing the impacts of earthquakes on buildings and structures, they can be applied for assessing the impacts on railway transport as well. A definition of the resilience elements is given in Table 29.

Table 29 Elements of the resilience of critical infrastructures

Resilience element	Definition given in [Tierney et al., 2007]	Influences on disaster resilience curve (Figure 33)
Robustness	Ability of systems, its elements or other units of analysis to withstand disaster forces without significant degradation or loss of performance.	Amount of reduction of the system performance
Redundancy	Extent to which systems, system elements or other units are substitutable, that is capable of satisfying functional requirements, if significant degradation or loss of functionality occurs.	
Resourcefulness	Ability to diagnose and prioritize problems, to initiate solutions by identifying and mobilizing material, monetary, informational, technological and human resources.	Shape of the system performance curve
Rapidity	Capacity to restore functionality in a timely way, containing losses and avoiding disruptions.	Duration of reduced system performance

The robustness of systems has been widely studied in the field of computer sciences and engineering [Nagurney et al., 2010]. Typically, the robustness is used as a measure for *«the ability of a system to continue to operate correctly across a wide range of operational conditions, and to fail gracefully outside of that range»* [Gribble, 2001]. In this study, the robustness term is understood as a measure for the impacts of node and link removals on network connectivity and the distribution of flows in the topologies, following [Albert et al., 2000]. This means that the robustness of railway networks measures the reduction of the system performance curve by comparing the planned and degraded operation state. The latter one is calculated as described in section 5.7. Identifying the nodes whose removal have the most severe robustness impacts on railway operation is important for improving emergency response, *«which are limited and, therefore, have to be deployed as efficiently as possible»* [Buzna, 2008]. Several developments have recently influenced the resilience of railway networks, both positively and negatively (Table 30).

In the field of mathematics and optimization, the term robustness is used in a different way: The authors of [Liebchen et al., 2009] extend the concept of *recovery robustness*, an optimization concept dealing with uncertainties. The authors applied the recovery robustness optimization problem to railway transport planning processes, for instance for improving delay resistant timetabling processes aiming to find optimal buffer times such that the planned travel times are chosen such that timetable deviations are reduced.

Table 30 Factors influencing the resilience of railway networks

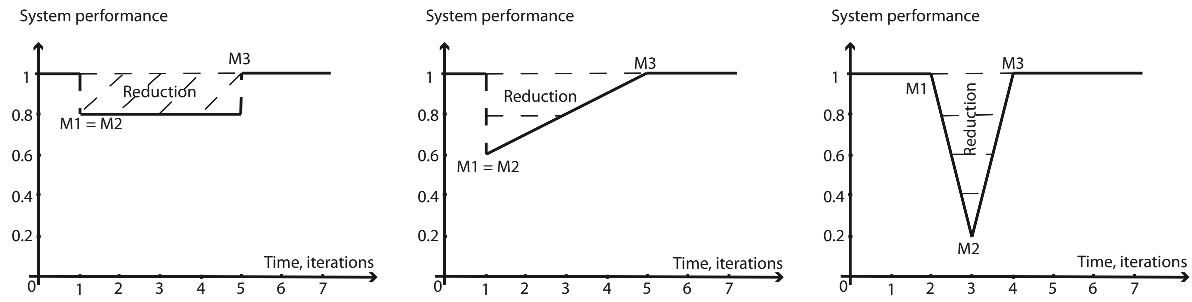
Resilience element		Current trends influencing the resilience element
Resilience of railway networks	Robustness / Redundancies	Improved system design; technological developments; risk acceptance of the society; automation of processes; centralization of CCS processes; restrictions by norms, laws and standardization; economization and increased focus on network efficiency, but also more interconnected subsystems and centralized processes
	Resourcefulness	Improved diagnosis ability; increased experience with prioritizing problems; developments in the identification and mobilization of material, informational, technological and human resources, but also centralization of processes and resources.
	Rapidity	New monitoring systems; computerization of data; availability of large data bases; improved detection methods; early warning systems; local concentration of emergency units; increased mobility of emergency units and equipment, centralization of resources.

5.4.2 Resilience quantification

Single value concept

Generally, there are two ways of assessing the resilience of railway networks in a quantitative way: In a first approximation (denoted *Approximation 1* in Figure 33), the resilience is quantified as the size of the area denoted as *Reduction*. This allows expressing the impacts of threatening events on railway networks by a single value. This value is zero if there is no reduction of the system performance. Higher values indicate more severe impacts on the system performance either in temporal terms or regarding the absolute decrease of the system performance. Then, different system performance curves can have identical resilience values as shown in Figure 34. All resilience values coincide even though the system performance curves have different shapes.

Figure 34 Illustration of the single value concept and multi-value concept



Interpretation of the curve		Interpretation of the curve		Interpretation of the curve	
Immediate drop down and normalisation		Immediate drop down, linear normalisation		Linear drop down and normalisation	
Approximation 1		**Approximation 1**		**Approximation 1**	
Reduction:	0.8	Reduction:	0.8	Reduction:	0.8
Disaster impact:	**0.8**	**Disaster impact:**	**0.8**	**Disaster impact:**	**0.8**
Approximation 2		**Approximation 2**		**Approximation 2**	
Robustness value 1:	0.8	Robustness value 1:	0.6	Robustness value 1:	1.0
Robustness value 2:	0.8	Robustness value 2:	0.6	Robustness value 2:	0.2
Rapidity value 1:	0.0	Rapidity value 1:	0.0	Rapidity value 1:	1.0
Rapidity value 2:	4.0	Rapidity value 2:	4.0	Rapidity value 2:	1.0
Resourcefulness value:	0.0	Resourcefulness value:	0.1	Resourcefulness value:	0.8

M1 - Measured value 1, M2 - Measured value 2, M3 - Measured value 3

Multi-value concept

The multi-value concept uses several measures for quantifying disaster impacts on the system performance as illustrated in Figure 33:

- **Approximation 2: Measured value 1:** Denotes the initial reduction of the system performance when a threatening event occurs and the corresponding point in time → Used for assessing robustness and redundancies.

- **Approximation 2: Measured value 2:** Denotes the minimal system performance value when a stable degraded operation state can be established and the corresponding point in time → Used for assessing robustness, redundancies and rapidity.

- **Approximation 2: Measured value 3:** The point in time when the system performance regains pre-disaster level → Used for assessing rapidity and resourcefulness.

Using these three measured values, the resilience and its elements may be quantified according to the definitions given in Table 31. Examples for the calculation of these values are contained in Figure 34.

Table 31 Values describing the impacts of failures on the system performance curve

Resilience element	Measure	Definition
Robustness / Redundancies	*Robustness value 1*	Initial value of the (reduced) system performance
	Robustness value 2	Minimal value of the system performance
Resourcefulness	*Resourcefulness value*	Mean increase of the system performance between *Measured value 2* and *Measured value 3*
Rapidity	*Rapidity value 1*	Time between *Measured value 1* and *Measured value 2*
	Rapidity value 2	Time between *Measured value 2* and *Measured value 3*

Table 32 reveals how the resilience of railway networks is measured in this study. The focus is put on quantifying the system robustness and the redundancies in both a structural and operational sense. This means that the values *Approximation 1: Measured value 1* and *Approximation 1: Measured value 2* are calculated.

Table 32 Potential measures quantifying the resilience elements

Resilience element	Meaning	Potential measures
Robustness → **Quantified in this study**	Initial reduction and state with minimal system performance	**Initial impact and degraded operational states:** Reductions of topology measures such as size and connectivity measures …
Redundancies → Influencing the robustness	Availability of rerouting alternatives.	**Initial impact of disastrous events on structural key values** Regularity and efficiency measures, fraction of rerouted lines…
Rapidity → Out of scope	Duration between occurrence of a disaster and returning to pre-disaster level	**Epidemiological models:** Failure spreading dynamics, convergence times …
Resourcefulness → Out of scope	Shape of the curve of the system performance e.g. effectiveness of emergency units and counteractions.	**Epidemiological models** Disaster spreading dynamics, shape of the curve until the system returns into stable state.

5.5 Quantifying the structural robustness

The structural consequences of threatening events are typically quantified for assessing the stability of the *Infrastructure* topologies and do not consider any operational data. Removing nodes and links from the Infrastructure topology immediately changes basic structural measures (see section 2.3). As [Barrat et al., 2004] states, *«these topological features turn out to be extremely relevant because they have a strong impact in assessing such networks' physical properties as their robustness or vulnerabilities.»*

As in most studies including the findings in [Albert et al., 2002] (see Figure 10), the dynamics of the giant cluster size and the average shortest path lengths within are used for measuring the structural robustness of railway networks in this study. While the giant cluster size refers to the number of nodes contained in the largest connected component, changes of the average shortest path length address to the connectivity within, i.e. the distribution of units with the degraded topology. Both quantities measure the relative changes compared to pre-disaster level and are calculated as follows:

- **Giant cluster size:** Fraction of nodes within the giant cluster relative to pre-disaster level. The removal of nodes decreases the giant cluster size since at least the removed node does not longer belong to the giant cluster. In case of removing edges, the giant cluster size may remain constant.

$$\boldsymbol{q_a := Giant\ cluster\ size = \frac{Nodes\ in\ the\ giant\ cluster}{n} \epsilon\ [0; 1]}$$

  where n denotes the number of nodes in the giant cluster in the non-degraded network, for railway networks typically all nodes are within a single component such that the network is connected. The value of the giant cluster size is ranged between 0 and 1.

- **Average shortest path length dynamics:** Removing nodes or links changes the average shortest path length within the giant cluster such that it can increase or decrease.

$$\boldsymbol{q_b := Average\ shortest\ path\ length\ dynamics = \frac{Average\ shortest\ path\ length\ in\ giant\ cluster}{Average\ shortest\ path\ length\ in\ non-degraded\ network}}$$

  The value of the average path length can increase or decrease. Values close to 1 indicate that the connectivity is only slightly affected, while large deviations indicate significant impacts of the removals on the network connectivity. Values larger than one are typically observed if the degraded network sustains in a large connected component, but the average shortest path lengths are increased. Values smaller than one are measured if the giant cluster size decreases.

The removal of nodes or links from the network changes the values of both simultaneously. In this study, both are integrated into a single value measuring the *structural robustness* of a network for quantifying measures the level of topology degradation in the following way:

$$\boldsymbol{Structural\ robustness = q_a \cdot Min\{q_b, {q_b}^{-1}\}}$$

The latter term pays attention to the fact that in the degraded network the average shortest path length may either increase or decrease, i.e. it takes values smaller or larger than one. In order to guarantee that the *structural robustness* only takes values between 0 and 1, the smaller value of the average shortest path length in the giant cluster and its reciprocal is taken.

The *«presence of a giant cluster is an indicator of a network that is at least partly performing its intended function, while the size of the giant clusters tells us exactly how much of the network is working»* [Newman, 2010].

If the giant cluster size decreases significantly, also the average shortest path length within it is likely to decrease as well. Both quantities are correlated and are combined by multiplication into a single value (Table 33).

Table 33 Method for measuring the structural impacts on the system performance

Measure	Explanation	Range
Integrity: Dynamics of the giant cluster size	Number of stations in giant cluster relative to pre-disaster level	0 - 1
Distance parameter dynamics: Dynamics of the average shortest path lengths within giant cluster	Minimum of the average shortest path length within giant cluster relative to pre-disaster level or its reciprocal	0 - 1
Structural robustness	Multiplication of the two values above	0 - 1

Then, *structural robustness* values close to 1 indicate that the topology is only slightly degraded, i.e. the network sustains is a large giant cluster and also the average shortest path lengths remains almost constant. Values of the *structural robustness* close to zero indicate severe impacts on the topology such that the network totally disintegrates and / or the average shortest path lengths are significantly changed. An example for measuring the structural system performance is shown in Table 34.

Table 34 Example for calculating values of the *structural robustness*

Measure	Planned state	Degraded state	→ Value
Giant cluster size	1.0	Giant cluster size: 0.9	$q_a = 0.9$
Average shortest path length	1.0	Mean shortest path length: 1.2	$q_b = 5/6$
Structural robustness	1.0 (100 %)	By multiplication	0.750

5.6 Quantifying the operational robustness

Measuring the effects of removing elements from the *Infrastructure* topologies typically assesses network robustness. However, *«the amount of traffic characterizing the connections in* *communication and large transport infrastructures is fundamental for a full description of these networks»* [Barrat et al., 2004]. Due to threatening events, nodes and links are removed such that these elements cannot be traversed any longer. Hence, the train paths of those lines traversing the removed elements in planned operation have to be changed, i.e. the affected lines have to be rerouted or truncated. Even in degraded operation, line paths should to be followed as close as possible such that it is the aim to locally drive around the removed elements if possible. Two different aspects are measured and included for the quantitative assessment of the *operational robustness* in this study: the connectivity and the capacity utilization of the degraded network.

Measuring the impacts on the connectivity in degraded operation

The **connectivity-related measures** quantify the degradation of the operated network. This concept relates to the *structural robustness* as introduced in the previous section. In contrast to the *structural robustness,* the connectivity related measures quantify the structure of the operated network containing only those nodes and links that are traversed by lines in degraded operation. Depending on the availability of turnaround alternatives and rerouting possibilities the networks of the degraded network and the degraded operated network may differ significantly. The following measures are included in the *connectivity value* all ranged between zero and one (this set can be extended, see section 9.4)*:*

- **Number of served stations:** Number of stations that are still operated by at least a single line relative to pre-disaster level, i.e.

  $$q_1 = \frac{Number\ of\ the\ stations\ that\ is\ still\ served\ in\ degraded\ operation}{Number\ of\ served\ stations\ in\ planned\ operation}$$

  This measure is ranged between 0 and 1. Small values indicate that many stations are not served anymore, while values close to 1 indicate that the majority of stations is still operated even in degraded operation state.

- **Number of stations within the operated giant cluster:** Number of served stations that are contained in the giant cluster, relative to pre-disaster level, i.e.

  $$q_2 = \frac{Number\ of\ served\ station\ in\ the\ giant\ cluster\ (degraded\ state)}{Number\ of\ served\ stations\ in\ largest\ component\ (planned\ state)}$$

  The giant cluster is the component in the degraded network that contains the majority of operated stations. Though operated, many stations may lie outside the giant cluster. This value relates to the giant cluster size used for measuring the *structural robustness*.

- **Average shortest path lengths within the giant cluster:** Average shortest path length within the giant cluster relative to pre-disaster level. This quantity is measured as follows:

  $$q_3 = Min\{q'_3; 1/q'_3\} \epsilon [0; 1]$$

  Where:

  $$q'_3 = \frac{Average\ shortest\ path\ length\ in\ giant\ cluster\ (Degraded\ state)}{Average\ shortest\ path\ length\ in\ the\ largest\ component\ (Planned\ state)}$$

  The calculated value take values in the interval [0;1] and relate to the mean shortest path length within the giant cluster used for measuring the *structural robustness*.

- **Average number of changing line processes from the customer's point of view:** The line path matrix allows drawing a bipartite graph connecting two nodes if a specific line serves both. Then, the mean shortest path length within this network determines the mean number of changing line processes for travelling between any two stations. This quantity can increase or decrease and is expressed relative to pre-disaster level and is quantified in the following way:

  $$q_4 = Min\{q'_4; 1\} \epsilon [0; 1]$$

  Where:

  $$q'_4 = \frac{Mean\ number\ of\ changing\ line\ processes\ (Planned\ state)}{Mean\ number\ of\ changing\ line\ processes\ \ (Degraded\ state)}$$

  The value of this measure are defined in a way such that only increasing values of the number of changing line processes reduce the quantity. If the values decrease, i.e. the mean number of changing line processes decreases due to the rerouting of lines, the quantity is not reduced.

All these measures are correlated and are hence integrated into a single value for measuring the impacts of node and link removals on railway operation, the *connectivity value* is calculated by multiplying the values of the introduced measures:

$$Connectivity\ value = q_1 \cdot q_2 \cdot q_3 \cdot q_4 \ \epsilon \ [0; 1]$$

The *connectivity value* takes small values if the network in degraded operation is severely reduced; large values show that the operated network is still highly connected.

Measuring the impacts on the capacity utilization in degraded operation

Beside the network integrity in degraded operation state, also the capacity utilization of tracks in degraded operation can be exceeded. This means that the network may remain connected such that the *connectivity value* remains high, but the capacity utilization of links may be exceeded in degraded state. Hence, a second set of measures is introduced quantifying different aspects of the capacity utilization of links in the degraded network. The following measures are integrated in the calculation of the *capacity value*:

- **Sum of track-kilometres of all lines:** Total sum of line path lengths relative to pre-disaster level. If the total sum of train path length significantly increases in degraded operation state, the financial costs for operating lines is likely to increase as well since longer routes have to be driven. This is measured in the following way:

  $$q_5 = Min\{q'_5; 1\} \in [0; 1]$$

  Where:

  $$q'_5 = \frac{\sum_{lines} Line\ path\ length\ in\ [km]\ \ (Planned\ state)}{\sum_{lines} Line\ path\ length\ in\ [km]\ \ (Degraded\ state)}$$

  The defined value is one in planned operation and only reduced if the total sum of track-lengths of all lines increases.

- **Number of vehicles for degraded operation:** Sum of the vehicles needed for operating all lines, relative to pre-disaster level, i.e.

  $$q_6 = Min\{q'_6; 1\} \in [0; 1]$$

  Where:

  $$q'_6 = \frac{\sum_{lines} Trains\ in\ operation\ \ (Planned\ state)}{\sum_{lines} Trains\ in\ operation\ \ (Degraded\ state)}$$

Rerouting lines can significantly increase the time needed for driving between the endpoints of a line such that additional trains are needed for operating lines with constant frequency. Only if the total number of trains increases, the introduced measure is reduced.

- **Number of edges utilized above the specified theoretical capacity thresholds:** Number of additional edges utilized above the specified theoretical capacity thresholds relative to the number of all edges, i.e.

$$q_7 = \frac{Number\ of\ additional\ edges\ utilized\ above\ theoretical\ capacity\ threshold}{m}$$

  Rerouting lines can exceed the specified capacity thresholds on the level of the theoretical capacity. Only those links are counted for which these thresholds are exceeded in degraded operation due to this rerouting, i.e. links for which the threshold is exceeded even in planned operation are not counted. The measure takes value between zero and one, with small values observed if many edges are utilized above the threshold in degraded operation.

- **Number of edges utilized above the specified operational capacity thresholds:** Number of additional edges utilized above the specified capacity thresholds relative to the number of all edges, i.e.

$$q_8 = \frac{Number\ of\ additional\ edges\ utilized\ above\ operational\ capacity\ threshold}{m}$$

  As for the theoretical capacity threshold, rerouting lines can exceed the operational capacity limits for additional edges. If this is the case for many links, the introduced quantity is significantly reduced.. In the degraded operation, link capacity thresholds may be exceeded such that lines may destabilize.

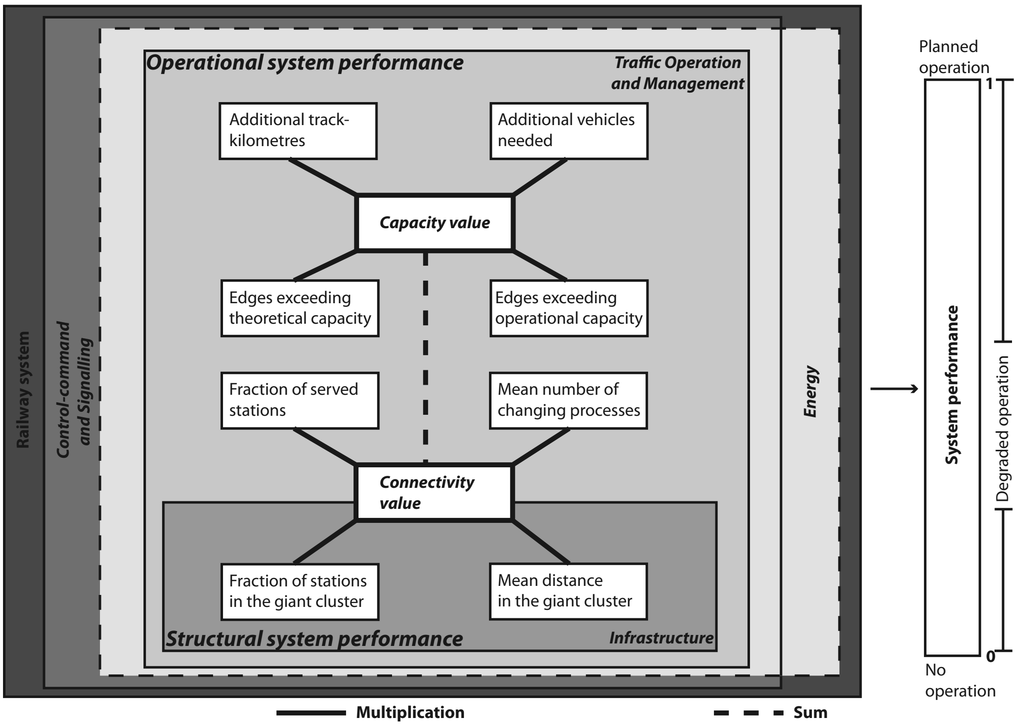
All these measures are correlated and are hence integrated into a single value for measuring the impacts of node and link removals on the capacity utilization in degraded operation, the *connectivity value* is calculated by multiplying the values of the introduced measures:

$$Capacity\ value = q_5 \cdot q_6 \cdot q_7 \cdot q_8 \in [0; 1]$$

Number of changing line processes

Since public transport customers *«dislike changing trains to reach their destinations»* [Sen et al., 2003], it is interesting to know how often customers have to change trains or lines on their travel from the origin to the destination. It is possible to derive a new matrix out of the line path matrix, such that nodes represent stations that are linked if they are served by the same line or train path. The average shortest path length in this bipartite graph quantifies the minimal number of lines travellers have to use for travelling between any two stations.

Figure 35 Scheme for quantifying the system performance of railway networks



Number of vehicles needed for operation

In degraded operation, rerouting lines may increase the running time between its end nodes. As a result, additional vehicles may become necessary. The truncation of line paths does not increase the number of vehicles needed for operation a line. According to [Weidmann, 2008a], this quantity can be calculated as follows:

$$|Vehicles| := \left\lceil \frac{Turnaround\ time}{Headway\ time} \right\rceil$$

$$= \left\lceil \frac{2 * (Driving\ time + Turnaround\ time\ at\ terminal)}{Headway\ time} \right\rceil$$

The *turnaround time* is defined as two times the time needed for driving from starting station to the final station plus two times the turn-around time at terminus. The factor two is needed for assessing the overall time for a vehicle to run the entire line path in both directions.

Measuring the degradation of railway operation

An overview over the definitions of the measures used for quantifying the *connectivity value* and the *capacity value* is given in Table 35. All values are ranged between zero and one.

Table 35 Method for measuring the operational impacts on the system performance

Aspect	Measure	Definition	Range
→ *Connectivity value*	Served stations	Served stations relative to pre-disaster level	0 - 1
	Served stations within giant cluster	Stations in operated giant cluster relative to pre-disaster	0 - 1
	Average shortest path length within giant cluster	Minimum of average shortest path length in the operated giant cluster relative to pre-disaster level and its reciprocal.	0 - 1
	Mean number of changing line processes	Minimum of the reciprocal of the average number of changing processes in giant cluster relative to pre-disaster and one (only increases are relevant)	0 - 1
→ *Capacity value*	Sum of additional line path lengths	Minimum of the reciprocal of the total line lengths relative to pre-disaster and one (only increases are relevant)	0 - 1
	Number of vehicles needed for operation	Minimum of the reciprocal of the total number of vehicles relative to pre-disaster and one (only increases are relevant)	0 - 1
	Edges exceeding theoretical capacity	Fraction of additional edges above theoretical threshold value	0 - 1
	Edges exceeding operational capacity	Fraction of additional edges above operational threshold value	0 - 1

The *connectivity value* and the *capacity value* are not necessarily correlated, i.e. there may be degraded states for which the *capacity value* is reduced (if lines are rerouted along heavily used edges) or it may happen that the value is not changed: If all lines needing dispositive efforts are truncated, the *capacity value* remains constantly at 1, while the *connectivity value* is likely to be significantly reduced. If in degraded operation all lines are rerouted, the *connectivity value* will remain close to 1 but the *capacity value* is likely to be reduced.

All measured quantities are combined in order to get a single value as displayed in Figure 35. The connectivity-related measures are multiplied. The same holds for the capacity-related ones. Since the connectivity-related and capacity utilization-related values are independent, both are connected by addition into a single value as follows:

$$Operational\ robustness\ =\ Max\{0; (Connectivity\ value + Capacity\ value - 1)\}$$

This guarantees that the operational consequences measure is also ranged between 0 (no operation) and 1 (operation according to planned operational state). Table 36 included two examples showing how to calculate the *operational robustness*.

Table 36 Example for calculating the *operational robustness*

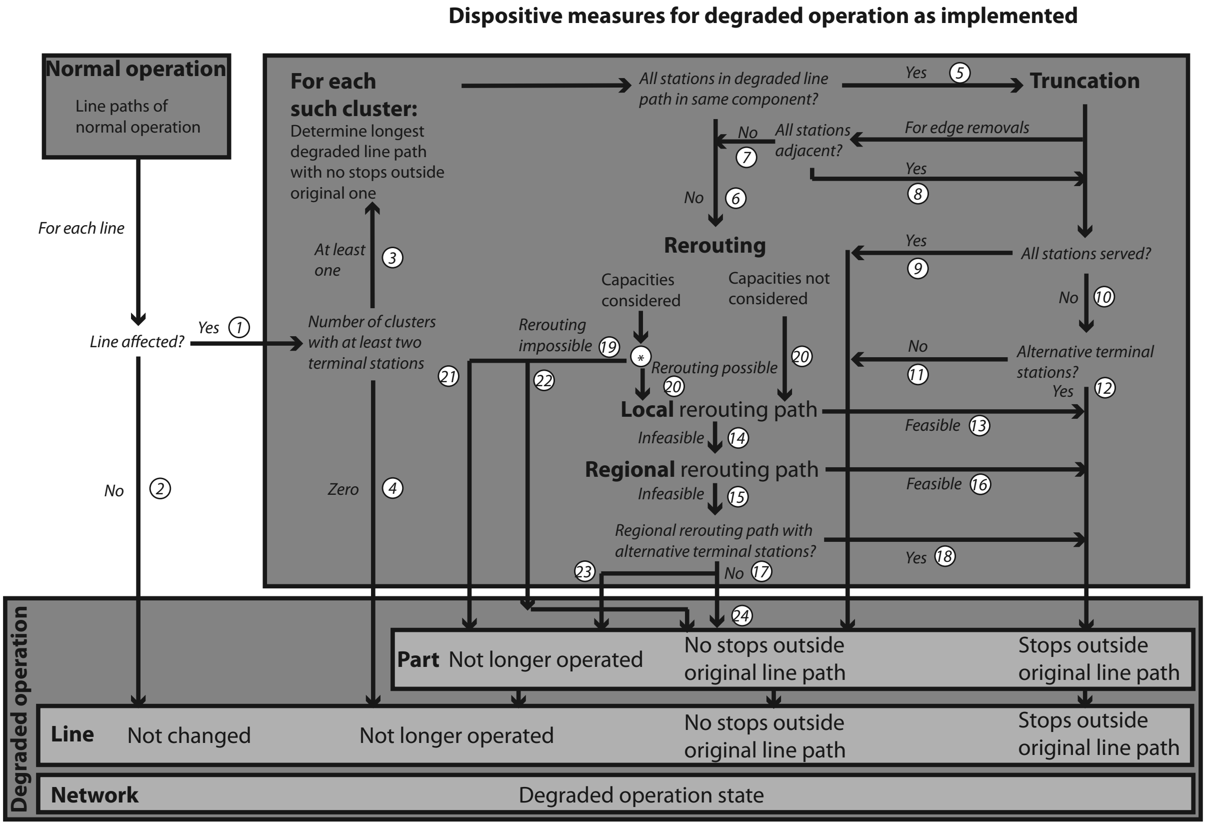
Dispositive measure	***Case 1:*** Blockaded link causes rerouting	Value	***Case 2:*** Truncation of a line	Value
q_1 : Served stations	All stations served	1.00	95 % of stations still served	0.95
q_2 : Giant cluster size	All stations within giant cluster	1.00	Giant cluster contains 75 % of the operated stations	0.75
q_3 : Mean distance	20 % increase relative to pre-disaster value	0.83	Mean distance decreases to 90 % of pre-disaster level	0.90
q_4 : Changing processes	Slightly less changing processes.	1.00	Slightly less changing processes.	1.00
Connectivity value	By multiplication	0.83	By multiplication	0.64
q_5 : Track-km	Increases by 7 per cent	0.93	Total track-km decreases	1.00
q_6 : Vehicles	+10 % additional vehicles	0.91	No additional vehicles	1.00
q_7 : Operational capacity	95 % of the links below operational capacity relative to pre-disaster value	0.95	No additional edges utilized above operational capacity	1.00
q_8 : Theoretical capacity	98 % of the links below theoretical capacity relative to pre-disaster level	0.98	No additional edges utilized above theoretical capacity	1.00
Capacity value	By multiplication	0.79	By multiplication	1.00
Operational robustness	According to formula	0.62	According to formula	0.64

The introduced quantification scheme allows to express the impacts of threatening events on railway operation by single values and to compare the impacts. Even though the operational consequences differ, the operational robustness values approximately coincide. While in the *case 1* scenario both the connectivity and the *capacity value* are reduced, for *case 2* only the *connectivity value* is reduced. This is due to the fact that truncating lines does not cause new capacity utilization problems.

5.7 Calculation of degraded operation states

This section shows how degraded operational states are calculated by introducing the developed line disposition framework. This framework is implemented in *R* for assessing the operational consequences due to removing nodes and links, which simulates the impacts of events threatening railway networks. Figure 36 illustrates the implemented dispositive measures that the analysis results presented in chapter 6 is based on.

Figure 36 Line disposition framework as implemented in *R*



The following dispositive measures are distinguished:

- **Line paths are not changed**, if a line does not traverse any failing *Infrastructure* element (→ Branching path (2))
- **(Parts of) Lines cannot longer be operated**, if for all parts of the line there are no two turnaround alternatives within the same component, or rerouting alternatives cannot be taken due to length or capacity utilization restrictions (→ Branching path (4), (21), or (23))
- **(Parts of) Line paths are truncated**, if rerouting a line is not possible or the rerouting paths are infeasible (→ Branching path (9), (11), (22) or (24)),
- **(Parts of) Line paths are rerouted**, if rerouting is both, possible and rerouting paths are feasible (→ Branching path (12), (13), (16) or (18)).

Explanation of the single steps and branching paths

The numbers within the circles indicate branching paths of the implemented model and are briefly described in the following:

1. For each operated line is checked whether it traverses a blockaded element of the *Infrastructure* topology → (1) or not → (2). In the latter case line paths are not changed.

2. For each affected line, clusters in the degraded network are searched that contain at least two turnaround alternatives of the corresponding line. For each such component further dispositive measures are considered → (3). If there is no such component, the line is not longer operated → (4).

3. For each component found in (3), it is checked whether all stations between the first and the last station lie within this component or not. If this is the case, the (part of the) line is potentially truncated → (5). Otherwise, the line is potentially rerouted in order to drive around blockaded elements → (6).

4. If single edges are removed from the topology, an additional check is made whether all stations of the analysed part of the line lie in the same component and are connected in the degraded network. Then, the line is potentially truncated → (8); otherwise the line is potentially rerouted → (7).

→ Truncation module

5. The part of the line actually considered might contain all stations that belong to that cluster and are served by the line in normal operation. If so, the degraded line path is found → (9). Otherwise, there are stations in that cluster that might be served if alternative turnaround stations outside the line path of the line exist → (10).

6. Alternative turnaround stations outside the line path can exist that would allow serving additional stations of that line. This would increase the number of stations that can still be served and therefor is beneficial → (12). If there is no such turnaround alternative within feasible distance, the line part cannot be extended → (11).

→ Rerouting module

7. Even though rerouting alternatives exist from the structural point of view, capacity restrictions may hinder the rerouting of lines. In other words, the rerouting tracks may not have enough capacity left such that the corresponding line can traverse them such that rerouting becomes impossible → (19). Depending on whether the found line part contains shorter line segments that can be operated, either the line part is shortened →

(22) or not operated anymore → (21). If either an alternative route exists with enough capacity left or capacity restrictions are not considered at all, local rerouting may be possible → (20).

8. The calculated local rerouting path may be of infeasible length. If so, longer regional rerouting alternatives are searched → (14). Otherwise, a new degraded line part including local rerouting is found → (13). A local rerouting path looks for the shortest path (in track-km) between the two neighbouring nodes with degree larger than two, lying before and after stations outside the considered component. Capacity restrictions may have to be considered.

9. Also the regional rerouting path may be of feasible → (16) or infeasible length → (15). A regional rerouting path is the shortest path (in track-km) between those two nodes before and after the removed elements that offer a turnaround possibility and have degrees larger than two. The calculated local and regional rerouting paths may coincide.

10. Even if both, the local and regional rerouting paths, are of infeasible lengths they may include feasible turnaround alternatives outside the original line path → (18). If this is not the case → (19), no rerouting solution is found such that the corresponding line part is either not operated anymore → (23) or truncated → (24).

***Additional statements about alternative turnaround stations* → Steps (11), (12)**

Alternative terminal stations are feasible if the following two conditions are both met:

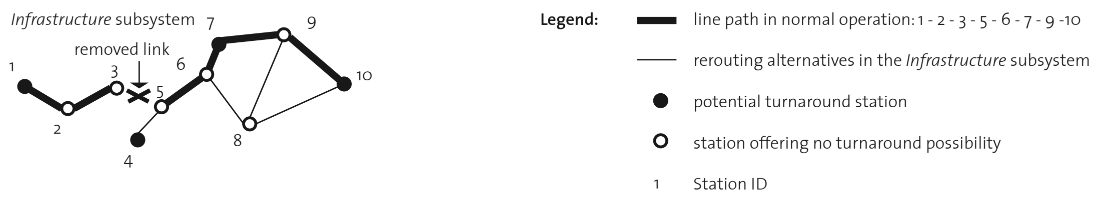
- The turnaround station is located within shorter distance (measured in track-kilometres) than a defined radius around the present turnaround station,

- Using this turnaround alternative in degraded allows to serve additional stations of the line (stations served by the line in planned operation).

For the *Swiss railway* network, the maximal allowed radius is set to 20 kilometres as the crow flies. For the *Zurich tramway* networks, a value of 2.5 km was found to give reasonable, that is realistic disposition results. Obviously, these values can easily be adjusted for allowing smaller or greater distances. An example visualising the steps made in (11) and (12) is given in Figure 37.

In the example illustrated in Figure 37, the line part found in step (3) is *Station 7 – Station 9 – Station 10 that all* lie in the same cluster in the degraded network. The second occurring cluster only contains a single turnaround alternative of the line and is not considered. In the first case, a part of the original line path can still be served. Step (5) determines that all three stations lie within the same component, hence the *truncation module* is started in order to check whether the line path can be extended to serve additional stations. Step (10) determines that *Station* 5 and *Station* 6 belong to the same cluster but are not served yet. Under the assumption that *Station* 4 is within the specified radius from *Station 5,* considering *Station 4* as a turnaround alternative allows to additionally serve *Station 5* and *Station 6* (step (12)). As a result of the implemented line disposition framework, the degraded line path is *Station 4 – Station 5 – Station 6 – Station 7 – Station 9 – Station 10.* The degraded line path contains stations outside the original line path and hence represents a rerouting measure.

Figure 37 Illustration and example of branching paths (11) and (12)



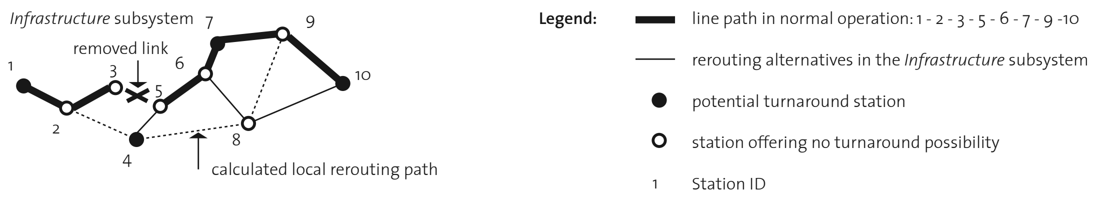
***Additional statements about the local rerouting path* → Steps (13), (14)**

The local rerouting path searches the shortest path between the last station before the first failing link with degree greater than two and the first station after the last link with degree greater than two. These two stations are referred to as the *local rerouting stations* (see Figure 39). Nodes with degree one or two offer no rerouting alternative.

A local rerouting path has *feasible length* if the calculated resulting degraded part of the line path is not longer than two times the line path length in planned operation. This condition refers to the fact that the length of rerouting paths cannot take arbitrarily large values. The value for the factor can be adjusted as well but is considered to be reasonable, i.e. the simulation results showed that the factor 2 gave realistic solutions for accepting or neglecting local rerouting paths. If the calculated rerouting paths contains previously served stations, the degraded line path is integrated as shown in Figure 38. The local rerouting path between *Station 2* and *Station 6* might be along *Station 2 – Station 4 – Station 8 – Station 9 – Station 7 – Station 6* if this path is the shortest path between *Station 4* and *Station 6* (measured in km). Then, the degraded line path is *Station 1 – Station 2 – Station 4 – Station 8 – Station 9 – Station 10.*

In the example illustrated in Figure 39, the line is locally rerouted between *Station 5* and *Station 6*, both having degrees greater than 2 in the original network. Hence, both stations offer rerouting alternatives. The local rerouting path with shortest length might be along *Station 5 – Station 4 – Station 8 – Station 6* such that the calculated degraded line paths is the following: *Station 1 – Station 2 – Station 3 – Station 5 – Station 4 – Station 8 – Station 6 – Station 7 – Station 9 – Station 10.*

Figure 38 Illustration and example of determining degraded line paths if the rerouting path contains previously served stations in branching paths (13), (14), (15) or (16)



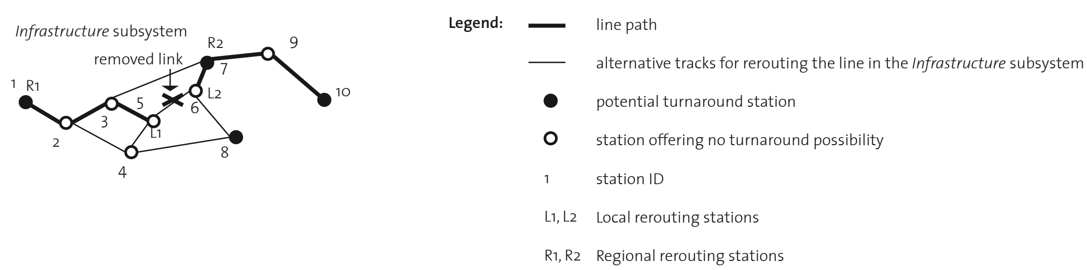
Additional statements about the regional rerouting path **→ Steps (15), (16)**

If the local rerouting path has infeasible length, regional rerouting may be possible. A regional rerouting path is considered to be of *feasible length*, if the distance between the two regional rerouting stations is not larger than the two times the corresponding distance in the original line path. This means that only regional rerouting paths are taken that are not too long in comparison with the distance in the non-degraded network. The value 2 was found to find realistic rerouting solutions mimicking the disposition measures in real world. If this value is too small, potential realistic rerouting paths are not found. Larger values may consider rerouting alternatives that are too long compared to real-world dispatching solutions.

In the example illustrated in Figure 39 the line is regionally rerouted between *Station 1* and *Station 7*, which are turnaround alternatives. The potential new, degraded line path may hence be along *Station 1 – Station 2 – Station 3 – Station 7 – Station 9 – Station 10.*

The length is *feasible*, if the distance between *Station 1* and *Station 7* of the regional rerouting path is not larger than two times the shortest path length between both in the original network (measured in km).

Figure 39 Illustration and example of branching paths (13) and (18)



Additional statements about turnaround alternatives → (17), (18)

Even if both, the local and regional rerouting path have infeasible lengths, potential alternative turnaround outside the line paths stations might be used. Only, if the local rerouting path contains potential turnaround stations, it is checked whether:

- The alternative turnaround lies within shorter distance than the length between the two local rerouting stations in the original line path
- And using the alternative terminal station allows serving at least one additional station of the original line path that would not be served otherwise.

In the example illustrated in Figure 39, both the local and regional rerouting path may be of infeasible length. Hence, the degraded line path would be along *Station 7 – Station 9 – Station 10* and hence be truncated. However, the local rerouting path along *Station 5 – Station 4 – Station 8 – Station 6* contains *Station 8* as a potential alternative terminal station. The alternative terminal can be used if it is assumed that the following two conditions are both met:

- The distance between *Station 6* and *Station 8* (in track-kilometres) is not longer than those between the local rerouting stations *Station 5* and *Station 6*,
- Additional stations of the original line path can be served. That is the case since using *Station 8* as an endpoint allows serving *Station 6.*

The degraded line path is along *Station 8 – Station 6 – Station 7 – Station 9 – Station 10.*

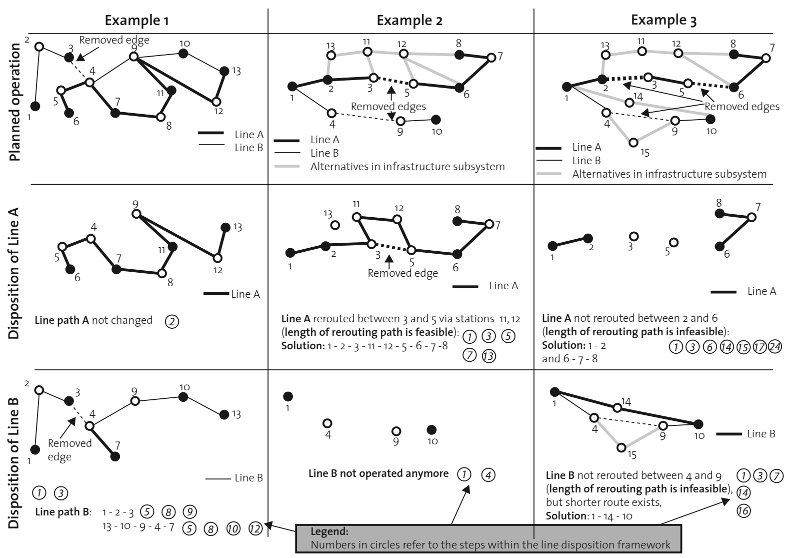
Examples

An illustration of the dispositive measures for calculating degraded operation states by application of the evaluated methodology is shown in Figure 40. Capacity utilization restrictions of potential rerouting alternatives are not considered. The figure presents examples of the working steps implemented in the robustness analysis tool for assessing the operational system performance. It includes three examples for transport networks comprising two lines, *Line A* and *Line B* and contains the solutions for degraded operation as computed with the implemented *R*-tool. The numbers in the circles show the steps as denoted in Figure 36.

Example 1 (left-hand side)

In the first example illustrated in Figure 40, a single link between *Station 3* and *Station 4* is removed from the *Infrastructure* topology. This does not affect *line A* such that the line path remains unchanged (*Step (2)* in the scheme in Figure 36). On the other hand, *Line B* contains this and dispositive measures can be taken. *Station 1, Station 2* and *Station 3* belong to the same component outside the giant cluster. Since *Station 1* and *Station 3* can be used as terminal stations; one part of the line is operated along stations *Station 1 – Station 2 – Station 3*. Within the giant cluster, *Line B* can be operated between the *Station 10* and *Station 13. Station 4* and *Station 9* belong to the giant cluster, but they do not offer turnaround possibilities. However, *Station 7* is found as an alternative turnaround station. Using this station as an endpoint allows serving *Station 4* and *Station 9*.

Figure 40 Examples illustrating the line disposition framework and the calculated solutions



Example 2 (middle)

Line B cannot be operated anymore since the removal of the link between *Station 4* and *Station 9* causes a disintegration of the network such that the line cannot be operated anymore. The component containing *Station 9* and *Station 10* only contains a single potential terminal station. On the other hand, from *Station 4* it is not possible to reach another potential end-station (other than *Station 1*). *Line A* can be rerouted between *Station 3* and *Station 5* via *Station 11* and *Station 13* that are both not contained in the original line path. The rerouting path allows *Line A* to be operated between *Station 1* and *Station 8*.

Example 3 (right-hand side)

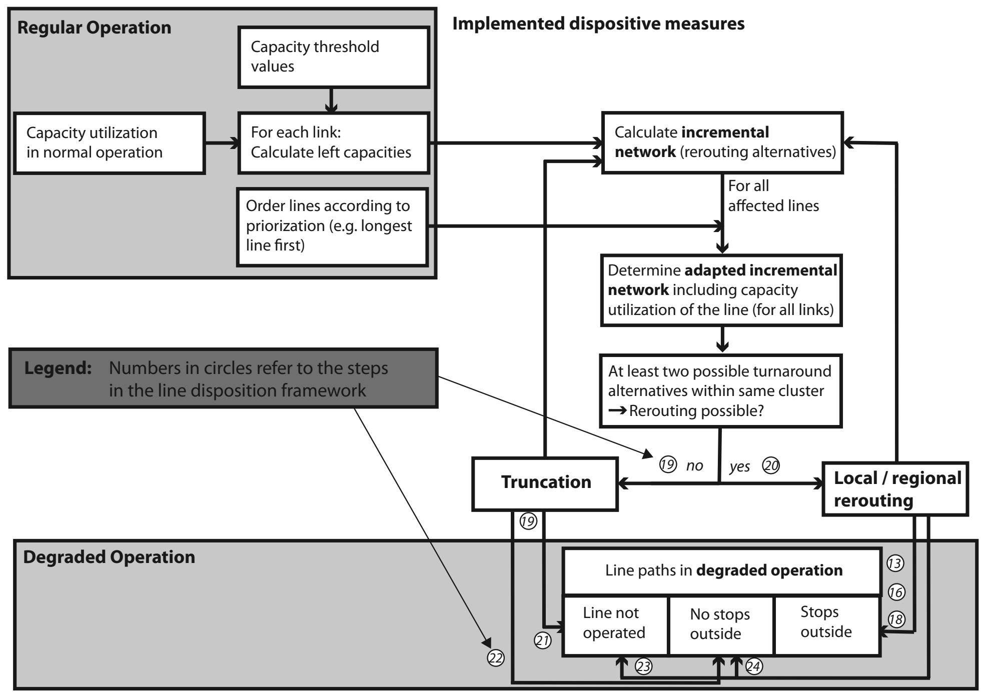
In degraded operation, *Line A* is split into two operated parts along the paths *Station 1 – Station 2* and *Station 6 – Station 7 – Station 8*. The rerouting possibility between *Station 2* and *Station 6* is considered as an infeasible alternative. *Line B* can neither be locally rerouted. However, in contrast to *Line A,* there exists a shorter alternative between the rerouting possibilities at *Station 1* and *Station 10* via *Station 14*.

Capacity-restricted rerouting

Figure 41 illustrates how alternative paths with consideration of capacity restrictions are calculated in this study. The introduced line disposition framework and the rerouting module remain unchanged, but the network is adapted by removing those links from the network that do not have enough free capacities left. The numbers in the circles correspond to those given in Figure 36. The steps described in the scheme within Figure 41 are situated at the position of (*) within Figure 36. In order to detect alternative routes with enough capacity left, the so-called *incremental network* is drawn containing only those links that have enough capacity left for offering rerouting alternatives. In other words, only those links remain, whose free capacity is at least as large as the frequency of the considered line.

In a first step, the incremental network is calculated by removing those links from the implemented *Infrastructure* topology, whose specified capacity threshold values are exceeded even in planned operation state. However, those links traversed by the analysed line are kept. The corresponding network is referred to as the *incremental* network within Figure 41. In a second step, those links are removed from it, whose values of capacity left are below the frequency of the analysed line. This means that the so-called *adapted incremental network* contains only those links that are either traversed by the line in planned operation or whose free capacity values are large enough such that the line can be rerouted along them without exceeding the pre-defined capacity thresholds.

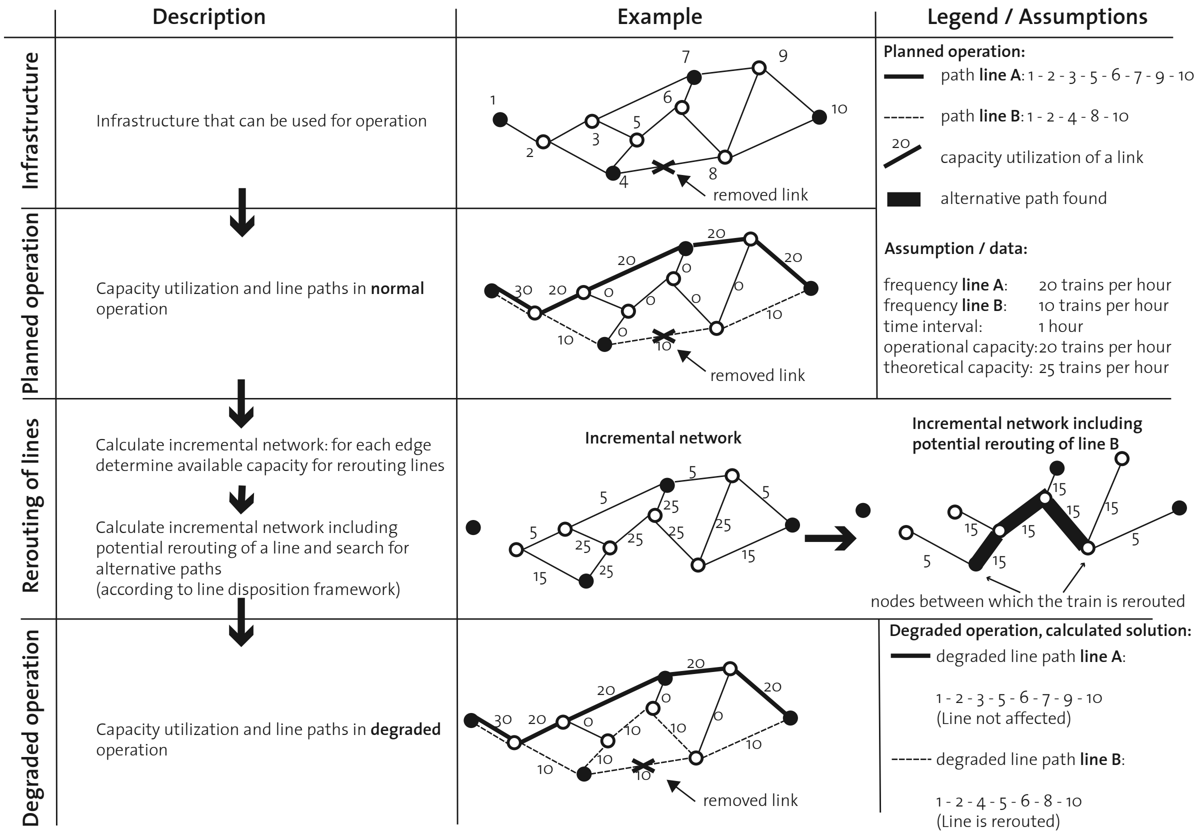
Figure 41 Scheme for capacity-restricted solutions within the line disposition framework



For the capacity-restricted rerouting it is important in which order lines are rerouted because this affects the availability of alternatives with enough free capacities. In this study, lines are dispatched according to their line path length (measured in distances between the endpoints in [km]). Longest lines are rerouted first.

The steps for capacity-restricted rerouting line paths are shown in the example in Figure 42. The analysed network contains 10 stations and 2 lines. The link between *Station 4* and *Station 8* is removed and cannot be traversed anymore. There are two lines operated. *Line B* is affected and has to be rerouted between *Station 4* and *Station 8*. The adapted incremental network shows that there exists an alternative route between *Station 4* and *Station 8* via *Station 5* and *Station 6*. The incremental network shows that for all edges along the alternative path there is capacity left for 25 courses per hour. Since *Line B* utilizes only 10 vehicles hourly, the alternative route exists and can be used for degraded operation.

Figure 42   Example illustrating the capacity-restricted disposition of lines



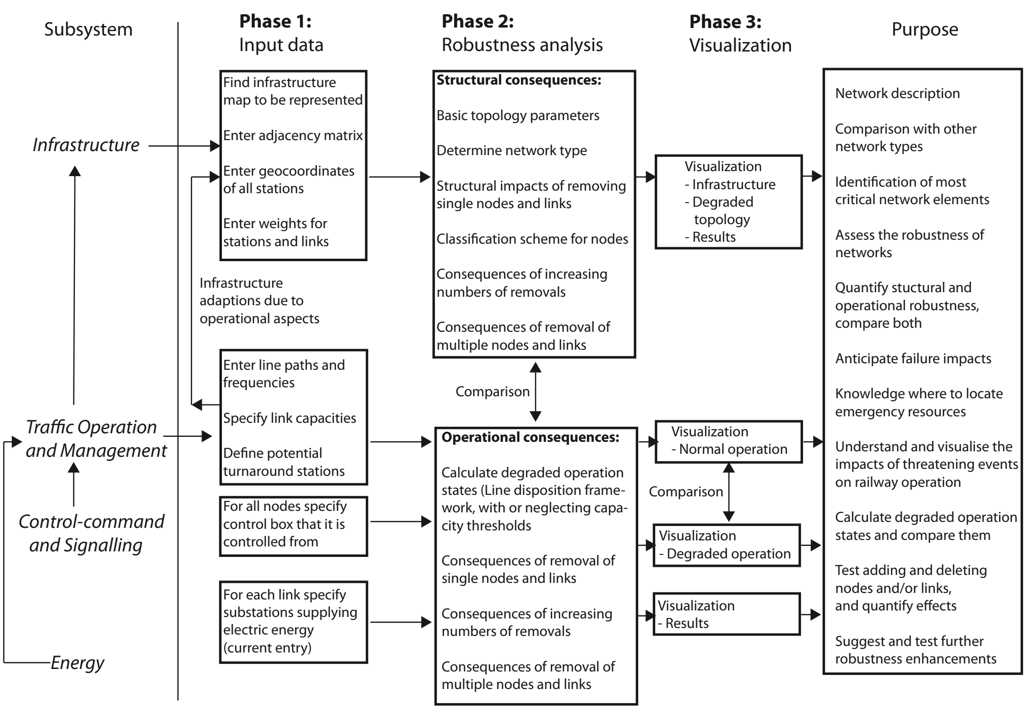
5.8 Features of the implemented analysis tool

The robustness of railway networks is analysed with a tool implemented in *R* with the functionalities illustrated in Figure 43. Three modules are distinguished:

- **Phase 1:** Preparation and specification of the input data, i.e. the network to be analysed
- **Phase 2:** Application of implemented robustness analysis methods including line disposition framework
- **Phase 3:** Visualization of the calculated degraded operational states and the results

The input data such as the topology (adjacency matrices, coordinates of the represented stations), edge weights (such as the distances between two stations in [km] and [min]), line paths or a set of potential turnaround stations is specified in **Phase 1**. In **Phase 2** the implemented robustness analysis methods are applied. The analysed networks can be manipulated and degraded operational states are calculated. The structural and operational robustness values are calculated and compared for different failure scenarios. **Phase 3** contains methods for visualizing degraded operational states and the calculated results.

Figure 43 Overview of the functionalities of the implemented robustness analysis tool



6 Robustness analysis results

6.1 Overview

Chapter 6 shows the results of applying the developed methodology and the implemented procedures to three case study networks. It is organized as shown in Table 37.

Table 37 Structure and contents of chapter 6

Section	Contents	Purpose
6.1	Overview	Contents of the chapter
6.2	Case study networks	Introduction of the case study networks analysed and the specified topological and operational input data
6.3	Structural robustness analysis results	Structural robustness results of the analysed railway networks
6.4	Operational robustness analysis results	Operational robustness results of the analysed railway networks

6.2 Analysed networks

Overview

Table 38 identifies the case study networks to which the implemented procedures and robustness analysis tool are applied. Beside the Swiss railway network, also two different networks representing the Zurich tramway network are analysed, the network in the year 2006 and in 2025. There are plans to build new stations, to add new tracks and to operate new lines. The results shall allow comparing the resiliencies of both networks.

Table 38 Analysed railway networks and represented subsystems

Network	*Swiss railway*	*Zurich tramway 2006*	*Zurich tramway 2025*
Location	Switzerland	Zurich (City)	Zurich (City)
Year	2009	2006	2025
Modes	Railway (standard gauge)	Tramway	Tramway
Infrastructure	Implemented	Implemented	Implemented
TOM	Implemented	Implemented	Implemented
CCS	Implemented	---	---
Energy	Implemented	---	---

The *Infrastructure* topologies were implemented using official maps as denoted in Table 39 and illustrated in the appendix. Each of the represented topology is adapted such that the functional Infrastructure network is represented (as described in section 5.3.2). This means that for each triangle present in the network, it was checked whether they have to be adapted or not. For the *Swiss railway* network, [Wägli, 1998] was used for checking the topology in detail and for determining the lengths of the represented tracks. The time needed for travelling along the edges was taken from the SBB Website. For the Zurich tramway networks, GIS-data was used to prove the correct macroscopic topology representation. The time needed for travelling along the edges are set to the travel times according to timetable data. The edge lengths for the tramway networks were measured in the maps of the GIS browser[14].

Table 39 Data used for representing the case study networks

Network	*Swiss railway*	*Zurich tramway 2006*	*Zurich tramway 2025*
Turnaround alternatives	Stops of long distance lines	Existing ones	Existing ones, endpoints of new lines
Infrastructure topology	Figure 107	Figure 105	Figure 106
Represented lines and their line paths	Table 85	Table 86	Table 87
Represented Control-command and Signalling nodes	Table 89	-	-
Represented Energy nodes	Table 90	-	-
Headways [min]	30 – 240, Timetable data for October 2009	All lines: 7.5	All lines: 7.5 Line 12: 15
Time interval	24 hours	60 minutes	60 minutes
Turnaround time [min]	5	2	2
Maximal radius for turnaround alternatives [km]	20	2.5	2.5
Operational capacity thresholds [trains/time interval]	Single-track: 80 Double-track: 250	30	30
Theoretical capacity thresholds [trains/time interval]	Single-track: 120 Double-track: 375	60	60

Data for representing the *Traffic Operation and Management* subsystem is implemented for both *Zurich tramway* networks and the *Swiss railway* network. For the *Zurich tramway 2025* network, it is assumed that the new lines also run with 7.5 minutes headway time like all lines recently do. The only exception is *Line 12* operated with a frequency of four courses per hour. *Control-command and Signalling* data was provided by the SBB. This data was implemented

[14] http://www.gis.zh.ch/gb4/bluevari/gb.asp

as schematically illustrated in Figure 20. For other Swiss railway operators it is assumed that a single control box controls each of the operator's stations.

Also for the *Energy* subsystem, data was provided by the SBB indicating for each node and link from where electrical current is distributed (see Figure 24). For the tramway networks, *Control-command and Signalling* devices are not considered since almost all switches and signals are controlled from the approaching tram vehicles.

Traffic Operation and Management

Table 39 also contains the values of operational data that were specified for calculating the presented results. All the specified values can be adjusted. For both tramway networks, all tramlines are represented. For the *Swiss railway* network, only regularly running long-distance trains were represented that are listed in Table 85. Urban railway lines and freight transports can be added to the model (see section 9.4). The specified capacity threshold values denote the maximal numbers of vehicles that can use an Infrastructure edge within the specified time interval and were taken from Table 40.

Table 40 Capacity threshold values as used in this study

	Tramways[1]	Railway transport[2]	
		Single tracks	Double tracks
Theoretical capacity	60	120	375
Operational capacity	30	80	250
Unit	Per hour and direction	Per day and direction	Per day and direction

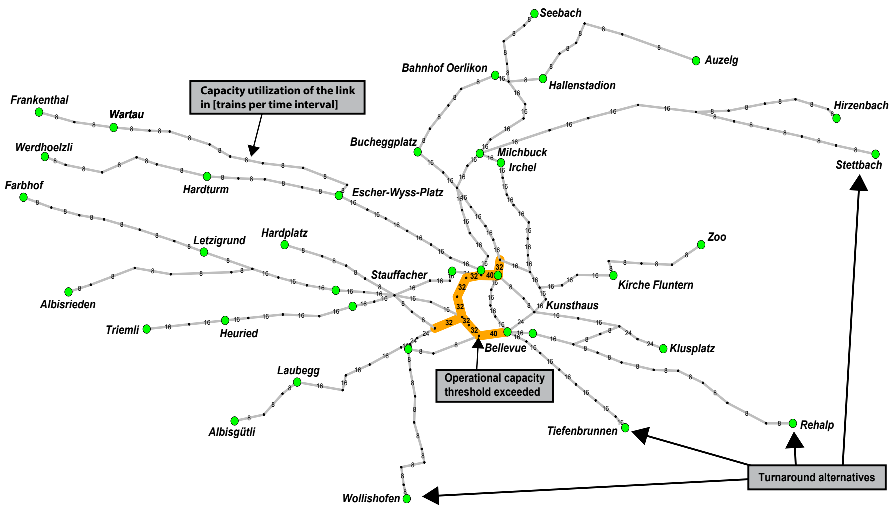
Source: [1] [Anderhub et al., 2008], [2] [Weidmann, 2008b] – theoretical capacity threshold values are set to 1.5 times the operational ones

The representations the tramway networks are illustrated in Figure 44 and Figure 45. The corresponding visualization of the *Swiss railway* network is depicted in Figure 46. The stations highlighted by green circles indicate the specified potential turnaround alternatives that can be used either in planned or degraded operation as end points of the line paths in degraded operation. Table 88 identified these stations for all the represented networks.

The numbers along the edges indicate the number of trains traversing a link per time interval and direction (the time interval is specified in Table 39). Edges utilized above the operational capacity thresholds are highlighted using orange colours. In all analysed networks edges are present that are utilized above the specified operational capacity thresholds (Table 40).

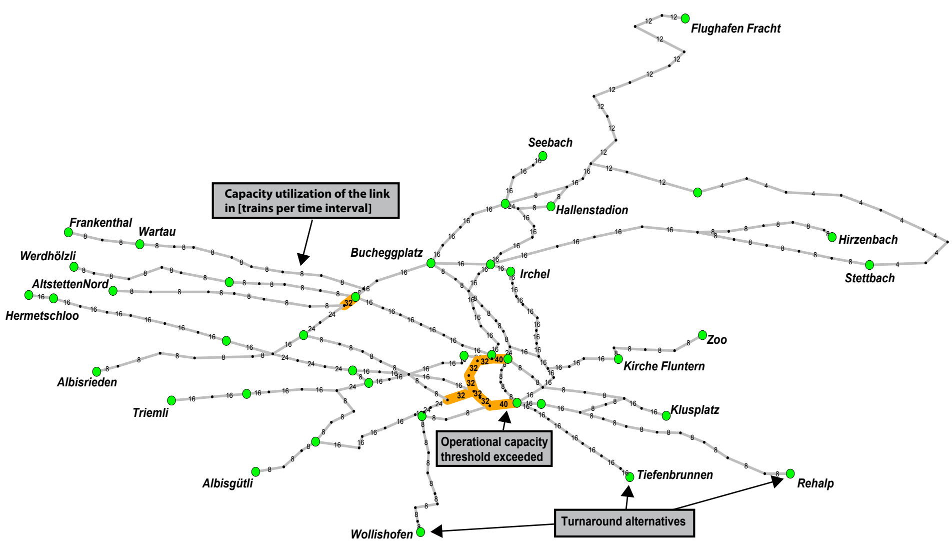
In *Zurich tramway 2006*, the corridor *Bellevue – Bürkliplatz – Paradeplatz – Bahnhofstrasse / HB* is intensively used in planned operation state such that the specified operational capacity thresholds are exceeded for the links in this corridor. The network contains 36 turnaround alternatives (identified in Table 88) and 13 lines (listed in Table 86) were represented.

Figure 44 *Traffic Operation and Management* representation of *Zurich tramway 2006* in *R*



For the *Zurich tramway 2025* network (Figure 45), beside the mentioned links in the city centre of Zurich also the capacity threshold for the link between *Schiffbau* and *Escher-Wyss-Platz* is exceeded on the level of the operational capacity threshold. This network contains 39 turnaround alternatives and 14 lines as denoted in Table 87 and Table 88 (in the appendix).

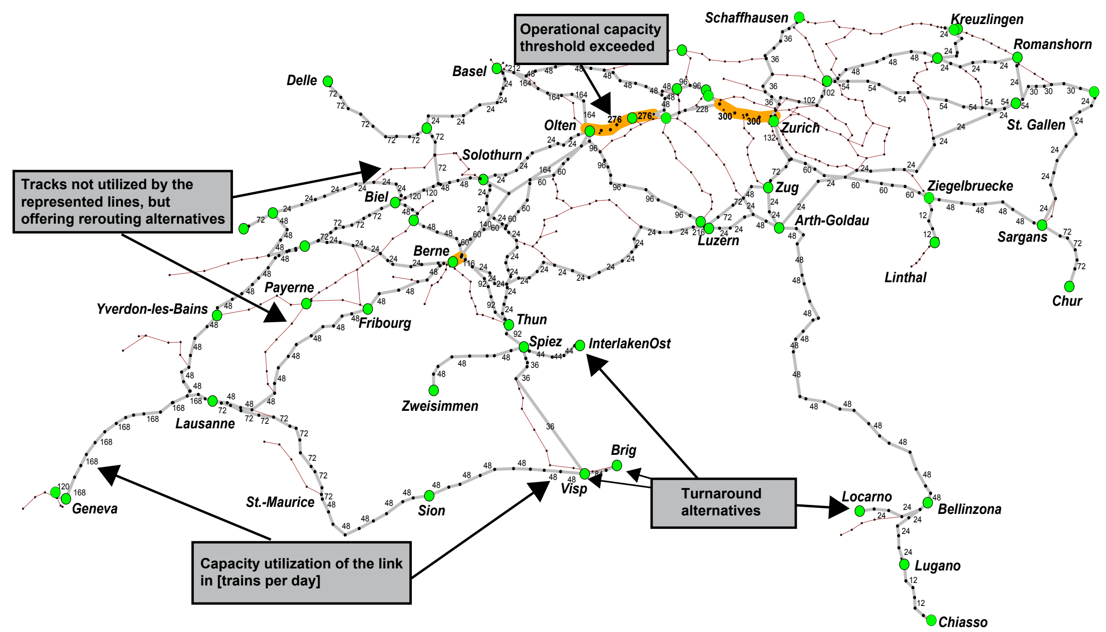
Figure 45 *Traffic Operation and Management* representation of *Zurich tramway 2025* in *R*



Also *Swiss railway* network (see Figure 46) contains edges that are utilized above the specified operational capacity thresholds, i.e. along the corridors *Bern – Wankdorf*, *Olten – Aarau* and *Killwangen – Zurich*. For each link was specified whether they contain single or double tracks and the capacity threshold values denoted in Table 40 are implemented. For this network, a more detailed representation of tracks would pay attention to the presence of multiple tracks: When approaching (or leaving) *Zurich HB* actually more than the represented double track-capacity is available such that higher capacity limits may be present in the real network.

Those links and nodes not traversed in the represented planned operation state are actually traversed by urban railway lines and other railway services that are not considered in the model. These lines and train movements can be added to the model. However, the non-utilized represented tracks can be used for finding rerouting solutions.

Figure 46 *Traffic Operation and Management* representation of *Swiss railway* in *R*



6.3 Structural robustness analysis results

6.3.1 Introduction

This section presents the results of the topology analysis of the *Infrastructure* subsystem gained by applying the implemented robustness analysis tool. In a first step, operational aspects are neglected such that the transformations mentioned in section 5.3.3 are not taken into account in the analysis results contained in section 6.3.2. The topological key parameters are evaluated to give a first assessment of the structures and to compare the results to those measured for other networks (Table 7). Afterwards, the *Infrastructure* topologies are adapted as explained in section 5.3.3. Some of the present triangles are eliminated depending on the connections that serve as rerouting alternative in degraded operation.

6.3.2 Structural analysis of the non-adapted *Infrastructure* representations

The calculated topological parameter values shown in in Table 41 give a first assessment about the structural properties of the represented topologies. The values can also be used for a comparison with the results gained for other networks as shown in Table 7.

Table 41 Topological key values calculated for the implemented *Infrastructure* topologies

Network	*Swiss railway*	*Zurich tramway 2006*	*Zurich tramway 2025*
Nodes	783	175	202
Edges	883	188	223
Sum of all edge weights [km]	3’716	72.8	91.1
Sum of all edge weights [min]	4’035	208.5	256.5
Number of connected components	1	1	1
Edge density	0.003	0.012	0.011
Mean degree	2.26	2.15	2.21
Assortative mixing by degree	-0.044	-0.02	-0.014
Transitivity C^2	0.08	0.045	0.036
Average shortest path length [hops]	28.3	13.6	13.1
Diameter [hops]	96	32	36
Eccentricity [hops]	66.0	24.2	26.2
Average shortest path length [km]	140.0	5.3	5.5
Diameter [km]	480.4	13.7	16.6
Eccentricity [km]	332.8	10.1	11.8
Average shortest path length [min]	133.1	15.3	15.1
Diameter [min]	470	36	41
Eccentricity [min]	319.5	27.3	30.1
Efficiency - global [%]	67.8	68.6	72.3
Efficiency - local [%]	3.4	2.1	1.8
Costs [%]	0.011	0.13	0.11

Table 42 compares the results calculated for the analysed railway network with those gained for other technological networks presented in Table 7. The analysed railway networks are comparatively small, i.e. they contain less nodes and edges than many other analysed networks. However, the calculated values match those derived for other technological networks. As stated in [Sen et al., 2003] technological networks typically are disassortative, i.e. the assortative mixing by degree values are negative.

The small transitivity values match the results gained for the topological features of the tramway system of Milano (Italy) in [Zio et al., 2008]. The authors state that urban public transport systems do not need to have high transitivity values since *«there is no need to build an extensive, highly-clustered physical network when the desired, efficient local connectivity behaviour is already ensured for free by the walkway.»*

The values quantifying the assortative mixing by degree match the results presented in [Sen et al., 2003] finding a value of -0.033 for the Indian railway network.

Table 42 Comparison of the calculated values with those presented in [Newman, 2010]

	Network	Nodes	Links	Mean degree	Mean distance	Fraction of vertices in largest component	C^2	Assortative mixing by degree
Technological	Power grid[15]	4'941	6'594	2.67	18.99	1	0.08	-0.003
	Train routes[16]	587	19'603	66.79	2.16	1	0.69	-0.033
	Software packages[17]	1'439	1'723	1.20	2.42	0.998	0.082	-0.016
	Electronic circuits[18]	24'097	53'248	4.34	11.05	1	0.030	-0.154
Railway networks	*Swiss railway*	783	883	2.26	28.3	1	0.08	-0.044
	Zurich tramway 2006	175	188	2.15	13.6	1	0.045	-0.02
	Zurich tramway 2025	202	223	2.21	13.1	1	0.036	-0.014

The results of the efficiency and cost values calculated for the analysed railway networks can be compared with the findings in [Latora et al., 2002] (see Table 43).

All networks are highly efficient on the global level. The global efficiency values lie in the range between 0.6 and 0.75, indicating that all topologies are only 25 – 40 % less efficient than networks with direct tunnels between all stations. This meets the observation was also made for the Boston underground transportation system in [Latora et al., 2002]. The small local efficiency values show that the removal of a single node has severe impacts transport services between the previous and the following station. Due to the immense costs for building tracks, the costs for transport networks are small [Latora et al., 2002].

15 Reference: [Watts et al., 1998]

16 Reference: [Sen et al., 2003]

17 Reference: [Newman, 2003]

18 Reference: [Ferrer i Cancho et al., 2001]

Table 43 Comparison of the efficiency and cost values of real-world networks presented in [Latora et al., 2002] and the calculated results

Network	Network efficiency	Local efficiency	Costs
Boston underground metro	0.63	0.03	0.002
Boston underground metro and bus service	0.72	0.46	0.004
Swiss railway	0.68	0.03	0.011
Zurich tramway 2006	0.69	0.02	0.13
Zurich tramway 2025	0.72	0.02	0.11

Evaluation of the network type

For many large-scale networks it was shown that they have small-world characters and scale-free node-degree distributions. A network shares the *small-world property* if the following two conditions are both met [Watts et al., 1998]:

1. Small average shortest path lengths, only slightly larger than those for the random graph equivalents
2. The transitivity values are larger than those of the corresponding random graph ones

Table 44 presents the calculated values for the analysed networks and their random graph equivalents. The values for the random networks are averaged for 10'000 realizations of random networks with the same number of links and nodes as the corresponding real-world ones. All networks can be assumed to fulfil the small-world properties.

Table 44 Determination of the network type for the case study networks

Network	*Swiss railway*	*Zurich tramway 2006*	*Zurich tramway 2025*
Nodes	783	175	202
Edges	883	188	223
Actual: Mean shortest path length [hops]	28.3	13.6	13.1
Actual: C^2	0.080	0.045	0.036
Random: Mean shortest path length [hops]	7.6	6.0	6.0
Random: C^2	0.003	0.012	0.011
Small-world property	✓	✓	✓

Many real-world networks are small-worlds with scale-free node-degree distributions, i.e. *scale-free networks*. These networks have node-degree distributions decaying as a power-law, which is indicated by plotting the histogram of node-degrees or the cumulative degree-distribution on a double logarithmically scaled plot. A straight line in this plot indicates a node-degree distribution decaying as a power-law with parameter γ. The results for the analysed network are shown in Figure 104 in the appendix. This method is the commonly used method and is called the *graphical method*. The calculated values of γ are presented in Table 45 (for nodes with degree 2 and larger). [Newman, 2010] states that *«the statistics of the histogram are poor in the tail of the distribution […] precisely the region in which the power law is normally followed most closely».* Analysing the cumulative degree distribution function can circumvent this. It preserves all the information contained in the data and can easily be calculated. However, it is less interpretable and the values highly correlated. The calculated values are comparatively high relative to those calculated for other networks (Table 7).

In [Clauset et al., 2009] another procedure of estimating the scaling parameter γ is introduced using maximum likelihood estimators for continuous and discrete data sets giving *«good results»* especially for large data sets. The authors state that both graphical methods can produce *«substantially inaccurate estimates of parameters for power-law distributions»*. All analysed topologies are scale-free, i.e. the node-degree distributions approximately follow straight lines on a plot with both axes being logarithmically scaled (see Figure 104). It has to be admitted that the data set is quite small, i.e. there are only a few different node degrees.

Table 45 Values of the exponent γ of the node-degree distribution

Network	*Swiss railway*	*Zurich tramway 2006*	*Zurich tramway 2025*
Graphical method – degree-distribution function	4.4 (R^2 = 0.93)	3.9 (R^2 = 0.96)	3.9 (R^2 = 0.99)
Graphical method – cumulative degree-distribution function	4.3 (R^2 = 0.93)	3.6 (R^2 = 0.89)	3.6 (R^2 = 0.87)
Maximum Likelihood estimator for γ [Clauset et al., 2009]	3.5	3.5	3.5

6.3.3 Analysis results for the functional *Infrastructure* representations

Adapting the *Infrastructure* topology according to the methods introduced in section 5.3.3, decreases the transitivity values. They even vanish for both tramway networks (see Table 46).

Identification of most central stations

The identification of the most *important* nodes and links is a major task when the structural robustness against *attacks* is analysed [Barthélemy, 2004]. Often, the robustness against biased removals focuses on the degree of a vertex, which can be calculated easily if the topology is known. In this study other definitions of the importance of nodes and links are considered as well and it is shown that other biased removal strategies induce even more severe impacts on the calculated structural robustness values. Especially, the removals of nodes with highest betweenness values have dramatic impacts on network integrity and operation within.

Table 46 Topological key values calculated for the adapted *Infrastructure* subsystems

Network	*Swiss railway*	*Zurich tramway 2006*	*Zurich tramway 2025*
Nodes	787	178	205
Edges	864	187	222
Sum of all edge weights [km]	3’585	71.0	89.3
Sum of all edge weights [min]	3’873	199	247
Number of connected components	1	1	1
Edge density	0.003	0.012	0.011
Mean degree of vertices	2.20	2.10	2.17
Assortative mixing by degree	-0.008	-0.003	-0.003
Transitivity C^2	0.022	0	0
Average shortest path length [hops]	29.5	14.1	13.3
Diameter [hops]	99	33	37
Eccentricity [hops]	68.5	25.3	26.8
Average shortest path length [km]	140.9	5.3	5.4
Diameter [km]	489.1	13.7	16.6
Eccentricity [km]	334.9	10.1	11.8
Average shortest path length [min]	133.1	15.4	15.1
Diameter [min]	472	37	41
Eccentricity [min]	320.5	27.8	30.2
Efficiency - global [%]	67.2	69.1	72.5
Efficiency - local [%]	1.1	0	0
Costs [%]	0.011	0.12	0.10

Table 47 identifies those three stations and links with minimal closeness values or highest betweenness in the non-weighted, functional *Infrastructure* networks. The betweenness values are calculated for both nodes and edges, closeness values are calculated for nodes only.

For the closeness values, the numbers in the brackets denote the relative closeness value calculated as the closeness divided by the average shortest path length. This allows comparing the importance of the most central nodes even for networks of different sizes.

The *Zurich tramway 2006* network contains the node with lowest relative closeness values being only 62 % of the average shortest path length value. This indicates a high degree of centralization in this network. The corresponding value for the *Swiss railway* topology is only

33 % below the average shortest path length. Almost every second shortest path among the nodes represented in the *Swiss railway* topology traverses the station *Rothrist Dreieck*.

Table 47 Most central nodes and links in the analysed adapted *Infrastructure* networks

	Rank	*Swiss railway*		*Zurich tramway 2006*		*Zurich tramway 2025*	
Closeness	1	*Zofingen*	19.673 (0.668)	*Bahnhofquai/HB*	8.65 (0.615)	*Bucheggplatz*	9.23 (0.692)
	2	*Aarburg*	19.677 (0.668)	*Central*	8.76 (0.623)	*Stadelhofen*	9.28 (0.696)
	3	*Rothrist*	19.689 (0.668)	*Bahnhofstrasse/HB*	8.88 (0.631)	*Stettbach*	9.39 (0.704)
Betweenness	1	*Rothrist Dreieck*	0.465	*Bahnhofquai/HB*	0.385	*Escher-Wyss-Platz*	0.344
	2	*Rothrist*	0.453	*Bahnhof Dreieck*	0.372	*Bucheggplatz*	0.322
	3	*Loechligut*	0.400	*Schaffhauser Platz*	0.327	*Schiffbau*	0.243
	1	*Rothrist – Rothrist Dreieck*	0.439	*Bahnhofquai/HB – Bahnhof Dreieck*	0.323	*Bucheggplatz – Rosengartenstrasse*	0.231
	2	*Löchligut – Rothrist Dreieck*	0.385	*Schaffhauser Platz – Guggachstrasse*	0.275	*Escher-Wyss-Platz – Rosengartenstrasse*	0.230
	3	*Aarburg – Zofingen*	0.268	*Guggachstrasse – Milchbuck*	0.268	*Escher-Wyss-Platz – Schiffbau*	0.225

Structural robustness results

Table 48 shows that removing a single element significantly change all measures. Removing the node representing *Arth-Goldau* from *Swiss railway* decreases the giant cluster size by 6 %. Removing *Stauffacher* from *Zurich tramway 2006* decreases the giant cluster size to 83 %. The average shortest path length can increase by more than 10 % for all networks. The results for the *structural robustness* identify those three nodes and links whose removal causes the most severe degradations of the network structures. The values are quantified according to the statements in section 5.5.

The results only refer to the most severe impacts of removing single nodes and links. Hence, it is interesting to determine the distribution of the reduced *structural system performance values* gained if each single node is removed from the functional *Infrastructure* topologies. Figure 47 shows the distribution of the giant cluster size, the values of the average shortest path lengths within them and the calculated values of the degraded *structural system performance* in a boxplot.

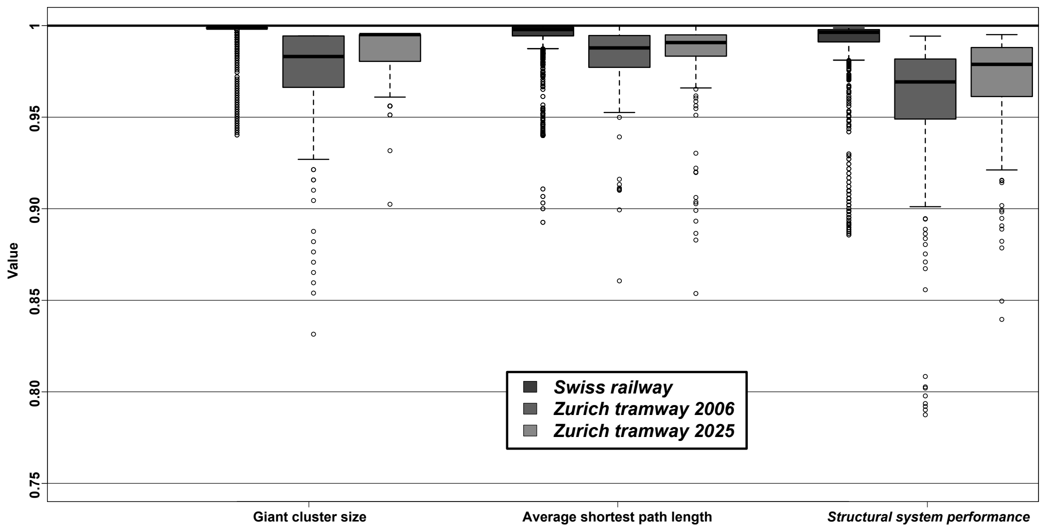
The *Swiss railway* network shows the most compact distribution of measured values. However, for all networks and measured quantities many negative outliers exist, identified by the single points. The nodes whose removal induces the largest impacts on the analysed measures are identified in Table 48. Figure 57 illustrates the impacts of removing a single node on the structural robustness by the thickness of nodes.

Table 48 Most severe structural impacts of removing single elements from the analysed networks

	Rank	*Swiss railway*		*Zurich tramway 2006*		*Zurich tramway 2025*	
Giant cluster size	**1**	*Arth-Goldau*	0.940	*Stauffacher*	0.831	*Escher-Wyss-Platz*	0.902
	2	*Steinen*	0.942	*Bahnhofquai/HB*	0.854	*Albisrieder Platz*	0.932
	3	*Schwyz*	0.943	*Sihlquai/HB*	0.860	*Wipkinger Platz*	0.951
	1	*Arth-Goldau – Steinen*	0.942	*Bahnhofquai/HB – Sihlquai/HB*	0.860	*Escher-Wyss-Platz – Wipkinger Platz*	0.951
	2	*Steinen – Schwyz*	0.943	*Sihlquai/HB – Museum für Gestaltung*	0.865	*Escher-Wyss-Platz – Förrlibuckstrasse*	0.956
	3	*Schwyz – Brunnen*	0.944	*Museum für Gestaltung – Limmatplatz*	0.871	*Wipkinger Platz – Waidfussweg*	0.956
Average shortest path length	**1**	*Rothrist*	1.120	*Bahnhof Dreieck*	1.162	*Milchbuck*	1.171
	2	*RothristDreieck*	1.111	*Schaffhauser Platz*	1.112	*Tierspital*	1.133
	3	*Thun*	1.107	*Guggachstrasse*	1.053	*Bucheggplatz*	1.128
	1	*Gwatt – Thun*	1.106	*Bahnhofquai/HB – Bahnhof Dreieck*	1.110	*Milchbuck – Tierspital*	1.144
	2	*Rothrist – RothristDreieck*	1.104	*Schaffhauser Platz – Guggachstrasse*	1.053	*Tierspital – Waldgarten*	1.130
	3	*Spiez – Gwatt*	1.103	*Guggachstrasse – Milchbuck*	1.051	*Waldgarten – Schoerlistrasse*	1.118
Structural robustness	**1**	*Steinen*	0.886	*Sihlquai/HB*	0.787	*Escher-Wyss-Platz*	0.840
	2	*Schwyz*	0.887	*Museum für Gestaltung*	0.790	*Milchbuck*	0.850
	3	*Brunnen*	0.888	*Stauffacher*	0.792	*Tierspital*	0.879
	1	*Arth-Goldau – Steinen*	0.886	*Bahnhofquai/HB – Sihlquai/HB*	0.787	*Milchbuck – Tierspital*	0.874
	2	*Steinen – Schwyz*	0.887	*Sihlquai/HB – Museum für Gestaltung*	0.790	*Tierspital – Waldgarten*	0.885
	3	*Schwyz – Brunnen*	0.888	*Limmatplatz – Museum für Gestaltung*	0.794	*Waldgarten – Schoerlistrasse*	0.895

The boxplots show that the *structural robustness* of the *Zurich tramway 2025* is larger than those for *Zurich tramway 2006.* For the latter one, especially the large range of giant cluster sizes is significant while for *Zurich tramway 2025* the average shortest path lengths differ more. This indicates that the *Zurich tramway 2006* network it mainly threatened by network disintegration while the one in *Zurich tramway 2025* is likely to remain connected if single nodes are removed, however, the average shortest path lengths may change significantly.

Figure 47   Boxplot of the *structural system performances* for the analysed railway networks



Correlation analysis for the structural robustness results

The analysis results shown in Table 49 quantify the linear regression calculated for the reduction of the *structural system performance* and the centrality of the removed node, measured by its degree, betweenness and closeness. The coefficient of determination R^2 expresses which extent both quantities linearly correlate. The values are ranged between zero, indicating no correlation, and one, indicating strong correlation.

Table 49   Correlation between the *structural system performance* and centrality measures

Quantity 1	Quantity 2	Network	R^2
Degree	*Structural system performance*	*Swiss railway*	0.03
		Zurich tramway 2006	0.17
		Zurich tramway 2025	0.22
Betweenness	*Structural system performance*	*Swiss railway*	0.22
		Zurich tramway 2006	0.47
		Zurich tramway 2025	0.46
Closeness	*Structural system performance*	*Swiss railway*	0.02
		Zurich tramway 2006	0.05
		Zurich tramway 2025	0.04

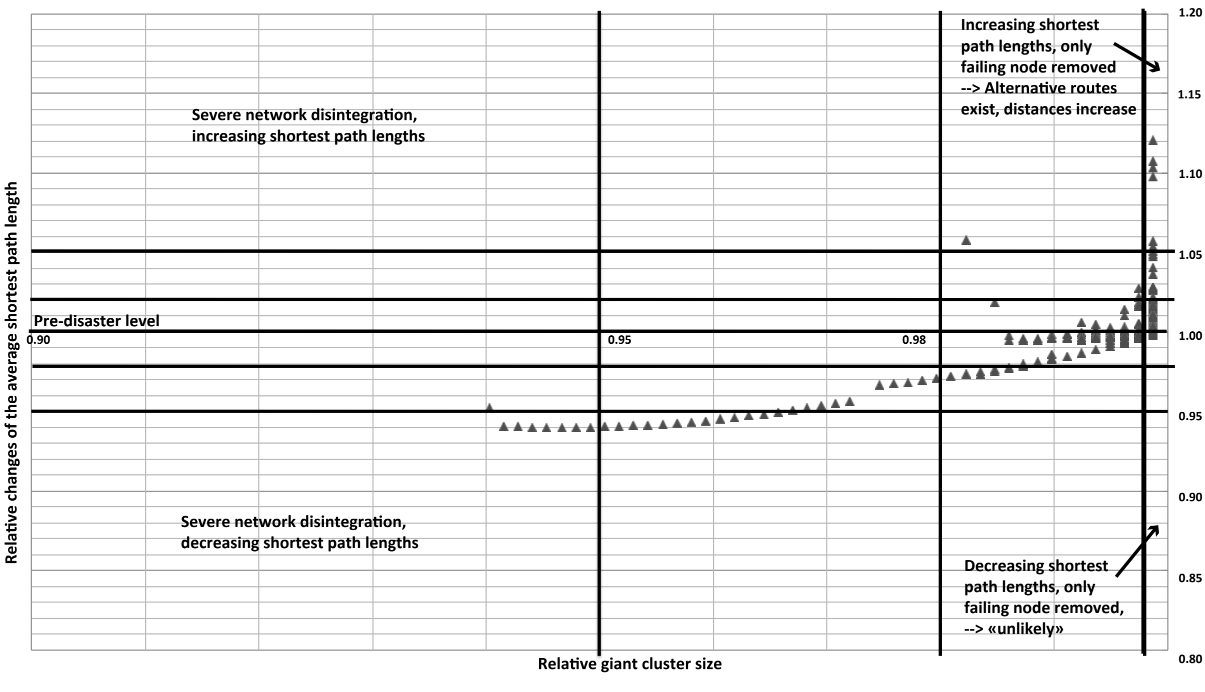
Literature often implicitly assumes that the degradation of network integrity depends on the degree of a node. However, the analysis results indicate that the correlation is poor and much better for the betweenness of a node. There is no indication, that the closeness and the structural system performance value correlate.

Introducing a classification scheme

This study introduces a new methodology of identifying the most *important* nodes in networks in the following way: Removing a single node has impacts on both, the giant cluster size and the average shortest path length within it. Both quantities can be used to classify the set of nodes as illustrated in Figure 48 for the *Swiss railway* network. Each point indicates the structural impacts of removing a single node on the giant cluster size and the average shortest path length within it.

The classification scheme will be used for finding those nodes in the topology, whose removal has most severe operational impacts. The classification scheme subdivides the set of nodes according to similar impacts of their removals on the giant cluster size and the average shortest path length within it. It will be shown that the classification of a node can be used for anticipating the implied operational consequences. This means that the classification of nodes can be used for assessing the *operational robustness* of railway networks.

Figure 48 Effects of removing single nodes from the *Swiss railway* topology on the giant cluster size and the average shortest path length within it



The borders highlighted in Figure 48 and the threshold values presented in Table 50 are used for subdividing the nodes into 16 different groups as shown in Table 51. The threshold values may be changed, however, they were found to give good results of distinguishing multiple consequences of node removals. The scheme can also be applied for classifying edges.

Table 50 Subdividing the set of nodes according to the structural impacts of their removals

Values relative to pre-disaster value		Fraction of nodes outside the giant cluster			
		No node but the removed one	At least one additional node	2 % or more	5 % or more
Average shortest path length in giant cluster	>1.05	Moderate decreases of the *structural system performance*		Significant decreases of the *structural system performance*	
	>1.02				
	>1.00	*Structural system performance* almost not changed		Moderate decreases of the *structural system performance*	
	≤ 1.00				
	≤ 0.98	Moderate decreases of the *structural system performance*		Significant decreases of the *structural system performance*	
	≤ 0.95				

While the letters refer to changes of the shortest path lengths in the giant cluster, the numbers relate to the reductions of the giant cluster sizes if a single node is removed. The most critical nodes and edges are those, whose deletion simultaneously increase the average shortest path lengths and reduce the giant cluster sizes, i.e. nodes classified as *A3*, *A4*, *B3* or *B4*. Removing nodes classified as *C1* have only minor effects on network integrity and the average shortest path lengths and are less important from a structural point of view.

Table 51 Definition of multiple node classes according to the structural impacts when removing them

Values relative to pre-disaster value		Fraction of stations outside the giant cluster			
		No node but the removed one	At least one additional node	2 % or more	5 % or more
Average shortest path length in giant cluster	>1.05	*A1*	*A2*	*A3*	*A4*
	>1.02	*B1*	*B2*	*B3*	*B4*
	>1.00	*C1*	*C2*	*C3*	*C4*
	≤ 1.00	*D1*	*D2*	*D3*	*D4*
	≤ 0.98	*E1*	*E2*	*E3*	*E4*
	≤ 0.95	*F1*	*F2*	*F3*	*F4*

The introduced classes of nodes are aggregated into six groups as illustrated by the background colours in Table 51. Table 52 compares the presence of classes in the analysed case study networks.

Table 52 Distribution of node classes for the case study networks

Fraction of nodes in belonging to a specific class in [%]	*A3, A4, B3, B4*	*A1, A2, B1, B2*	*C3, C4, D3, D4*	*C1, C2, D1, D2*	*E3, E4, F3, F4*	*E1, E2, F1, F2*
Swiss railway	-	3.7	-	91.1	3.9	1.3
Zurich tramway 2006	0.6	7.3	24.2	47.8	20.2	---
Zurich tramway 2025	2.0	11.2	16.6	64.4	5.4	0.5

In the *Zurich tramway 2025* network all node classes are present. 64 % of the nodes are classified as *C1*, *C2*, *D1* or *D2*. For *Swiss railway*, this class contains more than 90 % of nodes. For all networks, the majority of nodes are classified as *C1*, *C2*, *D1* or *D2* implying that a removal for the majority of nodes only has minor impacts on the average shortest path length dynamics and network integrity. Both *Zurich tramway* networks contain nodes classified as *A3*, *A4*, *B3* or B4, whose removal has major impacts on both quantities.

Table 53 shows that there are significant different structural values between different classes. Removing nodes classified as *A3*, *A4*, *B3* or B4 has the most severe impacts on the *structural system performance.*

Table 53 Mean topological key values for different node classes in the analysed networks

		A3, A4, B3, B4	*A1, A2, B1, B2*	*C3, C4, D3, D4*	*C1, C2, D1, D2*	*E3, E4, F3, F4*	*E1, E2, F1, F2*
Swiss railway	Degree	-	3.31	-	2.15	2.13	2.10
	Relative betweenness	-	0.17	-	0.03	0.08	0.03
	Structural robustness	-	0.96	-	0.99	0.91	0.96
Zurich tramway 2006	Degree	5	3	2.14	1.84	2.28	---
	Relative betweenness	0.28	0.22	0.06	0.04	0.12	---
	Structural robustness.	0.91	0.95	0.96	0.98	0.89	---
Zurich tramway 2025	Degree	4	3	2.15	1.97	2.18	2.00
	Relative betweenness	0.24	0.16	0.06	0.04	0.07	0.03
	Structural robustness	0.90	0.93	0.96	0.98	0.94	0.96

A summarization of the distribution of node classes and the implications of the classification and the consequences of removing the node is presented in Table 66.

Dynamics of the distribution of node classes

With every removal the classification of the remaining nodes may change. Hence, the distribution of node classes is not static but dynamic. Figure 49 shows the dynamics of the distribution of classes for *Zurich tramway 2025* if multiple nodes are removed. In each step a randomly chosen remaining node is removed. The curves are averaged over 100 simulations.

Table 54 Topological characterization of the node classes

<table>
<tr><td colspan="2" rowspan="2">Values relative to pre-disaster value</td><td colspan="2">Effects on giant cluster size</td></tr>
<tr><td>> 0.98</td><td>≤ 0.98</td></tr>
<tr><td rowspan="6">Effects on mean shortest path length</td><td rowspan="2">> 1.02</td><td>A1, A2, B1, B2 → Many nodes</td><td>A3, A4, B3, B4 → Very few nodes</td></tr>
<tr><td>Degree: High, BC: High
System performance reduction: Small</td><td>Degree: High, BC: Large
System performance reduction: High</td></tr>
<tr><td rowspan="2">0.98 – 1.02</td><td>C1, C2, D1, D2 → Majority of nodes</td><td>C3, C4, D3, D4 → Many nodes</td></tr>
<tr><td>Degree: Small, BC: Small
System performance reduction: Very small</td><td>Degree: Medium, BC: Medium
System performance reduction: Moderate</td></tr>
<tr><td rowspan="2">≤ 0.98</td><td>E1, E2, F1, F2 → Very few nodes</td><td>E3, E4, F3, F4 → Some nodes</td></tr>
<tr><td>Degree: Small, BC: Very small
System performance reduction: Moderate</td><td>Degree: Small, BC: Medium
System performance reduction: Large</td></tr>
</table>

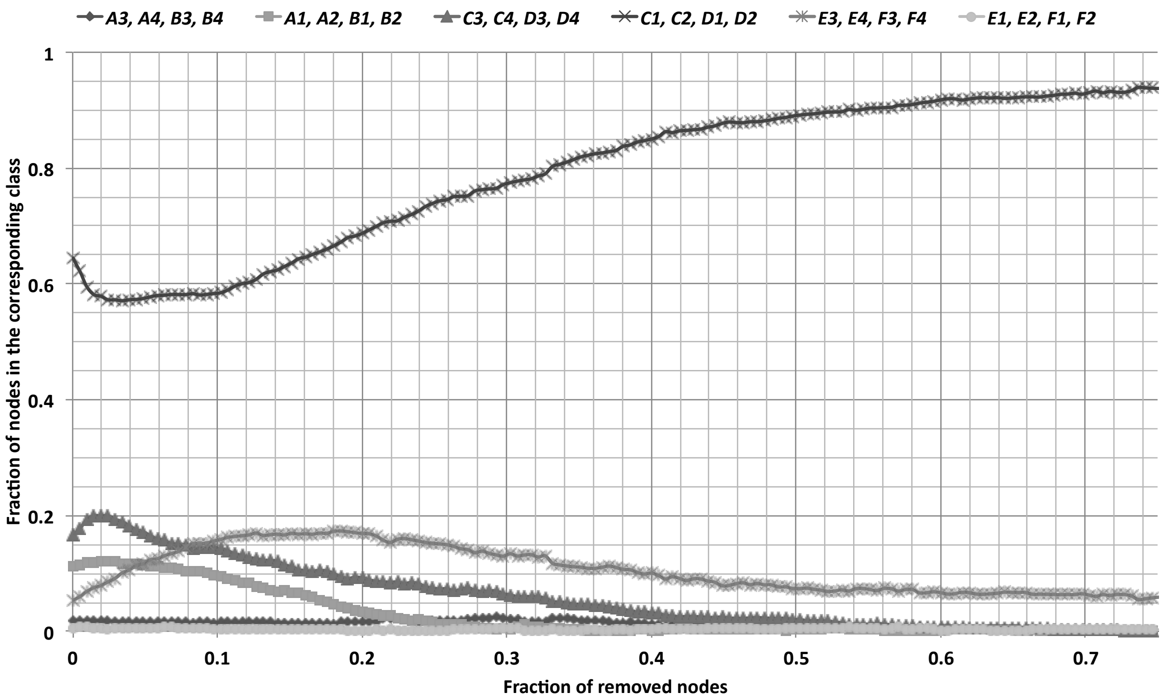
The network was chosen, because it is the only network containing nodes of all classes (Table 52). The results show that the number of nodes classified as *C1*, *C2*, *D1* or *D2* constantly increases since during the disintegration process many small size clusters occur such that either:

- A node **outside** the giant cluster is removed: Then both, the giant cluster size and the average shortest path lengths within it remain unchanged (nodes classified as *C1*, *C2*, *D1* or *D2)*
- A node **within** the giant cluster is removed: This decreases the giant cluster sizes (if there is no other cluster comprising the same number of nodes) and reduces the average shortest path lengths within (nodes classified as *E3*, *E4*, *F3* or *F4*)

Multiple failures

Now, the impacts of successively removing multiple nodes successively are analysed. Nodes can either be randomly removed or following a specific strategy, i.e. there are biased and non-biased removal strategies. In the latter case, a uniformly randomly chosen element is removed in each step. For random removals, the results are averaged over 1’000 simulations. Biased strategies focus on *important* network elements, often the high-degree nodes or but also those with high centrality values. Both, the degree and the betweenness of a node changes during the fragmentation processes such that it is possible to determine the order of importance in the original network – *static* strategies – or in the current, degraded network – *dynamic* strategies. [Newman, 2010] states that removing nodes according to their (initial) degree is a typically used non-uniform removal strategy.

Figure 49 Dynamics of the distribution of node classes for *Zurich tramway 2025*



The following removal strategies are considered in this study:

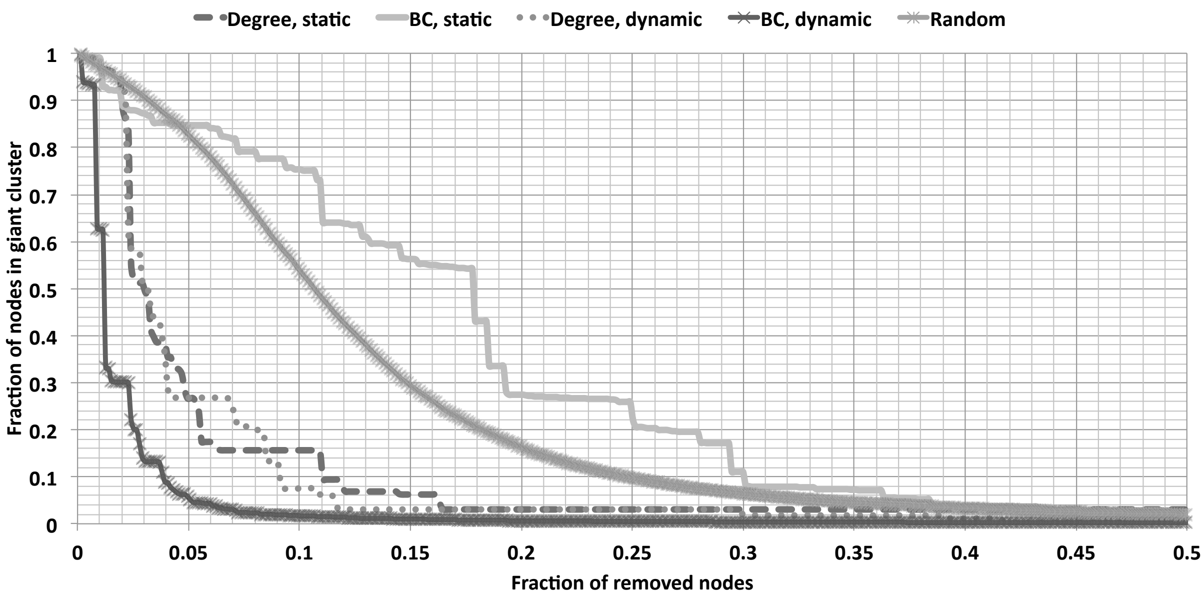
- ***Degree-static*:** Nodes are removed according to the initial order of degrees.
- ***Degree-dynamic*:** Node with current highest degree is removed.
- ***BC-static*:** Nodes and edges are removed according to the initial BC-value.
- ***BC-dynamic*:** Element with highest betweenness in current network is removed.
- ***Random*:** Removing randomly chosen elements (results averaged over 1’000 runs).

Dynamics of the giant cluster size

Figure 50 visualizes the dynamics of the giant cluster size for increasing fractions of nodes removed from *Swiss railway*. The removal of less than one per cent of nodes according to their betweenness in the current network reduces the giant cluster size by more than 50 %.

The results match those for many real-world networks having scale-free topologies (see Figure 10): Almost for all biased strategies, the network disintegrates very fast even for small fractions of removed nodes. Dynamic strategies have more severe impacts on network integrity than static ones. Strategies focussing on the current betweenness values have most severe impacts. The network is quite robust against the deletion of randomly chosen nodes such that the giant cluster size slightly decreases approximately decaying as a straight line.

Figure 50 Dynamics of the giant cluster size for different node removal strategies applied to the *Swiss railway* network



Number of clusters in the degradation process

The number of clusters present in the degraded networks gives useful additional information about the structural robustness of a network. Figure 51 shows the number of clusters present in the *Swiss railway* infrastructure if nodes are successively removed according to the introduced strategies. The curve for non-biased random removals of nodes is averaged over 1’000 simulations. If nodes are removed according to their current degree, the number of clusters constantly increases to the maximal value of 390 clusters reached when every second node is removed. In this case, each cluster consists of isolated nodes. The maximal number of clusters of the static degree-biased removal strategy is reached when 17 % of nodes are removed.

Dynamics of the average shortest path lengths in the giant cluster

The removal of nodes also changes the average shortest path lengths within the giant clusters (see Figure 52). 1’000 simulations are averaged for the curve of random node removals. The removal of randomly (uniformly) nodes initially causes a slight increase of the average shortest path lengths and reaches a maximal value of about 110 % compared to pre-disaster level and constantly decreases afterwards. Strategies focussing on the betweenness cause severe increases of the average shortest path length within the giant cluster, even for very small fractions of removed nodes. The strategy *BC static* causes the largest increases of the shortest path lengths since the degraded topology is likely to sustain in a large giant cluster (see Figure 50) such that long-range connections remain present.

Figure 51 Dynamics of the number of clusters for different node removal strategies applied to the *Swiss railway* network

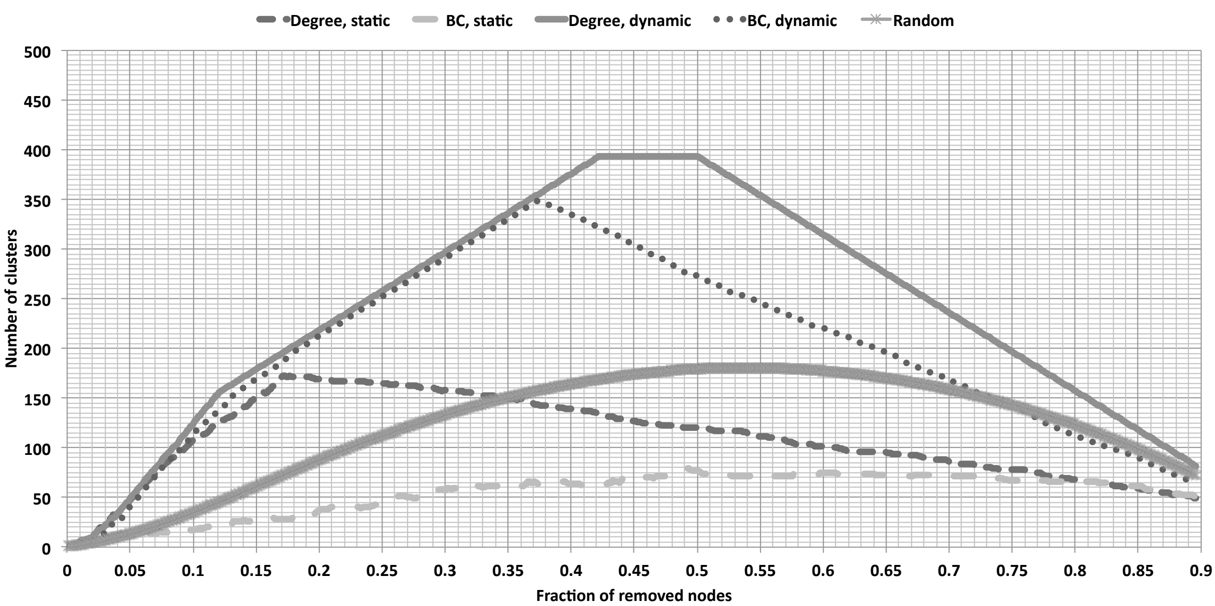
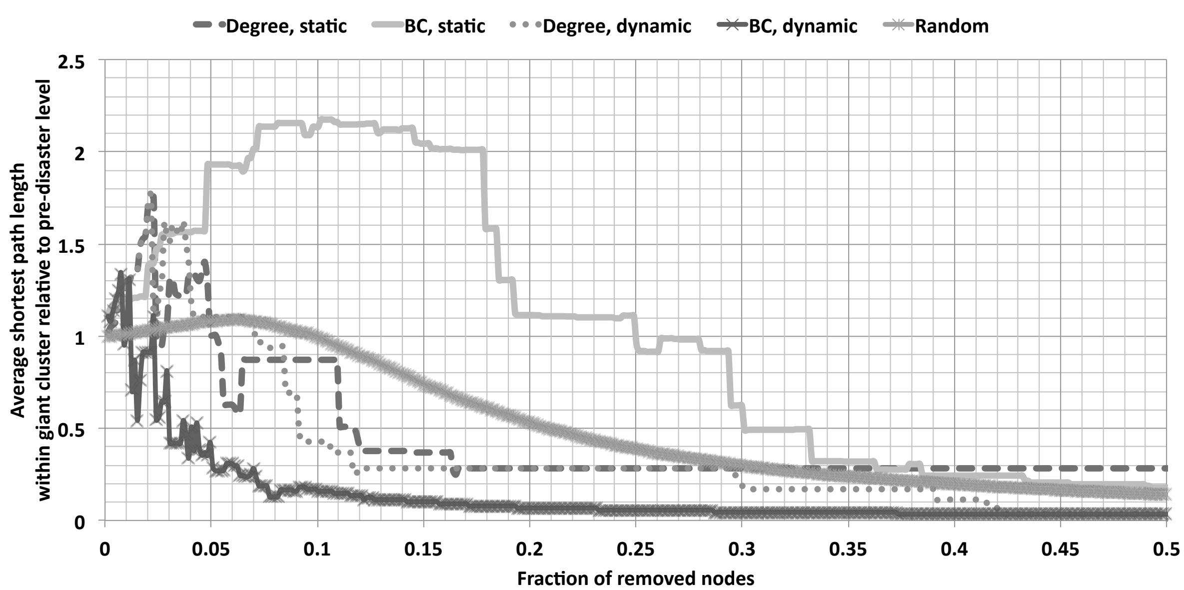


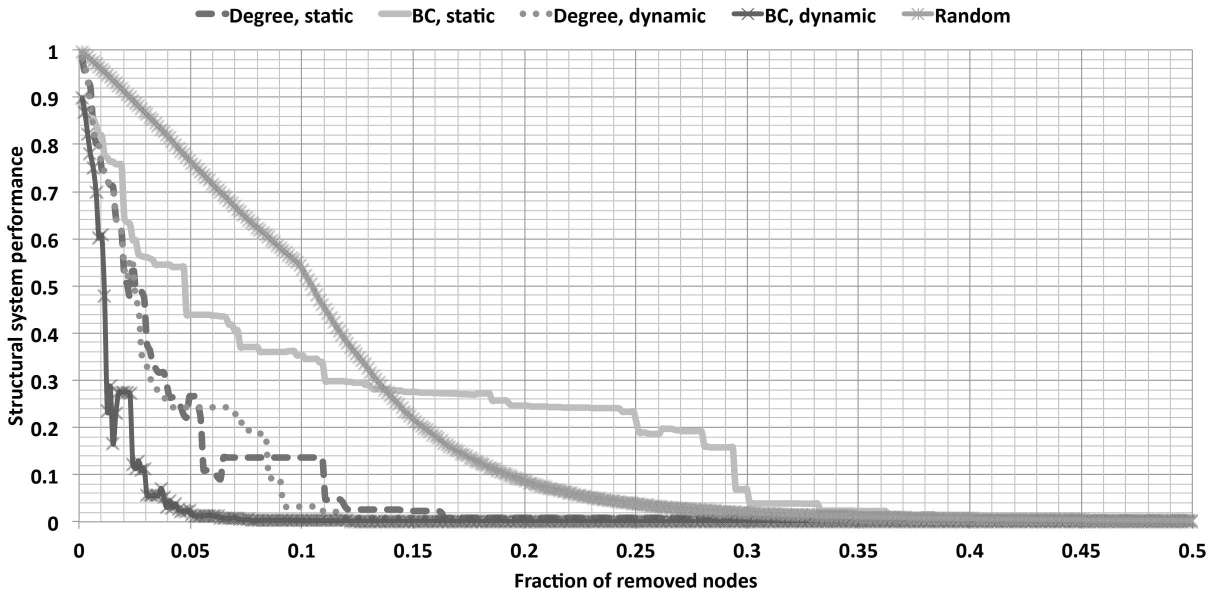
Figure 52 Dynamics of the average shortest path lengths within the giant cluster for different node removal strategies applied to the *Swiss railway* network



Dynamics of the structural system performance

Both, the dynamics of the giant cluster size and the shortest path lengths within contribute to the *structural system performance* in degraded state. Figure 53 shows its curve for increasing numbers of removed nodes. The curve for random node removals is averaged over 1’000 simulation runs.

Figure 53 Dynamics of the calculated *structural system performance* for different node removal strategies applied to the *Swiss railway* network



Non-biased strategies (*Random*) initially show an almost linear decrease of the system performance value, followed by an asymptotic decrease to zero. The curves for the degree-based strategies almost coincide. On the contrary, the difference between both betweenness-based strategies are immense. The *structural system performance* may increase due to its definition, according to which the giant cluster may become a different one.

Summary: Comparison of the removal strategies

This section summarizes the effects removing network nodes according to the introduced biased and non-biased removal strategies:

- **Non-biased strategies (*Random*):** The non-biased removal of uniformly randomly chosen nodes causes slight decreases of the giant cluster size and little increases of the average shortest path length in the giant cluster. The system performance decreases almost linearly. → The *Swiss railway* topology is robust against the removal of randomly chosen nodes and sustains in a large component with almost constant average shortest path lengths.

- **Degree-biased strategies (*Degree, static / Degree, dynamic*):** The removal of nodes according to the degree strongly reduces the connectivity of a network: The number of connected components increases fast and the giant cluster size promptly decreases. → The degree-based removal strategies severely threaten network integrity. The removal of only small fractions of nodes disintegrates the network. There are only small differences between the structural robustness curves for the static and dynamic strategy.

- **Betweenness-biased strategies (*BC, static / BC, dynamic*):** BC-biased strategies mainly change the shortest path lengths in the giant cluster. The average shortest path length within the giant cluster doubles even if only a few nodes are removed. There are large differences between the static strategy and the dynamic one: If nodes with highest betweenness in the current network are removed, the *structural system performance* value is drastically reduced. Among all biased strategies, the static degree-biased one causes the less decreases of the *structural system performance* value.

Influence of the location of the initial failure on the convergence time

Epidemiological models can be used for measuring the impacts of the network position of the initially failing node on the convergence time (see section 2.4.6). The values of the mean convergence times for the analysed railway networks are presented in Table 55.

Table 55 Impact of the initial failure location on the convergence time

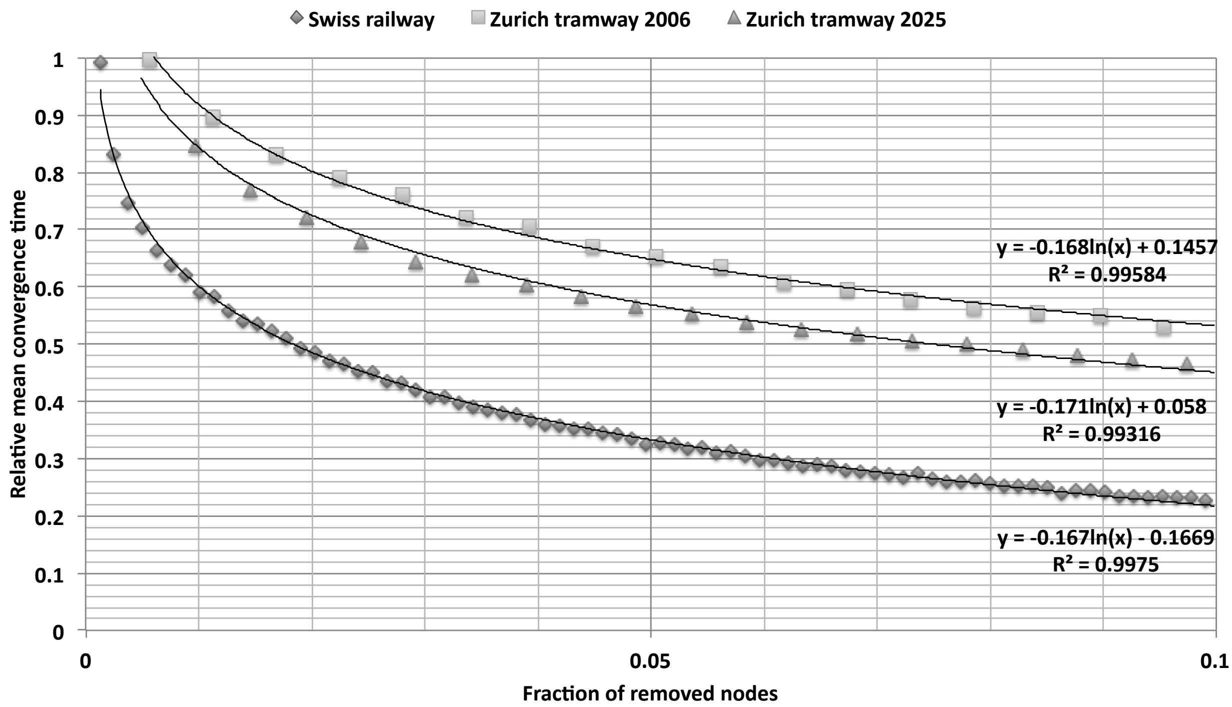
Network	*Swiss railway*	*Zurich tramway 2006*	*Zurich tramway 2025*
Minimal convergence time [hops]	50	17	19
Maximal convergence time [hops]	99	33	37
Range (= Maximum – Minimum)	49	16	18
Mean convergence time [hops]	68.5	25.3	26.8
Variance	106.8	15.9	16.9
Coefficient of variation	0.15	0.16	0.15

The results show the within the *Swiss railway* network, a failure agent needs at minimum 50 iterations until all nodes are reached (if the most central node is initially *infected*). The impact of the location of the initially failing node on the convergence time does not vary much between all the networks indicated by almost equal variation coefficient values.

Impact of the number of initially failing stations on the convergence time

Not only the location of the initial failure, but also the amount of initial failures influences the convergence time. Figure 54 shows how and to which extent the convergence time depends on the number of initially failing nodes. The results were measured by initially removing up to 10 % of nodes and were averaged over 1'000 simulations.

Figure 54 Regression analysis between the number of simultaneous node removals and the mean *convergence time* for all analysed networks



Instead of taking the absolute mean convergence time, the relative convergence time is considered, i.e. the mean convergence time measured for a specific number of removed nodes divided by the mean convergence time calculated for all nodes as given in Table 55.

Logarithmic trend lines can almost accurately approximate all measured data, which is indicated by the regression coefficient close to 1. For all networks, the slopes almost coincide indicating that the networks approximately depend to the same degree on the number of initially failing nodes. The differences of the absolute values show that for the *Swiss railway* network, the relative *convergence time* decreases faster than for the *Zurich tramway* networks. For the *Zurich tramway 2025* network more than 10 % of the network nodes have to be initially removed to decrease the *convergence time* by 50 %. The corresponding value for the network *Zurich tramway 2006* is approximately 7.5 % and for *Swiss railway* 1.8 %.

Impact of the classification of initially failing node on the convergence time

Table 56 shows the correlation between the classification of the initially failing node and the *convergence time*. The results show that the mean *convergence time* for *Swiss railway* is 68.5 iterations. If a node classified as *A3*, *A4*, *B3* or *B4* initially fails, the failure spreads faster such that the mean convergence time is 90 % relative to the mean one. From a structural point of view, any protection efforts should focus on nodes classified as *A1 – A4* or *B1 – B4* rather than on nodes classified as *E1 – E4* or *F1 – F4*.

Table 56 Mean convergence time for the different classes of initially failing nodes

Network	*100 =*	*A3, A4, B3, B4*	*A1, A2, B1, B2*	*C3, C4, D3, D4*	*C1, C2, D1, D2*	*E3, E4, F3, F4*	*E1, E2, F1, F2*
Swiss railway	68.5	---	90	---	99	112	132
Zurich tramway 2006	25.3	83	79	101	103	99	---
Zurich tramway 2025	26.8	87	87	97	102	112	127

Evaluating the benefits of protection efforts

This section further analyses the contribution of nodes to spreading processes by applying the so-called *SIR-model* that allows nodes to be in *recovered* state such that they do not transmit failures to their neighbours. The following two questions are addressed:

1. *Which classes of nodes should protection efforts focus on for positively influencing spreading processes?*

2. *To which extent are classification-biased protection efforts advantageous in comparison with other biased strategies?*

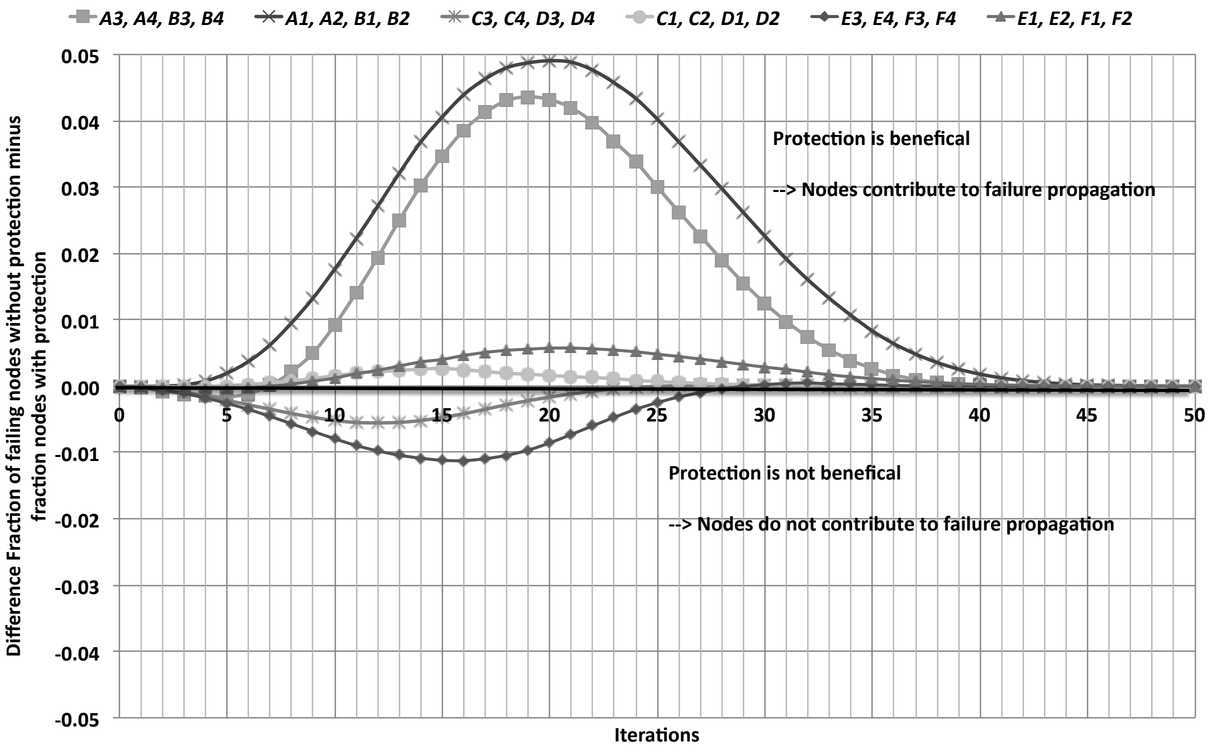
Figure 55 illustrates to which extent a node of a specific class contributes to the spreading of failures according to the SIR-model. The analysis comprises three major steps:

1. Removing all incident links protects a randomly chosen node of a specific class. Hence, this node cannot longer contribute to failure propagation processes.

2. Another randomly chosen node within the resulting largest connected component becomes *infected*.

3. The fraction of failing nodes within the giant cluster is analysed and the results with and without protection efforts are compared.

Figure 55 Benefits from classification-dependent protection efforts for *Zurich tramway 2025*



The curves in Figure 55 are averaged over 1'000 simulations. For the analysis the *Zurich tramway 2025* was chosen since nodes of all classes are present (see Table 52). The x-axis denotes the number of iterations or time steps. The y-axis shows the difference of the fraction of giant cluster nodes that are in *infected* state minus the corresponding value if a single node of a specific node class is protected as previously described. Positive y-values mean that the protection reduces spreading processes and negative ones that the efforts are not beneficial.

The results show that protecting nodes classified as *A1 – A4* and *B1 – B4* is most advantageous; a protection reduces the propagation by up to 5 %. Protecting nodes of classes *E1 – E4* and *F1 – F4* decrease the giant cluster size such that negative values are observed.

Comparison of different biased-protection strategies

In Figure 56, different biased strategies are compared in the following way:

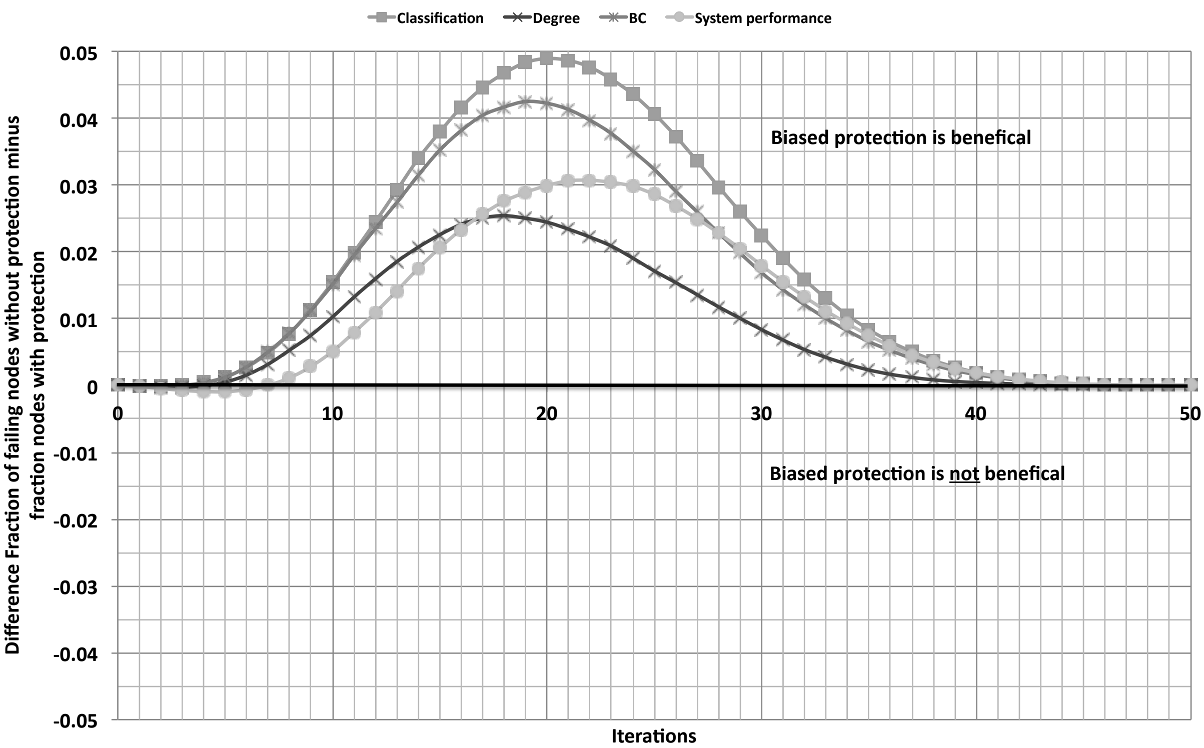
1. The number of nodes classified as *A1 – A4* and *B1 – B4* is determined. Equally sized sets of nodes are compared, i.e. sets of nodes with highest degree, highest betweenness and nodes with most severe impacts on the *structural system performance* values.

2. Within each of the defined sets, a randomly chosen single node is *protected*, such that it does not contribute to the spreading of failures. Its contribution to failure propagation is quantified as in the previous model.

3. Step 2 is performed for 1'000 simulations and the results are averaged.

4. The results are compared and visualised in Figure 56.

Figure 56 Comparison of multiple biased protection strategies for *Zurich tramway 2025*

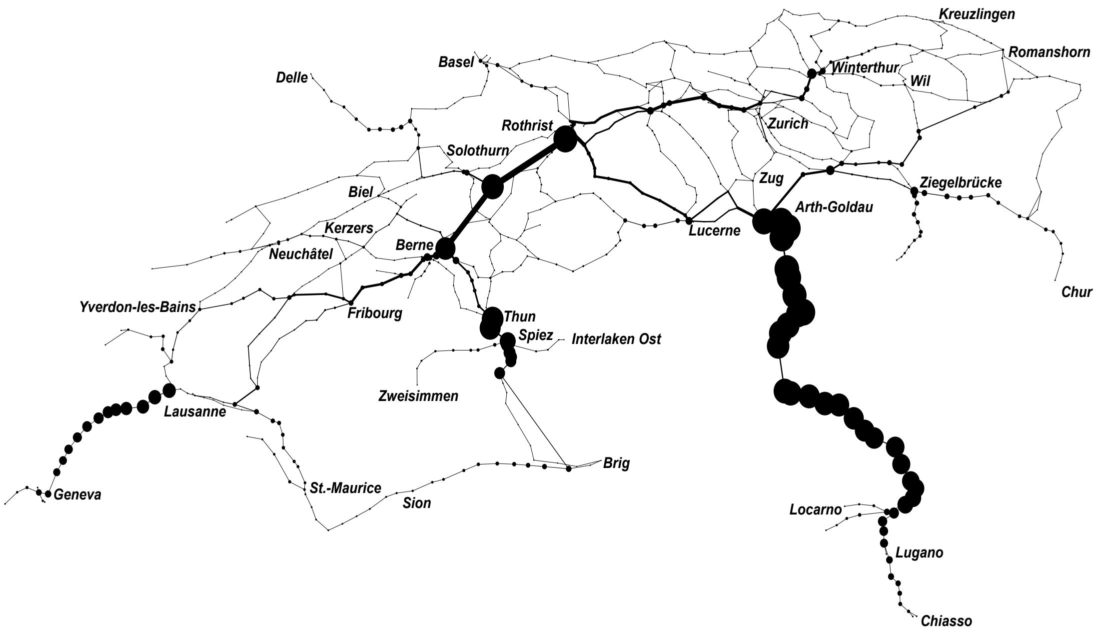


Even though all strategies are beneficial, the results indicate that the classification-biased one realizes the largest improvements. The degree-based strategy gives the smallest gains for the *Zurich tramway 2025* network

6.3.4 Visualization example

Figure 57 illustrates the *Infrastructure* representing the *Swiss railway* network and visualizes the location of nodes, whose removal causes the largest decreases of the *structural system performance*. Larger nodes indicate more severe impacts on the network topology. The thickness of edges depends on its betweenness such that the most central edges are highlighted.

Figure 57 *Swiss railway* representation in *R* and most nodes whose removal causes the most severe impacts of the *structural system performance*



Node size depends on the calculated decreases of the *structural system performance* if it is removed from the topology, thickness of edges depends on its betweenness

The links with high betweenness are located along the corridors *Bern - Zurich* and *Lucerne - Olten*. The *structural system performance* decreases significantly for nodes, whose removal either causes severe network disintegrations (e.g. along trans-alpine routes in Ticino) or significant increases of the average shortest path lengths within the giant cluster (for instance between the stations *Thun* and *Spiez*). The nodes whose removals cause the largest decreases of the *structural system performances* are identified in Table 48. Table 47 shows the links with highest betweenness values.

6.4 Operational robustness analysis results

6.4.1 Basic operational values

This section presents the operational robustness results calculated according to the evaluated methodology for assessing the operational robustness of railway networks. Due to the removals of Infrastructure nodes and links, degraded operation states are calculated according to the scheme introduced in section 5.7. The operational impacts of such removals are quantified as explained in 5.6. Basic values data such are shown in Table 57.

Table 57 Basic operative parameter values calculated for the case study networks

Network	*Swiss railway*	*Zurich tramway 2006*	*Zurich tramway 2025*
Operated Nodes	488 (62 %)	178 (100 %)	205 (100 %)
Operated Edges	510 (59 %)	187 (100 %)	222 (100 %)
Turnaround alternatives	49 (10 %)	36 (20 %)	39 (19 %)
Lines	52	13	14
Sum line path lengths [hops]	1’547	313	376
Sum line path lengths [km]	6’926.9	112.5	143.9
Operated tracks [km]	693.0	37.1	39.8
Mean line path length [km]	133.2	8.7	10.3
Fraction of track-km served by a single line	19 %	52 %	45 %
Mean number of lines per node	3.3	1.8	1.9
Mean number of lines per link	3.0	1.7	1.8
Relations with no changing process [%]	15.2	24.0	23.6
Relations with one changing process [%]	59.5	75.9	72.7
Relations with two changing process [%]	25.3	0.1	3.6
Diameter [Hops]	97	33	37
Diameter [Track-km]	480.2	13.7	16.6
Diameter [Lines]	3	3	3
Average shortest path length [Hops]	31.4	14.1	13.3
Average shortest path length [Track-km]	150.2	5.3	5.4
Average shortest path length [Lines]	2.1	1.8	1.8
Eccentricity [Hops]	69.0	25.3	26.8
Eccentricity [Track-km]	340.2	10.1	11.8
Eccentricity [Lines]	2.9	2.1	2.6
Links with exceeded theoretical capacity	0	0	0
Links with exceeded operational capacity	12	10	10
Number of trains in operation	220	104	121

6.4.2 Robustness analysis for *Traffic Operation and Management*

In a first step, the elements with highest *operational centralities* are determined. The *operational centrality* of a node or link is measured as the sum of all line path lengths traversing a specific node or link. Identifying the nodes with high operational centrality can be a valuable first assessment of the operational impacts when removing a specific node or link. The following quantities are measured:

- **Affected track-kilometres**: Sum of track-lengths of all lines traversing a specific element, each traversed link is counted once
- **Affected stations**: Number of stations that are served by lines traversing an element

- **Affected trains**: Number of trains used for operating the lines traversing a specific element

Figure 58 shows where the stations and links with highest operational centrality are located with respect to the affected track-kilometres.

Figure 58 Nodes and links with highest *operational centralities* for *Swiss railway*

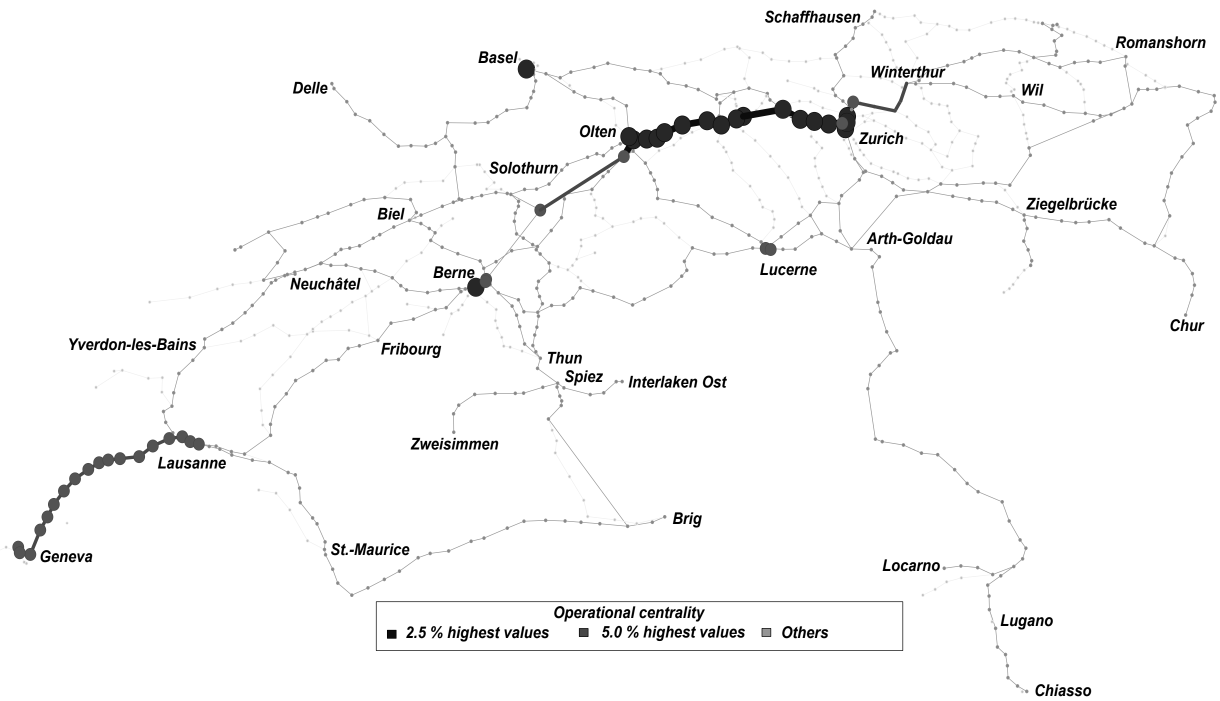


Table 58 identifies the three stations and links with highest operational centralities. The number in the brackets denotes the relative value in per cent and contains also the results with respect to the number of affected stations and affected trains.

For the *Swiss railway* network, the node representing the station *Zurich HB* is contained in paths of lines, whose overall line path length is about 1'400 kilometres (62 % of the operated track kilometres). If this node is removed from the network, 390 trains or 27 % need dispositive efforts such as the rerouting or truncation of lines. The network *Zurich tramway 2006* is the most centralized network from the operational view, since the largest relative numbers are measured, i.e. 56 trains (54 % of all trains) need are affected by a failure of the station *Paradeplatz*.

Table 58 Stations and links with highest operational centrality

	Rank	Swiss railway		Zurich tramway 2006		Zurich tramway 2025	
Affected track-km	1	*Zurich HB*	1’382 (62[19])	*Bahnhof Dreieck*	60.7 (86)	*Paradeplatz*	67.1 (75)
	2	*Olten Dreieck*	1’306 (58)	*Paradeplatz*	57.5 (81)	*Bellevue*	58.8 (66)
	3	*Olten*	1’189 (53)	*Bellevue*	50.6 (71)	*Bahnhof Dreieck*	56.8 (64)
	1	*Olten – Olten Dreieck*	1’189 (53)	*Bürkliplatz – Bellevue*	41.3 (58)	*Bürkliplatz – Bellevue*	52.9 (59)
	2	*Altstetten – Schlieren*	1’068 (48)	*Bahnhofquai/HB – Bahnhof Dreieck*	38.8 (55)	*Börsenstrasse – Paradeplatz*	44.5 (50)
	3	*Dietikon – Schlieren*	1’068 (48)	*Rennweg – Paradeplatz*	38.0 (53)	*Börsenstrasse – Bürkliplatz*	44.5 (50)
Affected stations	1	*Zurich HB*	310 (64)	*Bahnhof Dreieck*	157 (88)	*Paradeplatz*	167 (82)
	2	*Olten Dreieck*	291 (60)	*Paradeplatz*	148 (83)	*Bahnhof Dreieck*	147 (72)
	3	*Olten*	265 (54)	*Bellevue*	130 (73)	*Bellevue*	143 (70)
	1	*Olten – Olten Dreieck*	265 (54)	*Bürkliplatz – Bellevue*	106 (60)	*Bürkliplatz – Bellevue*	128 (62)
	2	*Altstetten – Schlieren*	244 (50)	*Bahnhofquai/HB – Bahnhof Dreieck*	103 (58)	*Börsenstrasse – Paradeplatz*	111 (54)
	3	*Hardbrücke – Zurich HB*	244 (50)	*Central – Bahnhof Dreieck*	101 (57)	*Börsenstrasse – Bürkliplatz*	111 (54)
Affected trains	1	*Zurich HB*	390 (35)	*Bahnhof Dreieck*	64 (62)	*Bahnhof Dreieck*	64 (59)
	2	*Olten Dreieck*	344 (30)	*Paradeplatz*	56 (54)	*Paradeplatz*	56 (52)
	3	*Bern*	320 (28)	*Bellevue*	56 (54)	*Bellevue*	48 (44)
	1	*Altstetten – Schlieren*	300 (27)	*Bürkliplatz – Bellevue*	40 (39)	*Bürkliplatz – Bellevue*	40 (37)
	2	*Killwangen – Dietikon*	300 (27)	*Central – Bahnhof Dreieck*	40 (39)	*Central – Bahnhof Dreieck*	40 (37)
	3	*Dietikon – Schlieren*	300 (27)	*Stockerstrasse – Paradeplatz*	32 (31)	*Stockerstrasse – Paradeplatz*	32 (30)

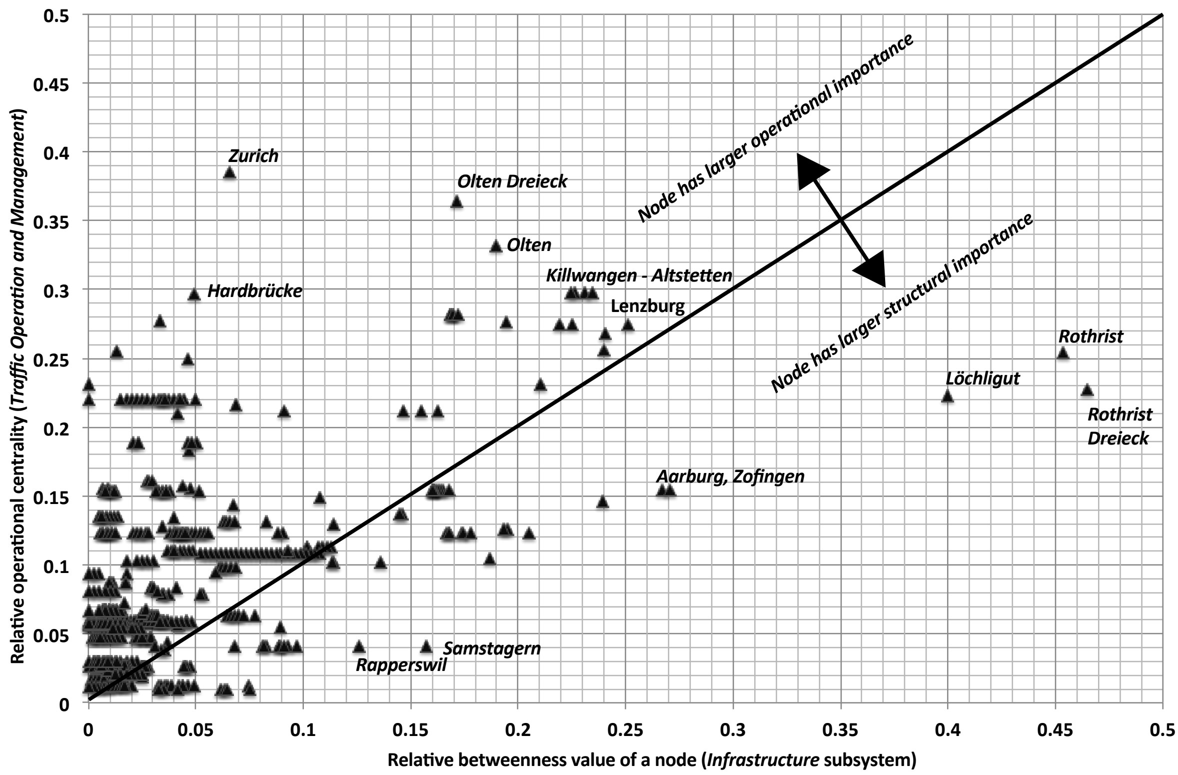
Comparing structural and operational centrality of nodes

Figure 59 compares the calculated structural and operational centrality values in the following way: The relative betweenness of a node in the adapted *Infrastructure* topology is used for quantifying the *structural centrality*, i.e. the fraction of shortest paths in which the node is contained. The *operational centrality* is measured by the affected track-kilometres. For some nodes, both quantities significantly differ indicating that there are nodes with low *structural centralities* but high operational ones and vice versa.

[19] Fraction relative to the total length of operated tracks, resp. operated stations or trains, in [%]

It is possible to distinguish nodes with larger operational centrality, those with larger structural centrality and nodes having pretty equal values for both quantities.

Figure 59 Comparison of structural and operational centralities for *Swiss railway*



Operational system performance results for removing single nodes

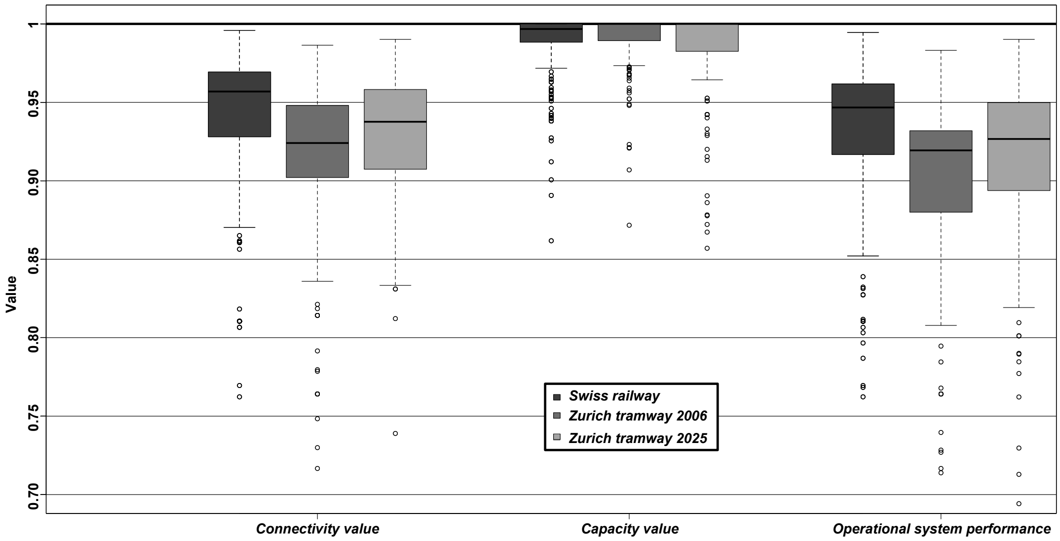
Table 59 identifies the three nodes and links whose removal has most severe impacts on the *connectivity value*, the *capacity value* and the *operational system performance* as defined in section 5.6. Capacity restrictions were neglected for the calculation of degraded operation states. But each additional edge that is utilized above the specified operational or theoretical capacity threshold reduces the *capacity value* and hence the *operational system performance* in degraded operation. Figure 60 shows how the results for removing single nodes are distributed for all analysed networks.

Table 59 Most severe operational impacts of removing single elements for the case studies

	Rank	Swiss railway		Zurich tramway 2006		Zurich tramway 2025	
Connectivity value	1	*Thun*	0.762	*Escher-Wyss-Platz*	0.717	*Escher-Wyss-Platz*	0.739
	2	*Bern*	0.770	*Stauffacher*	0.730	*Milchbuck*	0.812
	3	*Bellinzona*	0.807	*Bahnhofquai/HB*	0.748	*Leutschenbach*	0.831
	1	*Arth-Goldau – Steinen*	0.811	*Bahnhofquai/HB – Sihlquai/HB*	0.764	*Leutschenbach – Oerlikerhus*	0.831
	2	*Steinen – Schwyz*	0.811	*Sihlquai/HB – Museum für Gestaltung*	0.764	*Oerlikerhus – Glattpark*	0.831
	3	*Schwyz – Brunnen*	0.811	*Limmatplatz – Museum für Gestaltung*	0.764	*Tierspital – Waldgarten*	0.874
Capacity value	1	*Löchligut*	0.862	*Paradeplatz*	0.872	*Bucheggplatz*	0.857
	2	*Wankdorf*	0.891	*Börsenstrasse*	0.907	*Rosengartenstrasse*	0.867
	3	*Winterthur*	0.901	*Guggachstrasse*	0.921	*Bahnhof Dreieck*	0.872
	1	*Bern – Wankdorf*	0.891	*Central – Bahnhof Dreieck*	0.857	*Bucheggplatz – Rosengartenstrasse*	0.867
	2	*Mägenwil – Othmarsingen*	0.909	*Bahnhofquai/HB – Bahnhof Dreieck*	0.875	*EscherWyss-Platz – Rosengartenstrasse*	0.867
	3	*Olten – Olten Dreieck*	0.920	*Bürkliplatz – Bellevue*	0.896	*Bürkliplatz – Bellevue*	0.884
Operational system performance	1	*Thun*	0.762	*Stauffacher*	0.714	*Bucheggplatz*	0.694
	2	*Löchligut*	0.769	*Escher-Wyss-Platz*	0.717	*Escher-Wyss-Platz*	0.713
	3	*Bern*	0.770	*Bahnhofquai/HB*	0.727	*Schiffbau*	0.730
	1	*Bern – Wankdorf*	0.789	*Bahnhofquai/HB – Sihlquai/HB*	0.764	*Bucheggplatz – Rosengartenstrasse*	0.762
	2	*Arth-Goldau – Steinen*	0.811	*Sihlquai/HB – Museum für Gestaltung*	0.764	*EscherWyss-Platz – Rosengartenstrasse*	0.762
	3	*Steinen – Schwyz*	0.811	*Limmatplatz – Museum für Gestaltung*	0.764	*Schiffbau – Bf. Hardbrücke*	0.801

The boxplots show that the network adaptations made from *Zurich tramway 2006* to *Zurich tramway 2025* are advantageous also from the operational point of view. Especially the *connectivity value* is improved, but new capacity problems may occur. The *Swiss railway* network faces capacity problems indicated by the comparatively small mean *capacity value* and the number of outliers.

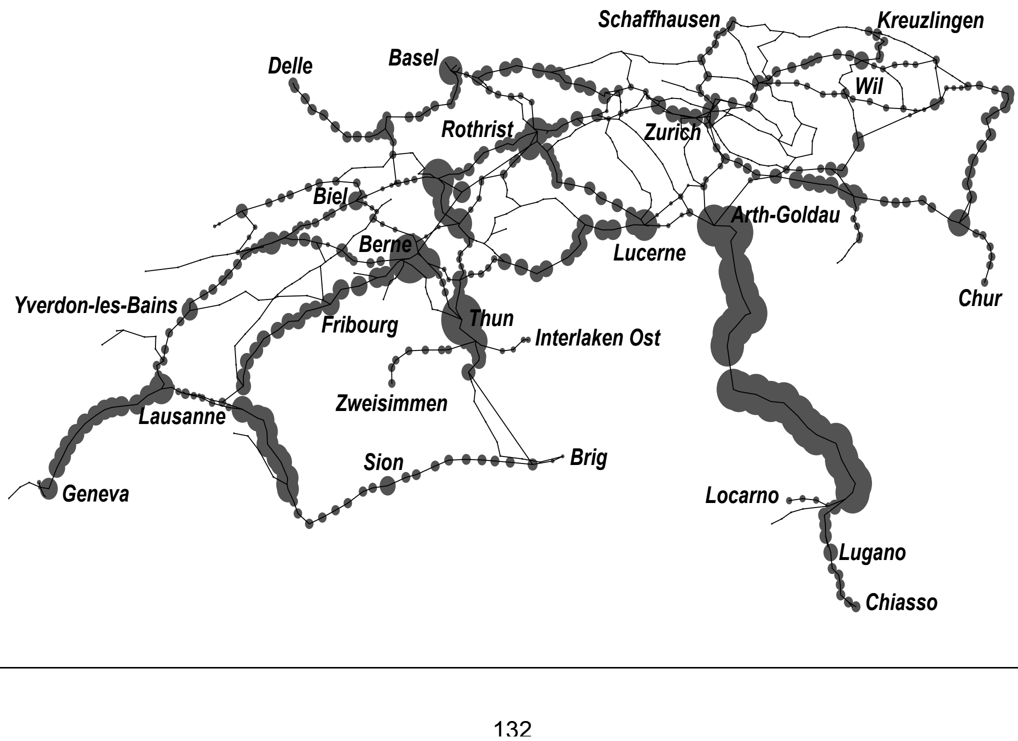
Figure 60 Boxplot of the calculated *operational robustness* values for the analysed networks



Results for the connectivity value

Figure 61 shows for each station how much the *connectivity* value decreases if the representing node is removed. The three nodes with largest reductions are identified in Table 59. Larger circles indicate more severe impacts. Most severe connectivity impacts are measured for *Arth-Goldau – Bellinzona* and *Lausanne - Geneva* and for the nodes *Bern* and *Thun*.

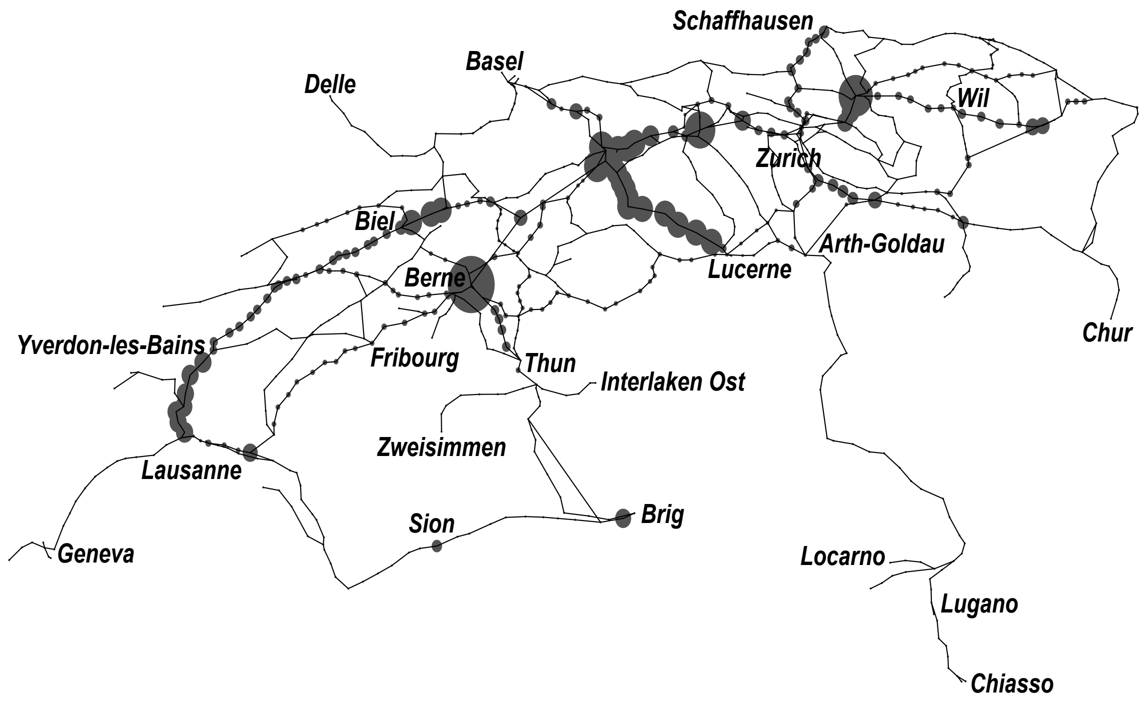
Figure 61 Impacts of removing single nodes from *Swiss railway* on the *connectivity value*



Results for the capacity value

Figure 62 identifies the impacts of removing a node on the *capacity value.* As for the *connectivity value*, larger circles indicate more severe impacts. The capacity-related system performance value is reduced only if lines are rerouted. The results show that removing the nodes *Bern* and *Winterthur* and nodes along *Lucerne – Olten* as well as *Lausanne – Yverdon-les-Bains* cause the most severe reductions of the *capacity value*.

Figure 62 Impacts of removing single nodes from *Swiss railway* on the *capacity value*

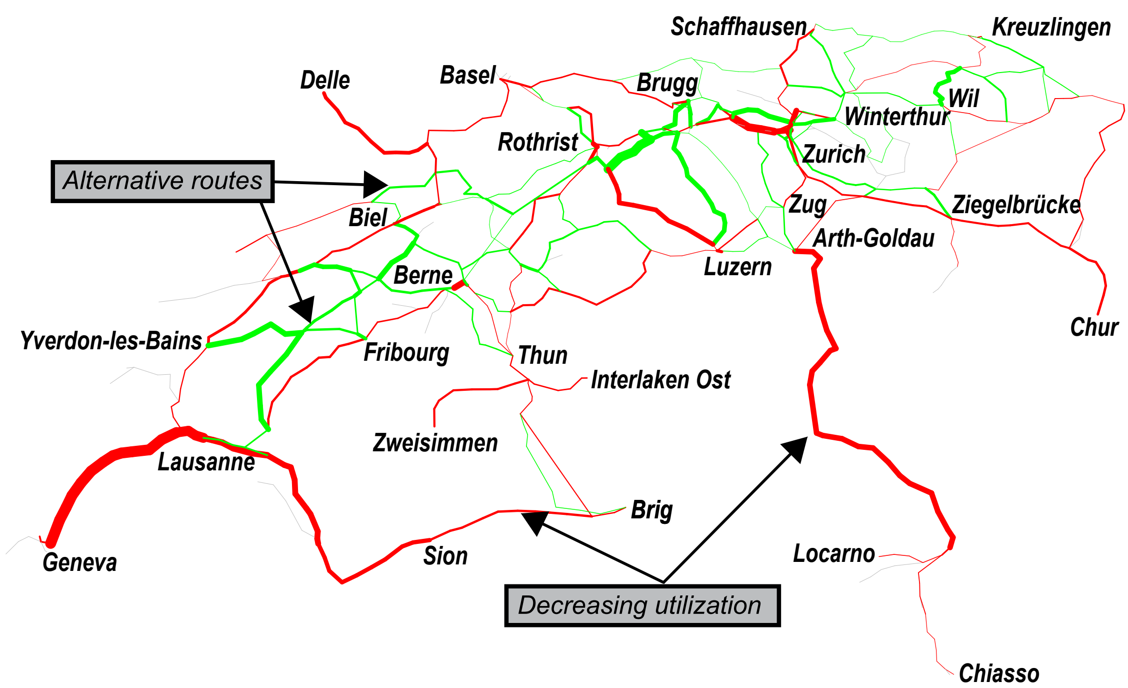


Changes of the capacity utilization

The utilization of edges changes if lines are rerouted or truncated due to node or link removals. Figure 63 gives information about routes more intensively used in degraded operation and those less traversed. For the illustration, each single node in the *Swiss railway* network was removed and the corresponding degraded operation state was calculated.

For each such removal, the difference between the capacity utilization in planned and degraded operation was calculated. All these values were summed up. Green edges are extensively used, i.e. they are often used for rerouting lines in degraded operation. Red edges are less utilized due to truncation of line paths or rerouting of lines along other corridors. The thickness of edges indicates the amount of changes. Capacity thresholds are not considered for the calculation of degraded operation states.

Figure 63 Utilization changes in planned and degraded operation if each single node is removed from the *Swiss railway* network

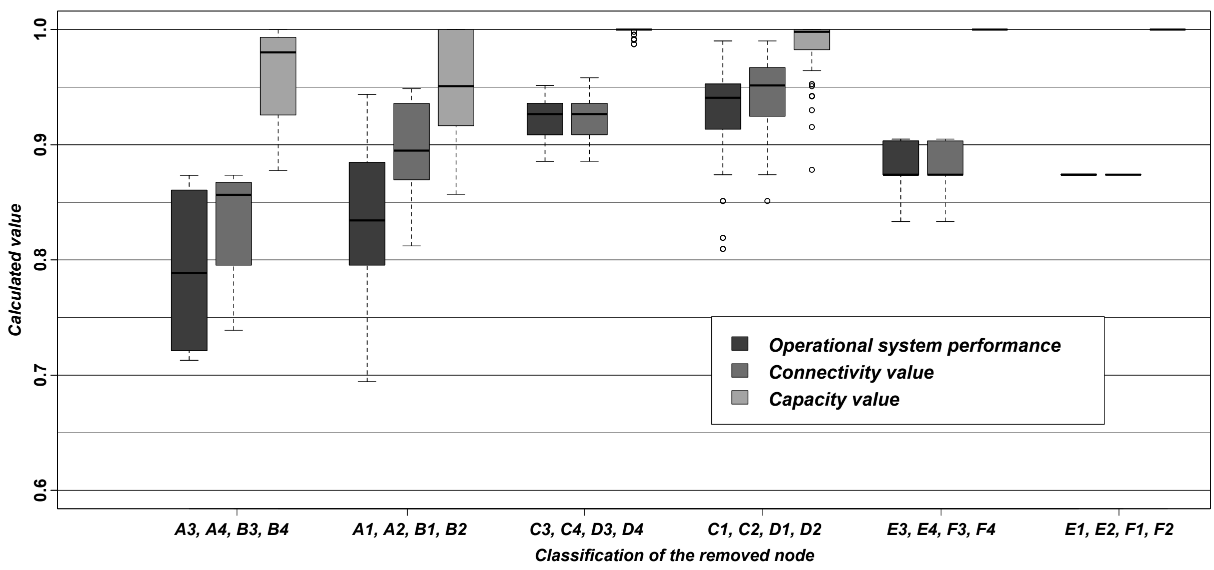


Regression between structural quantities and operational robustness results

Figure 64 shows how the calculated values for the *operational system performance*, *connectivity value* and *capacity value* for removing nodes of a specific class are distributed. The analysis was performed for *Zurich tramway 2025*, since nodes of all classes are present for this network (see Table 52). The corresponding results for the networks *Swiss railway* and *Zurich tramway 2006* are depicted in Figure 108 and Figure 114 in the appendix. Figure 65 shows the fraction of dispositive measures taken per node class for the network *Zurich tramway 2025*. The results for the other analysed networks are shown in Figure 109 and Figure 115 in the appendix.

The boxplots show large differences of the calculated *operational robustness* values between the different node classes. Nodes are classified according to the scheme illustrated in Table 51. The classification scheme can give useful first information about the operational impacts of removing nodes of a specific class. As for the *structural system performance*, removing nodes classified as *A1 – A4* and *B1 – B4* are likely to have most severe impacts on the *operational system performance*. Even though the nodes of the fourth column in most cases lie above the mean *operational system performance* (being 0.915), outliers are present.

Figure 64 Calculated values of the *operational system performance* for different classes of removed nodes (*Zurich tramway 2025)*



The results for the different node classes can be summarized as follows:

- **Nodes classified as *A3*, *A4*, *B3* or *B4*:** Both, the *connectivity value* and the *capacity value* significantly decrease such that very small *operational system performances* are measured in the calculated degraded operation states. There are large ranges between the calculated *operational system performances.* Many lines are dispatched, mostly re-routed but also truncated.

- **Nodes classified as *A1*, *A2*, *B1* or *B2*:** Both, the *connectivity value* and the *capacity value* are reduced. A comparison of both quantities shows that in many cases, they are in fact simultaneously reduced indicating that severe integrity and utilization problems occur. The *operational system performance* is severely reduced if nodes of this class fail. Many lines are affected and rerouted in the majority of cases.

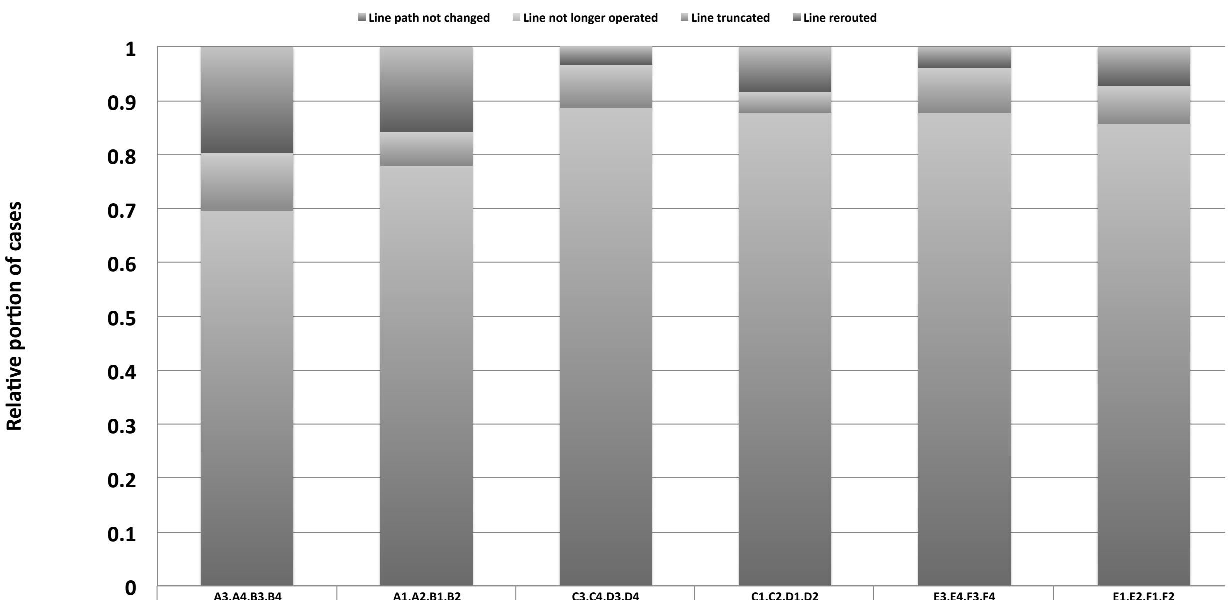
- **Nodes classified as *C3*, *C4*, *D3* or *D4*:** Removing nodes that belong to this class reduces the *connectivity value*. The *capacity value* is slightly reduced, but only in very few cases. Lines are often truncated if nodes of this class fail (Figure 65) since the removal per definition reduces the giant cluster size while the average shortest path length is not affected indicating that outside regions become isolated.

- **Nodes classified as *C1*, *C2*, *D1* or *D2*:** For both, the *connectivity value* and the *capacity value* moderate decreases are measured. Lines are rerouted in most cases, reducing the *capacity value*. Removing nodes with small structural importance can induce severe operational impacts.

- **Nodes classified as *E3*, *E4*, *F3* or *F4*:** The removal decreases the *connectivity value* and reaches values between 0.8 and 0.9. The *capacity value* is not affected indicating that capacity utilization problems do not occur. Lines paths are most often truncated.

- **Nodes classified as *E1*, *E2*, *F1* or *F2*:** There is only a single measure indicating that removing nodes of this class decreases the *connectivity value* by about 10 %, while the *capacity value* is not reduced. Line paths are likely to be truncated.

Figure 65 Calculated distribution of dispositive measures for different node classes (*Zurich tramway 2025)*



	A3,A4,B3,B4	A1,A2,B1,B2	C3,C4,D3,D4	C1,C2,D1,D2	E3,E4,F3,F4	E1,E2,F1,F2
Line rerouted	0.196	0.158	0.034	0.084	0.039	0.071
Line truncated	0.107	0.062	0.08	0.038	0.084	0.071
Line not longer operated	0	0	0	0.001	0	0
Line path not changed	0.696	0.78	0.887	0.877	0.877	0.857

Table 60 shows how the topological centrality measures of nodes correlate with calculated *operational system performances*. The *operational system performance* values correlate to a greater extent with the betweenness of a node than with its degree verifying previous results contained in Table 49: The closeness of a node and the operational or structural system performance values do not correlate. For the degree and the betweenness, even higher coefficients of determination are measured.

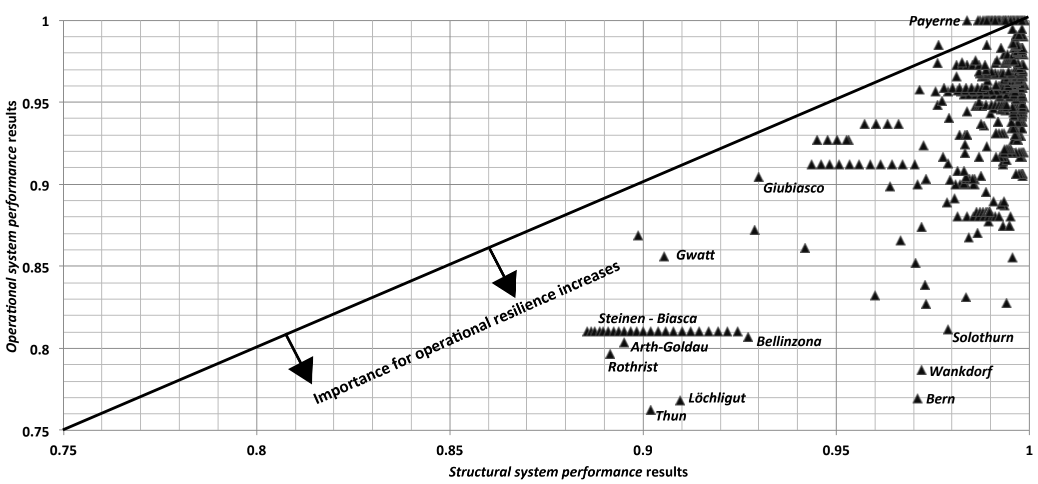
Table 60 Correlation between the centrality and *operational system performances* of nodes

Quantity 1	Quantity 2	Network	R^2
Degree	*Operational system performance*	*Swiss railway*	0.09
		Zurich tramway 2006	0.32
		Zurich tramway 2025	0.37
Betweenness	*Operational system performance*	*Swiss railway*	0.32
		Zurich tramway 2006	0.55
		Zurich tramway 2025	0.47
Closeness	*Operational system performance*	*Swiss railway*	0
		Zurich tramway 2006	0.07
		Zurich tramway 2025	0.02

Comparison of structural and operation system performance results

Figure 66 shows whether and to which extent the calculated structural robustness and operational robustness values coincide. Each point represents the quantified consequences of removing single nodes from the network. The coordinate along the x-axis is the calculated *structural system performance* value if the node is removed. The value on the vertical axis denotes the calculated *operational system performance* value.

Figure 66 Comparing the results for the structural and operational robustness for removing single nodes from the *Swiss railway* network

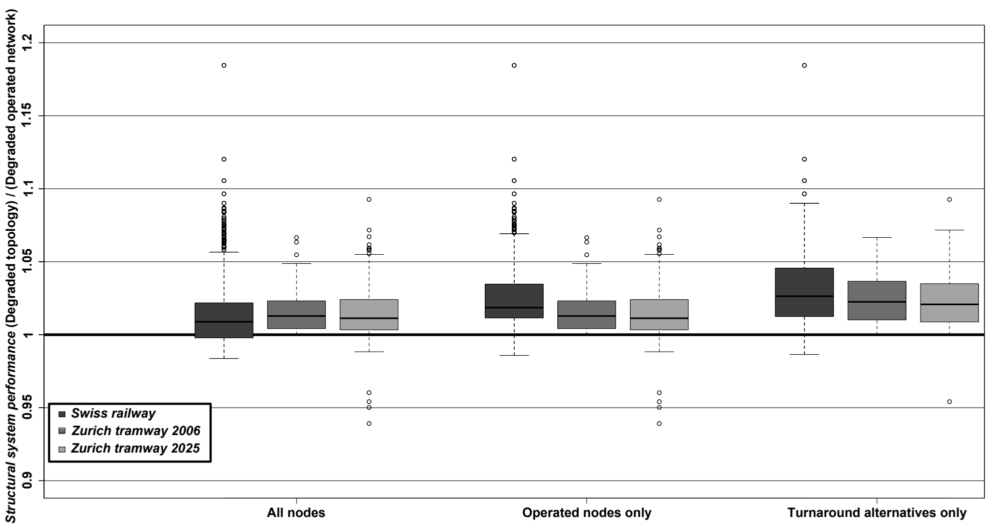


Generally, for nodes with small structural robustness also less *operational system performances* are calculated. However, there are many nodes whose removal decreases the *struc-*

tural system performance only slightly, but whose deletion results in degraded operation states with very small *operational system performance* values. The results show that for railway networks, a pure topology analysis is not sufficient for entirely assessing the robustness and the operational impacts of removing nodes. For the node *Bern* the calculated structural robustness values is comparatively small (about 0.97), but the operational one is very small (about 0.77). Hence, removing this node has significant impacts on railway operation, but only slight impacts on the topology in degraded state.

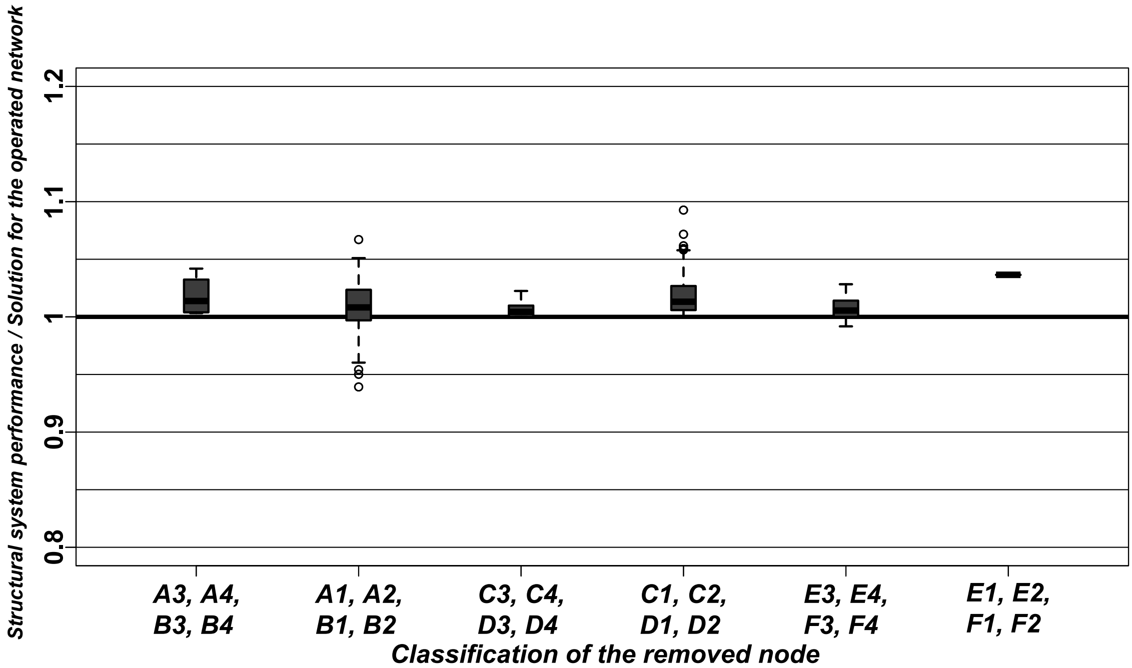
In Figure 67 the *structural system performance* values and the product of the giant cluster size and the average shortest path length within it the operated degraded network are compared. Both measure the impacts of removing a node on the network topology, but in the first case for the degraded topology and in the second case for the operated network in degraded operation. If both values coincide, dividing the *structural system performance* value for the degraded *Infrastructure* network by the corresponding one of the degraded operated topology gives values 1 indicating that the topological solution and the operated network coincide. Figure 67 shows the distribution of this relation for all case study networks.

Figure 67 Comparing the results for the *structural robustness* and those for operated networks



In the vast majority of cases, the *structural system performance* values are larger than the corresponding ones in the operated degraded network. Both quantities deviate by up to 20 %. The reason is that giant cluster size in degraded operation can be much smaller than the topological giant cluster, depending on the existence and location of rerouting alternatives and the calculated disposition measures. Values smaller than 1 are measured if the degraded topology remains connected but rerouting alternatives cannot be used since they are too long. This means that the degraded operated network contains less nodes or longer average shortest path lengths than the degraded topology. Figure 68 shows that values below 1 are observed if nodes classified as nodes of class *A1*, *A2*, *B1* or *B2* are removed, i.e. nodes whose removal significantly increases the average shortest path lengths in the giant cluster. Also for the removal of nodes that belong to the class *E3*, *E4*, *F3* or *F4* values smaller than one occur. The corresponding results for the *Swiss railway* network and the *Zurich tramway 2006* network are shown in Figure 110 and Figure 116.

Figure 68 Comparing the *structural system performance* and those for operated networks for different classes of *Zurich tramway 2025* nodes



Consideration of capacity utilization thresholds

So far, the capacity thresholds of alternative routes were neglected such that degraded operational states were calculated according to the scheme illustrated in Figure 36. This section shows the results if the degraded operation states are calculated respecting the specified operational or theoretical capacity thresholds of links, i.e. the capacity-restricted rerouting scheme illustrated in Figure 41 is applied.

Table 61 compares the distribution of dispositive measures as calculated if in a network all nodes are removed from the network and distinguishes between the degraded operation states that were calculated without considering capacity thresholds (denoted as *No cap*) and the degraded operation states in which the specified capacity thresholds are not exceeded for further edges on the level of the theoretical capacities (denoted as *Cap Theo*) or operational capacities (denoted as *Cap Oper.*). The term *line parts per operated line* denotes to which extent line paths are split into several disjoint parts. Values close to 1 indicate that the lines are not split or only in very few cases. Larger values show that lines are likely to be split into multiple segments in degraded operation states.

Table 61 Distribution of dispositive measures for single node removals

Network	*Swiss railway*			*Zurich tramway 2006*			*Zurich tramway 2025*		
Considered capacity thresholds	No Cap	Cap Theo	Cap Oper.	No Cap	Cap Theo	Cap Oper.	No Cap	Cap Theo	Cap Oper.
Line not changed [%]	93.7	93.7	93.7	85.9	85.9	85.9	86.4	86.4	86.4
Line not longer operated [%]	0.4	0.4	0.4	---	0.04	0.04	0.03	0.03	0.03
No stops outside original line path [%] → Truncation	1.7	2.0	2.2	5.7	5.9	9.7	5.2	5.4	9.3
Stops outside original line path [%] → Rerouting	4.2	4.0	3.7	8.4	8.2	4.4	8.4	8.2	4.2
Line parts per operated line	1.01	1.01	1.01	1.02	1.03	1.05	1.01	1.02	1.05

For the *Zurich tramway 2006* network, in 85.9 % of cases line paths do not have to be changed since the blockaded element is not traversed. The portion of lines that are rerouted such that the degraded line paths contain stops outside the original line path is 8.4 % and decreases to 8.2 % if lines cannot be rerouted such that the specified theoretical capacity utilization thresholds are exceeded for additional edges. If operational threshold values are considered, the value further decreases to 4.4 %. The results indicate that all networks are highly robust against the blockades of single network elements: only in a very few cases, lines cannot longer be operated at all.

The condition that for no additional link the specified operational capacity threshold shall be exceeded is more restrictive than the capacity-restricted solution considering theoretical capacity threshold values. This means that fraction of lines that are truncated increases if operational capacity thresholds are considered.

Figure 69 shows how the calculated values of the *operational system* performances are distributed with and without considering capacity thresholds. The boxes on the left are the results of the *operational system performance* if capacity thresholds are neglected and coincide with the results displayed in Figure 60. The three columns in middle show the results if theoretical capacity thresholds are not exceeded for any additional edge. The right columns show the analysis results if rerouting lines consider the specified operational capacity thresholds. The results show that *Zurich tramway 2025* is much more robust against the removal of single nodes than *Zurich tramway 2006* even though the minimal value slightly decreases.

Figure 69 *Operational system performance* values with and without capacity restrictions

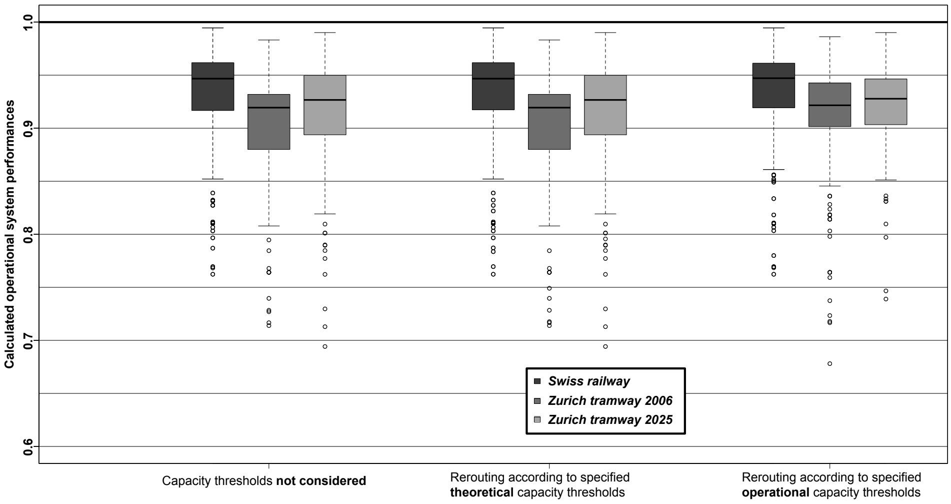


Figure 70 illustrates for which edges the utilization changes if capacity thresholds are considered on the level of theoretical capacities. Decreasing capacity utilizations are observed if the non-restricted rerouting solution exceeds the specified theoretical capacity thresholds for some edges. In these cases, a different capacity-restricted rerouting solution is calculated. The figure gives valuable information where capacity problems occur and which routes are important for offering rerouting alternatives in the capacity-restricted case.

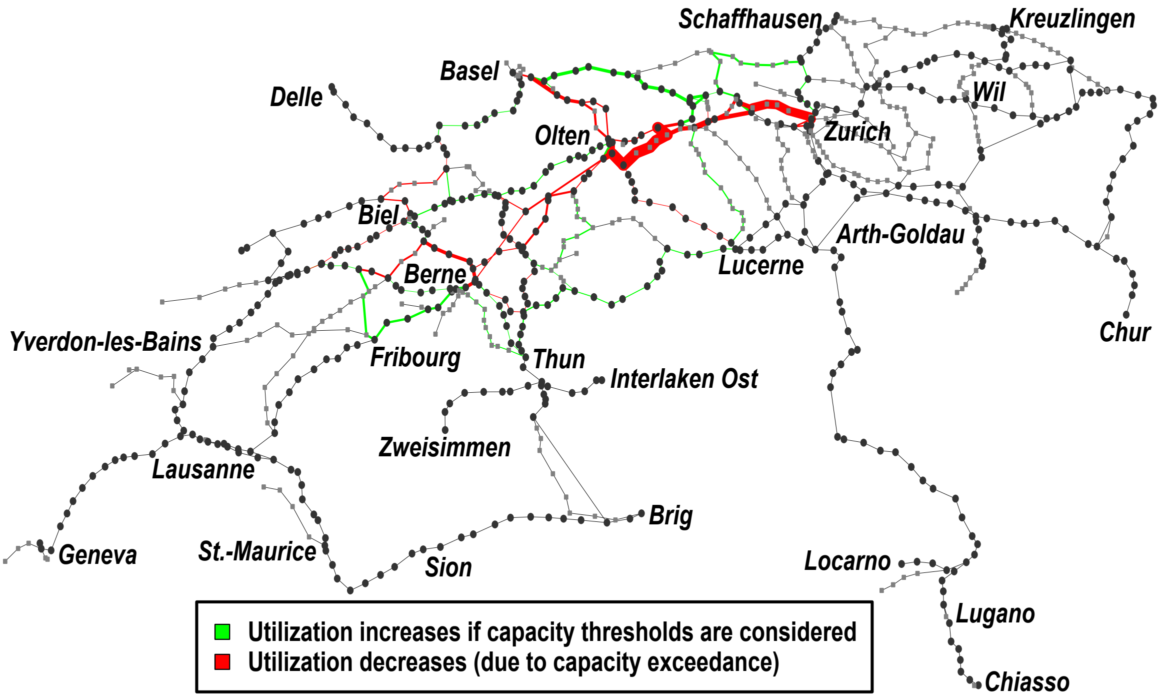
Multiple simultaneous removals

Table 62 shows the results of removing multiple nodes simultaneously from the analysed networks. This means that a sample containing a specific amount of nodes is removed and degraded operational states are calculated. The results are averaged over 500 simulations.

Table 62 Distribution of dispositive measures for multiple simultaneous node removals

Network	*Swiss railway*			*Zurich tramway 2006*			*Zurich tramway 2025*		
Fraction of removed elements	0.1%	1 %	2 %	0.1%	1 %	2 %	0.1%	1 %	2 %
Line path not changed [%]	93.7	73.2	56.8	85.7	75.1	56.1	86.4	64.7	48.2
Line not longer operated [%]	0.4	1.9	3.4	---	0.02	0.2	0.03	0.3	0.5
No stops outside original line path [%] → Truncation	1.8	7.5	11.3	5.7	9.9	17.8	5.5	13.5	18.0
Stops outside original line path [%] → Rerouting	4.1	17.5	28.6	8.6	15.0	25.9	8.1	21.6	33.3
Line parts per operated line	1.01	1.04	1.07	1.02	1.04	1.08	1.01	1.04	1.08

Figure 70 Changes of the capacity utilization with and without capacity restrictions for removing single nodes from the *Swiss railway* network



The calculated number of removed nodes is rounded up, i.e. removing 0.1 % nodes from the *Swiss railway* network means that

$$Removed\ nodes = \lceil n_{SBB} * 0.1\ \% \rceil = \lceil 787 * 0.001 \rceil = \lceil 0.787 \rceil = 1$$

a single node is removed. Hence, the results in these columns correspond with those in Table 61. Small deviations may occur since the removed node is chosen randomly among all nodes instead of removing each single node from the network once.

If the number of removed nodes increases, more lines are likely to be dispatched. For the *Swiss railway* network the majority of the affected lines can be rerouted and the line path is truncated only in few cases. In 3 % of cases, a line cannot longer be operated at all. The portion of lines that do not need any dispositive measures remains comparatively high.

The results of removing multiple nodes simultaneously from the analysed networks with consideration of theoretical capacity thresholds are shown in Table 63. Results were again averaged over 500 simulation runs. The results only slightly differ from those contained in Table 62. The number of lines that are truncated in degraded operation increases for all networks.

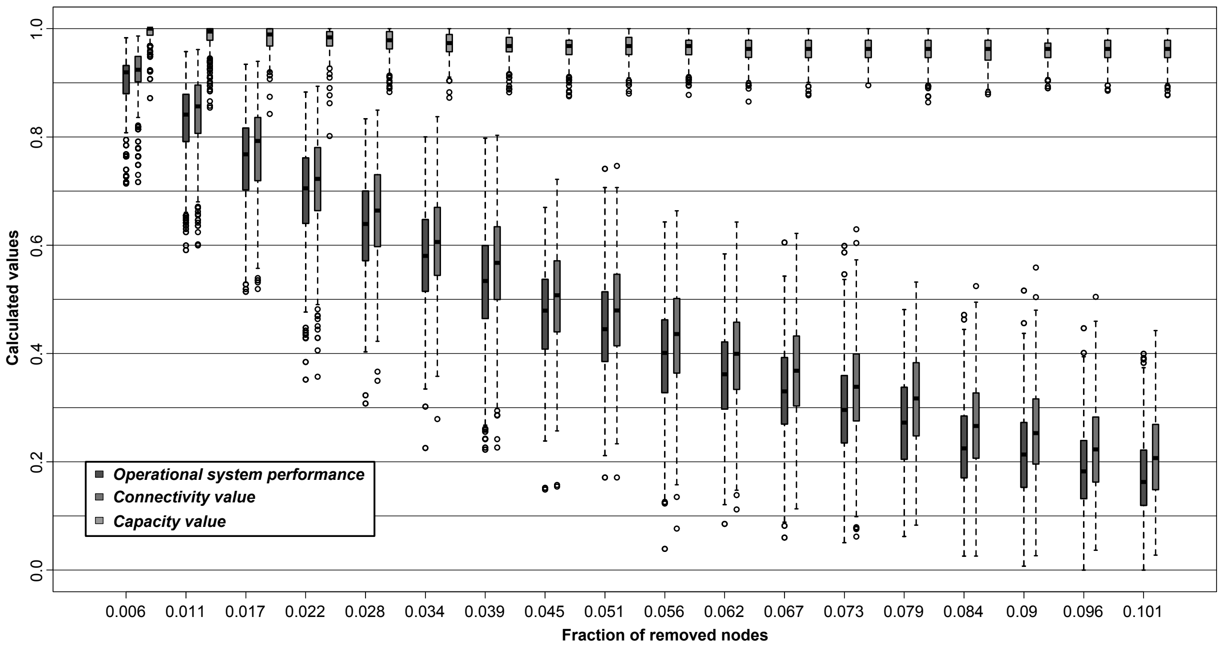
Table 63 Distribution of dispositive measures for multiple simultaneous node removals if theoretical capacity thresholds are considered

Network	*Swiss railway*			*Zurich tramway 2006*			*Zurich tramway 2025*		
Fraction of removed elements	0.1%	1 %	2 %	0.1%	1 %	2 %	0.1%	1 %	2 %
Line path not changed [%]	93.7	73.2	56.8	85.5	73.4	54.3	86.3	65.1	49.3
Line not longer operated [%]	0.4	1.9	3.5	0.05	0.1	0.3	0.04	0.1	0.5
No stops outside original line path [%] → Truncation	2.0	8.5	13.2	5.6	11.0	18.4	5.7	13.0	18.4
Stops outside original line path [%] → Rerouting	3.9	16.4	26.6	8.8	15.5	27.0	8.0	21.9	31.8
Line parts per operated line	1.01	1.05	1.08	1.02	1.05	1.08	1.02	1.04	1.08

For *Zurich tramway 2006,* a detailed analysis of the operational consequences of removing increasing fractions of nodes provides a deeper insight into the dynamics of the *operational system performances* and distribution of dispatching measures.

Figure 71 shows the results for the *operational system performance*, the *capacity value* and the *connectivity value* if up to 10 % of the nodes are removed from the *Zurich tramway 2006* network. For each removed fraction, the plots show the results gained in 500 simulations.

Figure 71 Dynamics of the *operational system performance* for increasing fractions of removing nodes from the *Zurich tramway 2006* network



For increasing numbers of removed nodes both, the *operational system performance* and the *connectivity value* rapidly decrease: If about 10 % of the nodes are removed simultaneously cases occur where the calculated *operational system performances* reduce to zero. The *capacity values* are almost equally distributed for increasing values of removed nodes. For larger values, the *capacity value* will approach 1 since lines are less likely to be rerouted.

For small numbers of removed nodes, outliers with comparatively small *operational system performances* are likely to exist. This means that there exist combinations of node removals with severe operational impacts. For larger fractions of removed nodes, outliers with comparatively high *operational system performances* occur indicating that there are combinations where additional node removals do imply further decreases of the measured quantities.

The differences of the *structural system performances* and the degraded operated topology (the topology served by lines in degraded operation) increase as shown in Figure 72. The results of comparing these two quantities for removals of single nodes were illustrated in Figure 68. It can be concluded that for increasing fractions of removed nodes, the solutions of a pure topology analysis such as calculating the *structural system performance* values deviate significantly from those calculated for the topology that is still served by lines in degraded operation. In other words, especially for multiple node removals operational data has to be considered for assessing the robustness of railway networks.

Figure 72 Comparing structural impacts on the topology and the operated network for *Zurich tramway 2006* for increasing fractions of removed nodes

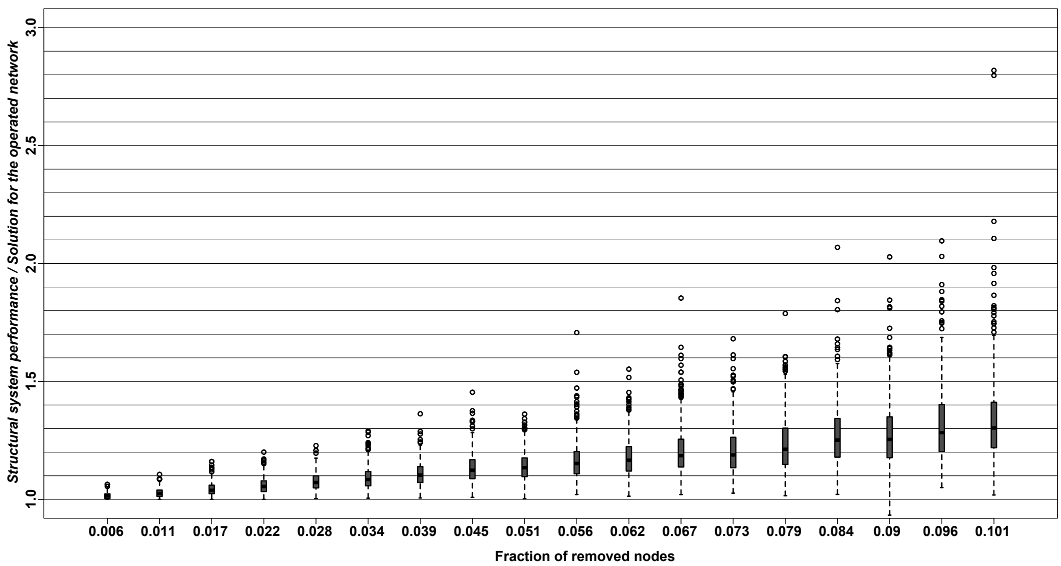
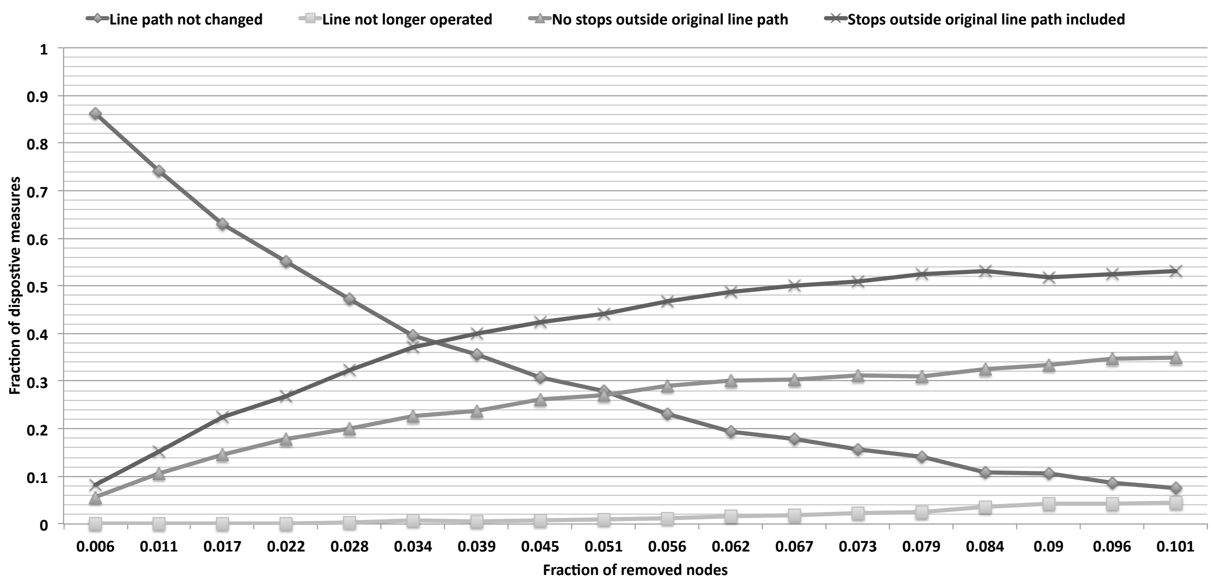


Figure 73 shows the dynamics of the dispositive measures for increasing numbers of node removals. If the number of removed nodes increases, the fraction of lines whose line path is not changed continuously decreases approximating zero. The number of lines that cannot longer be operated also increases but remains at low levels even if 10 % of nodes are removed. Both, the number of degraded line paths that contain nodes outside the original line path (→ rerouting) and those that do not (→ truncation) constantly increase. The curve of the number of lines that can be rerouted lies above those measuring the truncation of line paths. If almost all nodes are removed, both quantities will decrease to zero and the majority of lines cannot longer be operated.

Figure 73 Distribution of dispositive measures for increasing number of initial node removals from *Zurich tramway 2006*



6.4.3 Results for the *Control-command and Signalling* subsystem

Removing a single *Control-command and Signalling* node may induce the removal of multiple *Infrastructure* subsystem ones, if stations are remotely controlled (see Figure 20). This can imply severe operational impacts. The SBB provided data specifying for each station whether they are locally operated or remotely controlled. This data was implemented, but cannot be displayed as maps due to data confidentiality reasons. The represented Control-command and Signalling nodes are listed in Table 89 in the appendix. Table 64 identifies those three *Control-command and Signalling* nodes whose removal most severely reduces the *operational system performances* as well as the *connectivity value* and the *capacity value.*

The results show that *Olten*, *Bern* and *Lausanne* are the *Control-command and Signalling* nodes whose removal has most impacts on the *connectivity value* and the *operational system performance* in degraded operation. Removing all stations remotely controlled from *Zurich*

Oerlikon and *Winterthur* causes the most severe reductions of the *capacity values* such that rerouting lines is possible but exceeds the specified capacity thresholds or the number of trains is exceeded due to longer line path lengths in degraded operation.

Table 64 Most severe impacts of removing single *Control-command and Signalling* nodes from the *Swiss railway* network

Quantity and Rank		*Swiss railway*					
		No thresholds		Theoretical capacity		Operational capacity	
	1	*Bern*	0.501	*Bern*	0.501	*Bern*	0.501
Connectivity value	2	*Olten*	0.586	*Olten*	0.588	*Olten*	0.585
	3	*Lausanne*	0.695	*Lausanne*	0.695	*Lausanne*	0.695
	1	*Olten*	0.874	*Zurich Oerlikon*	0.903	*Sion*	0.964
Capacity value	2	*Zurich Oerlikon*	0.903	*Winterthur*	0.967	*Zurich Oerlikon*	0.965
	3	*Winterthur*	0.944	*Olten*	0.969	*Ziegelbrücke*	0.972
	1	*Olten*	0.460	*Bern*	0.501	*Bern*	0.501
Operational system performance	2	*Bern*	0.501	*Olten*	0.556	*Olten*	0.585
	3	*Lausanne*	0.695	*Lausanne*	0.695	*Lausanne*	0.695

Table 65 shows the distribution of dispositive measures calculated by the implemented line disposition framework. The results distinguish between removing any represented *Control-command and Signalling* node, those remotely controlling others and locally operated ones, i.e. nodes where single stations in the *Infrastructure* subsystem fail.

Table 65 Distribution of dispositive measures if single *Control-command and Signalling* nodes are removed

Network	*Swiss railway*		
No capacity thresholds considered	All *CCS* nodes	Remotely-controlled	Locally-operated
Line not changed [%]	93.8	90.5	96.3
Line not longer operated [%]	0.8	1.5	0.3
No stops outside original line path [%] → Truncation	2.7	3.9	1.7
Stops outside original line path [%] → Rerouting	2.7	4.1	1.7
Line parts per operated line	1.0127	1.0137	1.0119

Removing *Control-command and Signalling* nodes remotely controlling multiple *Infrastructure* stations affects more lines to need dispositive efforts. Approximately 10 % of all lines need dispositive measures for nodes remotely controlling others. The number of lines that are rerouted and those that are truncated are also larger than for locally controlled nodes. The distribution of the *operational system performances*, the *connectivity* and *capacity value* is plotted in Figure 74. The most severe impacts are observed for nodes remotely controlling others.

Figure 74 Boxplots for the operational robustness results if each single CCS node is removed from the *Swiss railway* network

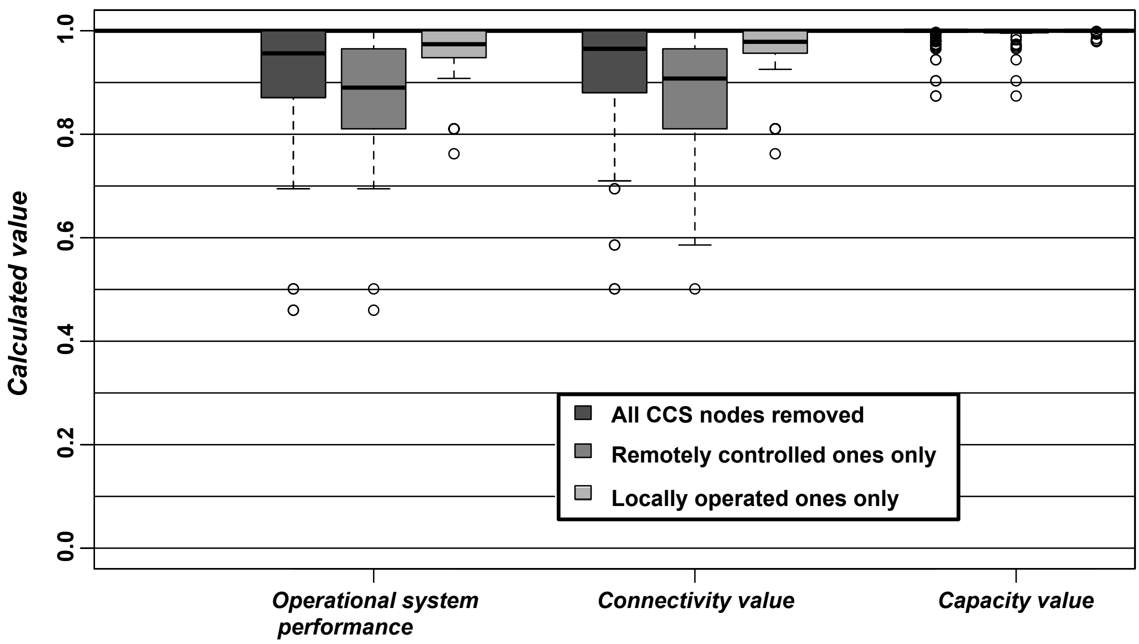


Figure 75 identifies for each modelled link how the capacity utilization changes if every single *Control-command and Signalling* node and all incident *Infrastructure* nodes are removed. Due to these removals, some lines are dispatched according to the scheme illustrated in Figure 36. Capacity restrictions are not neglected for finding rerouting alternatives. For each removal of a single *CCS*-node, the capacity utilization in planned and degraded operation is compared for all *Infrastructure* links. The corresponding balances are summed up for each removal of a *CCS*-node. Positive balances are highlighted by green colours and indicate that the corresponding edge is used for rerouting lines. Edges that are less utilized are marked with red colours. The thickness of an edge depends on the amount of increasing or decreasing capacity utilizations.

Figure 76 shows the differences between the results of removing single *Control-command and Signalling* nodes from *Swiss railway* with and without considering the specified theoretical capacity thresholds of links.

Figure 75 Calculated changes of the capacity utilization of *Infrastructure* links if each single CCS node is removed from the *Swiss railway* network (capacity restrictions are neglected)

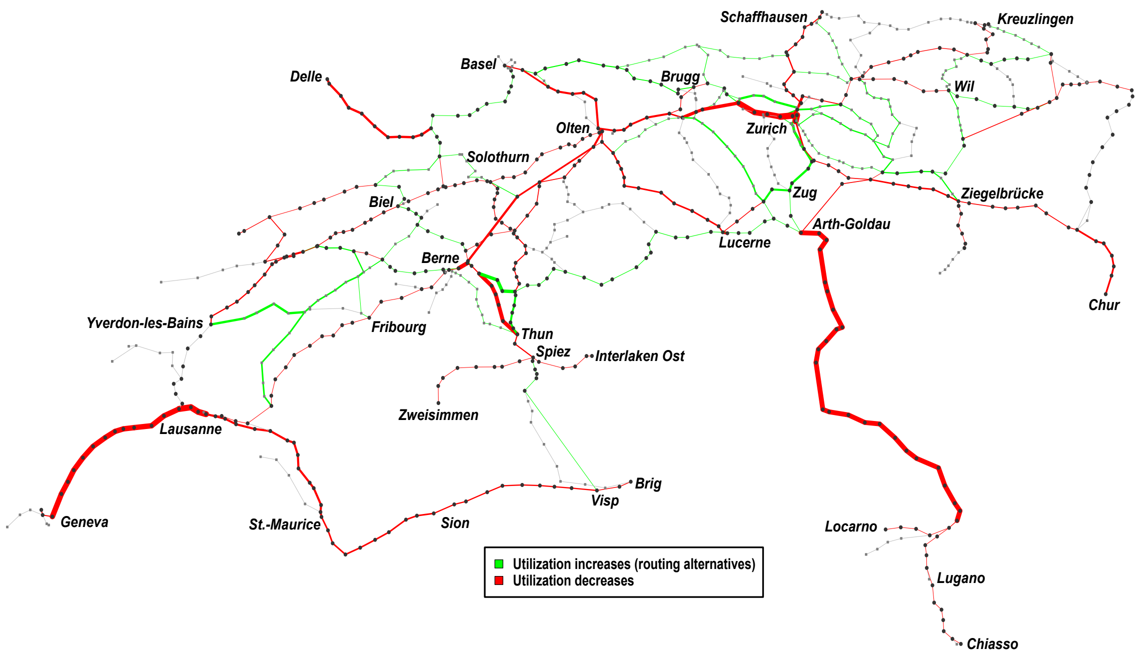
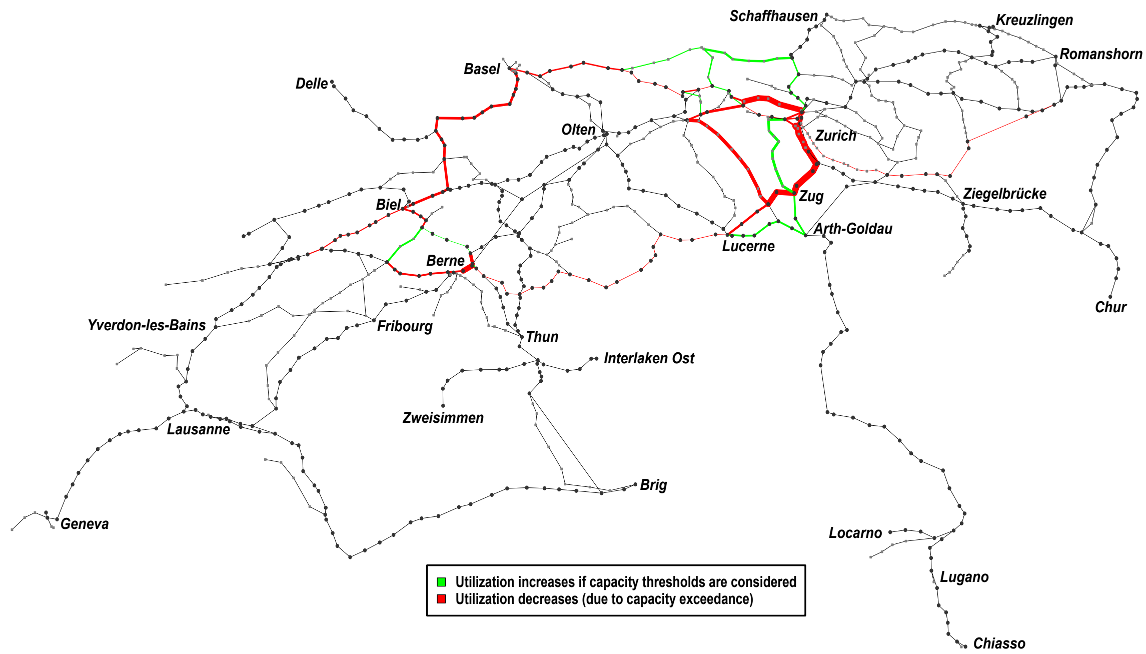


Figure 76 Capacity utilization changes if capacity thresholds are considered when removing single *CCS* nodes from the *Swiss railway* network



For each removal of a single *CCS*-node, the balance of the non-restricted and the capacity-restricted solution is calculated. These results are summed up for all such removals of the *CCS-nodes*. For each edge, the thickness denotes the amount of increasing or decreasing capacity utilization values. Green colours indicate increasing capacity utilizations. Red edges show that the calculated non-restricted solution exceeds the theoretical capacity threshold of the link and hence capacity problems occur. A comparison of the number and strength of the ties shows that in some cases rerouting lines is no longer possible if capacity restrictions are regarded.

6.4.4 Analysis of the *Energy* subsystem

The data specifying for each node and link from where electrical current is supplied was provided from the SBB. This data was implemented, but cannot be displayed as maps due to data confidentiality reasons. The represented substations and the number of links receiving electrical current from a substation are shown in Table 90 in the appendix.

Two different kinds of node removals can be distinguished for the *Energy* subsystem:

- **Removing all nodes and links within single traction current areas:** All links and nodes are removed for which no traction current is supplied if single traction current areas fail

- **Removing entire substations:** Each substation contains multiple traction current areas, all *Infrastructure* nodes and links are removed that are not longer provided with electrical current

Table 66 identifies those three substations and traction current areas whose removal have most severe impacts on the *connectivity value*, the *capacity value* and the *operational system performance*. The results show that removing the node representing substation *Bern* leads to a degraded operation state with an *operational system performance* of about 50 %, mainly due to decreases of the *connectivity value*.

Table 66 Most severe impacts of removing single *Energy* nodes from the *Swiss railway* network

Quantity and Rank		*Swiss railway*			
		Entire substations		Single traction current area	
Connectivity value	**1**	*Bern*	0.493	*Thun – Station*	0.762
	2	*Thun*	0.766	*Giubiasco – North*	0.793
	3	*Olten*	0.772	*Flüelen – North*	0.811
Capacity value	**1**	*Olten*	0.804	*Bern – Station*	0.856
	2	*Zurich Seebach*	0.903	*Bern – Thun*	0.857
	3	*Hendschiken*	0.910	*Bern – Löchligut*	0.862
Operational system performance	**1**	*Bern*	0.492	*Bern – Thun*	0.695
	2	*Olten*	0.576	*Bern – Station*	0.705
	3	*Wanzwil*	0.760	*Thun – Station*	0.762

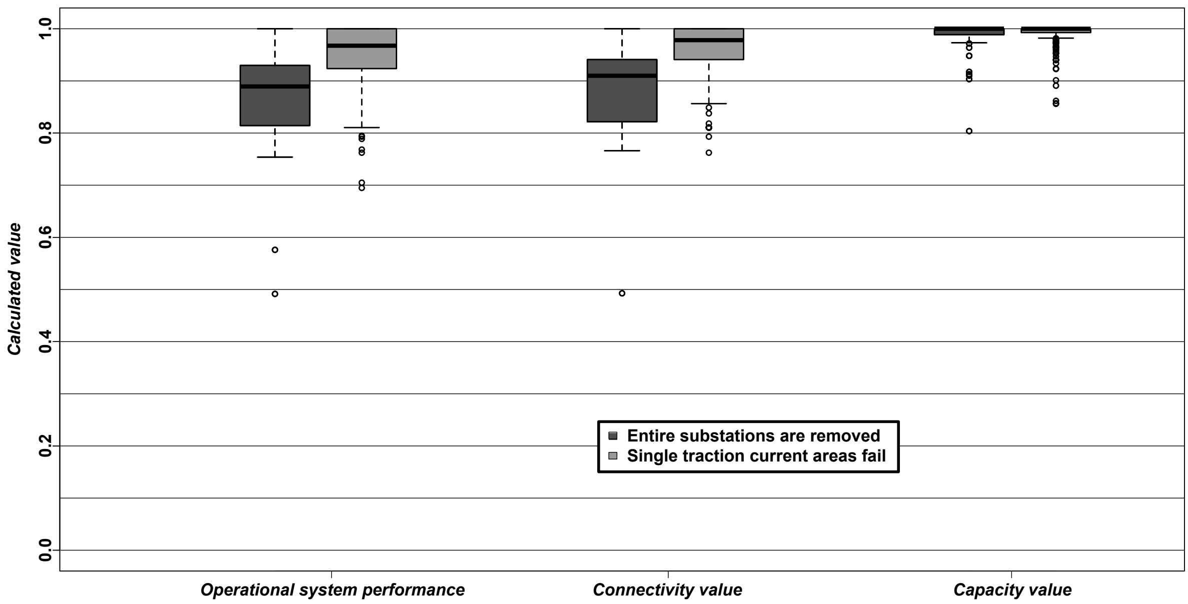
Table 67 shows the distribution of dispositive measures if each single *Energy*-nodes is removed. The results are summed up for removing the corresponding links from the *Infrastructure* subsystem, calculating degraded operational states according to the scheme visualised in Figure 36 and summing up all the dispositive measures. In the majority of cases, where lines need dispositive efforts, rerouting alternatives are found. Only in 1 % of cases, lines cannot longer be operated.

Table 67 Distribution of dispositive measures if single *Energy* nodes are removed

Network	*Swiss railway*	
Considered capacity thresholds	Entire substations	Single traction current areas
Line not changed [%]	90.3	95.1
Line not longer operated [%]	1.1	0.3
No stops outside original line path [%] → Truncation	3.2	1.3
Stops outside original line path [%] → Rerouting	5.5	3.3
Line parts per operated line	1.02	1.01

The distribution of calculated values of the *connectivity value,* the *capacity value* and the *operational system performance* are shown in Figure 77. Obviously, the removal of entire substations reduces the *operational system performance* much more than the failure of single traction current areas. A few outliers are present; three of them are identified in Table 66.

Figure 77 Calculated operational robustness results if each single *Energy* node is from the *Swiss railway* network



A closer look at the graphs shows that there is a single substation, whose removal induces severe connectivity reductions. Since the operational system performance value is not further decreased, the corresponding *capacity value* remains close to one. For the second outlier, it can be concluded that both the *connectivity value* and the *capacity value* are reduced.

For each *Infrastructure* link, Figure 78 shows how its capacity utilization changes if each single substation is removed. The results were calculated as follows: each single substation was removed inducing the removal of specific *Infrastructure* edges. The causes disposition efforts for all lines traversing the removed *Infrastructure* links in planned operation. The degraded operation state was then calculated according to the scheme illustrated in Figure 36. The capacity utilization of each link in both, planned and degraded operations were compared and the balance was calculated. This was done for removing each single substation. The results were summed up and are illustrated in Figure 78. Red-coloured edges are less utilization while the green ones are more traverse than in planned operation and hence offer important rerouting alternatives. The thickness of edges depends on the amount of the increases or decreases.

Figure 78 Calculated changes of the capacity utilization of *Infrastructure* links if each single *Energy* node is removed from the *Swiss railway* network (capacity restrictions are neglected)

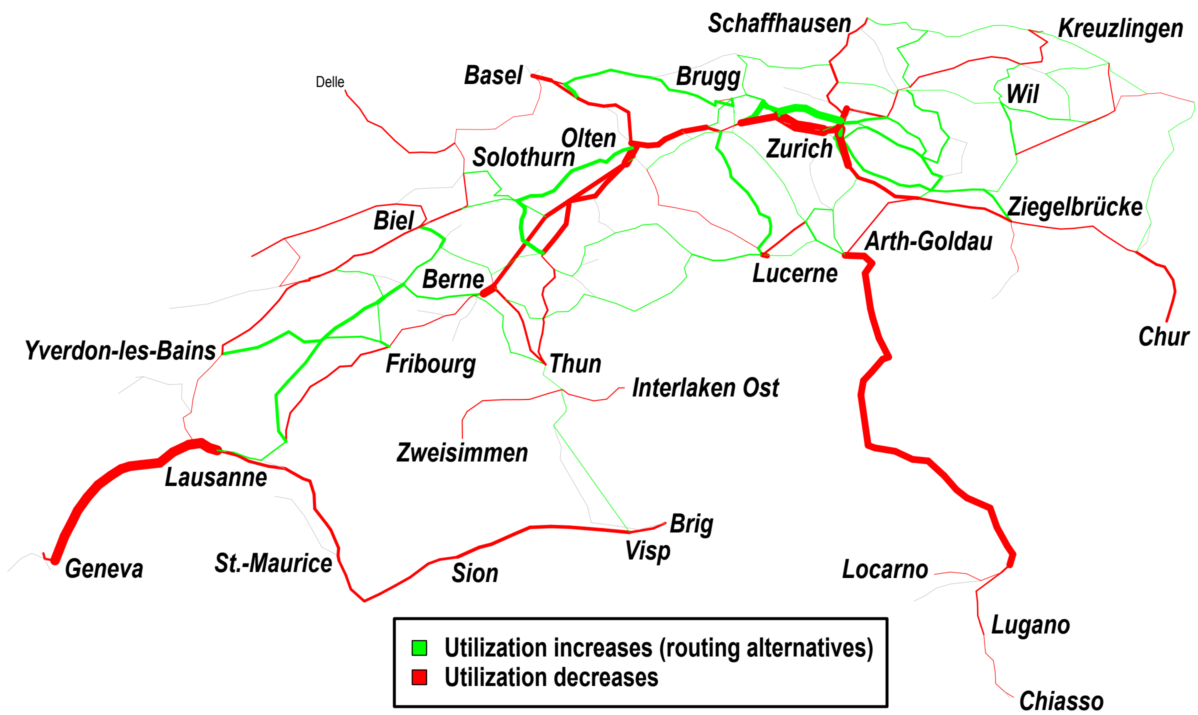
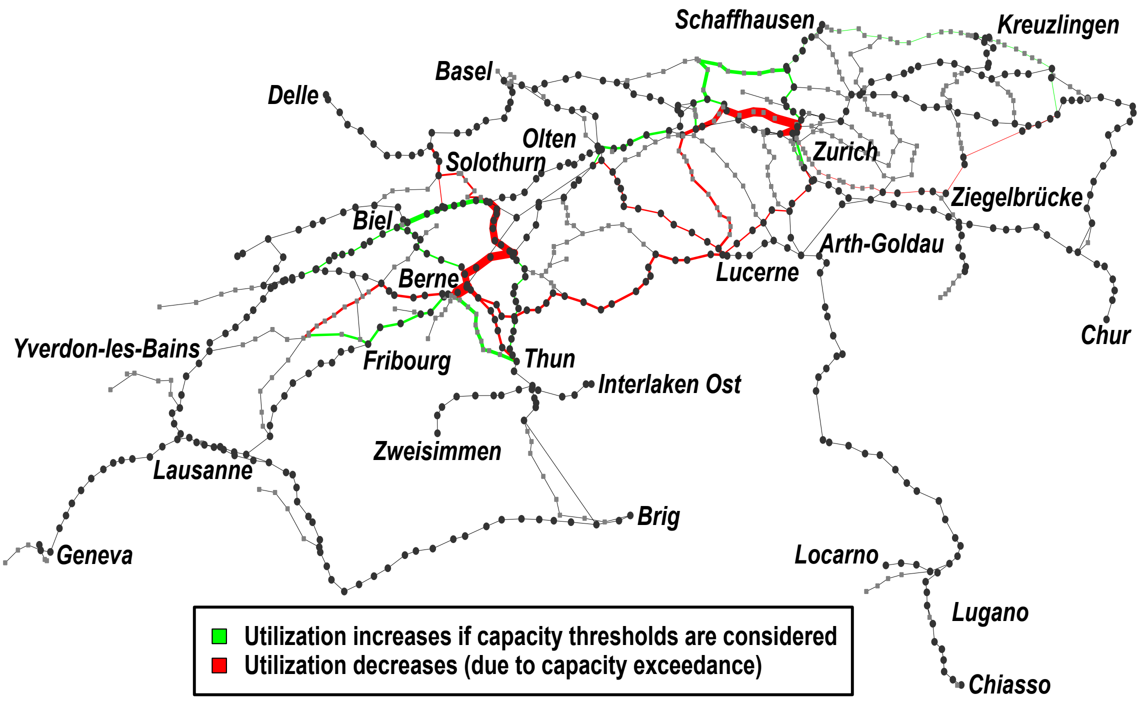


Figure 79 shows all *Infrastructure* links, how the solution in Figure 78 changes, if rerouting lines shall not exceed the specified theoretical capacity thresholds in the degraded operation state for additional edges. For each link the colours illustrate whether the capacity utilization increases (green colours) or decreases (red colours) relative to the solution depicted in Figure 78. The thickness of edges depends on the amount of changing values. Red colours edges indicate that capacity problems are present, i.e. rerouting lines is hindered due to theoretical capacity thresholds.

An example shall illustrate the results calculated for removing each single *Energy*-node: If no capacities are considered in the line disposition framework shown in Figure 36, many lines are rerouted between *Killwangen* and *Zurich* via *Würenlos* and *Regensdorf.* However, this corridor has a theoretical capacity threshold of only 120 trains per day since only single tracks are present (see Table 40). The specified theoretical threshold value is exceeded. Hence, the capacity-restricted rerouting solution will not find this corridor for rerouting the lines. Consequently, capacity utilization of the corridor in the capacity-restricted case decreases significantly, highlighted by the red colour of the corridor.

Figure 79 Capacity utilization changes if capacity thresholds are considered when removing each single *Energy* node from the *Swiss railway* network



Large differences between the capacity-restricted and non-restricted solutions are also observed around the nodes representing the stations *Bern, Thun, Solothurn* and *Zurich.* Since the amount of decreases is larger than the increases, capacity restrictions cause that lines cannot longer be rerouted but have to be truncated instead (or lines are even put out of service).

7 Sensitivity analysis and model verification

7.1 Overview

Contents

This chapter verifies both the applicability of the line disposition framework (Figure 36) and the implemented robustness analysis tool (Figure 43) by a detailed case study analysis. The results shall not only verify the plausibility of results, but also show that both the model and the calculated results change if the input data varies. Hence, this chapter contains a sensitivity analysis and it additionally verifies that degraded operation states are calculated meeting the real-world ones. Table 68 shows how this chapter is structured.

Table 68 Structure and contents of chapter 7

Section	Contents	Purpose
7.1	Overview	Introduction, goals and purpose of this chapter
7.2	Case study 1	Benefits from extending the *Zurich tramway 2006* network to *Zurich tramway 2025* focussing on the *Infrastructure* and *Traffic Operation and Management* subsystem
7.3	Case study 2	Importance of a specific corridor for the operational robustness of the *Swiss railway* network, all represented subsystems considered

Case studies

Two case studies were chosen providing interesting results extending those in the previous section. A first example analyses the benefits realized by the network evolution from *Zurich tramway 2006* to *Zurich tramway 2025* regarding the operational resiliencies. The analysis focuses on the subsystems *Infrastructure* and *Traffic Operation and Management* and measures the structural and operational robustness by application of the developed robustness analysis tool and the formulated line disposition framework. The first case study shows that the developed methodology can be used for comparing two network states with respect to the dynamics of the structural and operational resiliencies for concrete scenarios.

The second case study analyses the importance of a specific corridor for the robustness of the *Swiss railway* network. It may happen that a specific corridor cannot be used for some period of time due to long-term maintenance works or deconstructing the tracks for instance. The case study shows that even corridors that are not intensively utilized in planned operation state may offer important rerouting alternatives and hence contribute to the operational robustness of railway networks. The second case study also considers node removals originating in the *Control-command and Signalling* subsystem and the *Energy* subsystems.

Model verification, plausibility of the results

The presented case studies shall also show that degraded operation states are calculated mimicking the dispositive efforts taken in real-world operation. For this purpose, the results calculated for the first case study analysis were discussed with the VBZ, the public transport operator in Zurich. Since the stability of railway networks is an explosive issue and for data confidentiality reasons, no documents could be provided, but information was given orally. This means that the results of the first case study were discussed with the VBZ, whether they give realistic solutions for real-world scenarios. Additionally, the VBZ provided information about how degraded operation states are determined and in which order steps are taken to inform emergency units, train drivers or the customers.

For the results calculated for the *Swiss railway* network, such discussions were not taken mainly due to the politically relevance of the issue. However, the second case study analyses a concrete problem and hence provides important quantitative information from an operational point of view for decision-makers, infrastructure owners and transport operators: There were ideas (that was abandoned meanwhile) for refitting the infrastructure in the following way: There were plans for turning the tracks of the analysed corridor from standard gauge to metre gauge. The consequences on the stability of the standard gauge network in both planned and degraded operation were only hypothetic and quantitative data was needed. This tool can provide such data by analysing the operational robustness of the present, implemented network with the corresponding results gained for the adapted network. Removing the corridor stations and links from the network can represent the reconstruction measures. In this context, the second case study provides valuable information for real-world decisions concerning the operational robustness of railway networks.

Table 69 summarizes the purpose of the two case studies, shows the research questions and provides information about the practical relevance of the calculated results.

Table 69 Purpose of the analysed case studies and practical relevance of the results

	Case study	Analysed network	Practical questions	Purpose
1	Comparing the robustness of a specific scenario in both Zurich tramway networks	*Zurich tramway 2006, Zurich tramway 2025*	Information about the applicability of the tool for determining and visualizing degraded operation states, information whether the results are realistic…	Model verification, sensitivity analysis
2	Importance of a specific corridor in planned or degraded operation	*Swiss railway*	Importance of a specific corridor for the robustness of the entire network, consequences of refitting measures on network stability, cases in which the corridor is used for rerouting lines…	Sensitivity analysis

7.2 Case study 1: Benefits from the *Zurich tramway* evolution

For *Zurich tramway 2006* and *Zurich tramway 2025*, the structural and operational consequences of removing the nodes representing the stations *Tüffenwies* and *Limmatplatz* are measured and compared. The stations were chosen since interesting results are gained that simultaneously verify the correct application of the implemented procedures. The calculated degraded operation states for the *Zurich tramway 2006* network were discussed with the VBZ, the public transport operator in Zurich.

7.2.1 Real-world solutions for determining degraded operation states

Information about the actions taken to establish degraded operation states is a sensitive issue and cannot be published in this document. However, the basic conclusions of discussing the calculated results for case study 1 and general information provided by the VBZ about dealing with threatening events are summarized in the following.

The VBZ uses rules of action that specify for each occurring event threatening tramway (and bus) operation how to establish degraded operation states. When the infrastructure links and nodes are identified that cannot be used any longer for operation, the rules of action provide all the necessary information that is essential for dealing with occurring hazardous events such as:

- Contact number of emergency units
- Operational information such as routing decisions
- Customer information

- Degraded operation states, i.e. information about rerouting alternatives or truncation of lines
- Information about bus services, additional trains that become necessary
- …

Different rules of action are available for specific corridors, i.e. multiple stations and connections are integrated into a corridor if a removal of the nodes and links lead to identical degraded operation states. For each such failure, several severity levels are distinguished denoting for instance whether a single or both parallel tracks cannot be traversed anymore. In this study, the implemented methodology (see Figure 36) calculates degraded operation states assuming that both tracks simultaneously fail. Hence, it is not possible to represent failures of only a single track while the other one can still be used for operation. These failures are distinguished in the rules of action used by the VBZ.

The operational rules used by the VBZ include other operational measures that cannot be modelled with the implemented methodology such as connecting different truncated line parts into a single line. Beside the rules of actions, situation-dependent aspects are integrated into decision processes such that the experience and knowledge of the decision-maker also contributes to the decision about how to deal with an occurring threatening event. Both cannot be modelled and represented by any simulation tool. However, the tool calculates feasible degraded operation states that can provide essential additional information supporting the decision processes. Especially, if multiple failures occur simultaneously (these events are very rare), the tool gives valuable information since the rules of action are specified for specific single corridors. If multiple corridors fail simultaneously, the problem is reduced to subproblems and focuses on the most severe event.

The discussion with the decision makers concluded that especially for removals of stations and links in the outer parts of the network realistic degraded operations states are calculated coinciding with real-world solutions (under the assumption that both tracks simultaneously fail). If failures occur in dense parts of the networks, i.e. stations and tracks in the city centre are removed, feasible degraded states are calculated but the experience of the decision maker cannot be represented such that in real-world situations slightly different rerouting alternatives are found. This means that for failures occurring in dense network parts exact rerouting decisions are not calculated in all cases since they are case specific and include the knowledge of decision makers. Also for cases in which only one of two available tracks cannot longer be used, different (but in most cases feasible) solutions are likely to be calculated.

In summarization, the discussion revealed that the calculated degraded operation states and the real-world solutions can deviate in the following cases:

- Even in cases in which lines are rerouted to drive around failing infrastructure elements, extra services using bus shuttles are established.
- Not all calculated rerouting solutions can practicable from an operational point of view, i.e. not all routing alternatives actually exist due to the assumptions made when modelling the infrastructure topology.
- Cases in which a single track can still be used for operation.
- Rerouting decisions in which additional vehicles are needed may not always be taken.
- Truncated line parts may be integrated into the line path of a single line.
- Failures within dense areas with multiple rerouting alternatives.

However, it was stated that the tool provides useful information especially regarding the visualisation of operational impacts of occurring events and hence contributes to the decision made for establishing degraded operation states. The tool is not an expert tool, but allows to suggest solutions quickly even for multiple simultaneous events, which is essential in complex situations immediately after the occurrence of hazardous events. The described results for case study 1 for the *Zurich tramway* network are realistic and mimic the real-world solution (assuming that both tracks cannot longer be used for operation and the number of trains in the degraded component is large enough to run the lines within the specified headway).

7.2.2 Results for the *Zurich tramway 2006* network

Two lines, i.e. Line 4: *Bahnhof Tiefenbrunnen - Werdhölzli* and Line 13: *Frankenthal - Albisgütli*, traverse the removed nodes *Tüffenwies* and *Limmatplatz*. The following dispositive measures are calculated:

- ***Line 4:*** operated between *Escher Wyss Platz - Hardturm* and *Hauptbahnhof – Bahnhof Tiefenbrunnen* → *Line 4* is truncated and split into two distinct line parts.
- ***Line 13:*** operated between *Escher Wyss Platz - Frankenthal* and *Hauptbahnhof – Albisgütli* → *Line 13* is truncated and split into two distinct line parts.

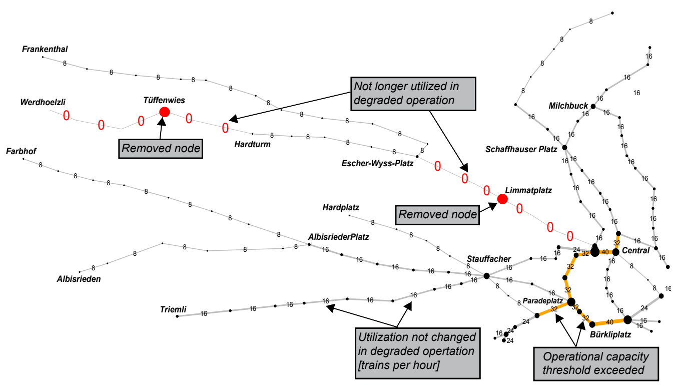
Table 70 shows the calculated *operational system performance* values in degraded operation. The results are calculated neglecting the capacity thresholds of links and respecting the specified theoretical capacity limits, i.e. the theoretical capacity thresholds are not exceeded for additional edges in the degraded operation state. For the *Zurich tramway 2006* network, both cases coincide.

Table 70 Operational robustness results for case study 1 (*Zurich tramway 2006*)

	No capacities considered		Considering operational capacity thresholds	
q_1 : Served stations	168 / 178	0.944	168 / 178	0.944
q_2 : Giant cluster size	153 / 178	0.860	153 / 178	0.860
q_3 : Mean distance	12.82 / 14.07 [hops]	0.916	12.89 / 14.07 [hops]	0.916
q_4 : Changing processes	1.757 / 1.761 [lines]	1	1.757 / 1.761 [lines]	1
Connectivity value	Product	**0.743**	Product	**0.743**
q_5 : Track-km	106.15 / 112.48 [km]	1	106.15 / 112.48 [km]	1
q_6 : Vehicles	101 / 104	1	101 / 104	1
q_7 : Operational capacity	No additional edge	1	No additional edge	1
q_8 : Theoretical capacity	No additional edge	1	No additional edge	1
Capacity value	Product	**1**	Product	**1**
Operational robustness	Formula	**0.743**	Formula	**0.743**
Line parts per operated line	= 15 / 13	1.154	= 15 / 13	1.154

Figure 80 shows calculated degraded operation state and denotes for each link the capacity utilization in degraded operation. The corridors *Hardturm – Werdhölzli* and *Hauptbahnhof – Escher-Wyss-Platz* are not served any longer by tramway lines. In real-world situations bus services are organized connecting the non-connected components.

Figure 80 Capacity utilization in degraded operation for case study 1 (*Zurich tramway 2006*)



In many cases the values for the *structural system performance* and the corresponding value for the degraded operated network can significantly differ. Table 71 shows the corresponding results for case study 1. Both values are approximately equal.

Table 71 Structural robustness results for case study 1 (*Zurich tramway 2006*)

	Degraded topology		Degraded operated network	
q_a: Giant cluster size	155 / 178	0.871	153 / 178	0.860
q_b: Average shortest path length	12.82 / 14.07 [hops]	0.911	12.89 / 14.07 [hops]	0.916
Structural robustness	Product	**0.794**	Product	**0.787**
Relation between both	0.794 / 0.787 = 1.009			

7.2.3 Results for the *Zurich tramway 2025* network

Removing both nodes from *Zurich tramway 2025* now affects three lines, i.e. *Line 4: Bahnhof Tiefenbrunnen – Bahnhof Altstetten*, *Line 8: Rehalp - Werdhölzli* and *Line 13: Frankenthal - Albisgütli.* The following dispatching solution is calculated:

- ***Line 4:*** rerouted between *Hauptbahnhof - Schiffbau* via *Hardplatz*
- ***Line 8:*** operated between *Rehalp - Hardturm* → *Line 8* is truncated
- ***Line 13:*** rerouted between *Hauptbahnhof – Escher Wyss Platz* via *Hardplatz*

The quantities calculated for assessing the *operational robustness* are shown in Table 72.

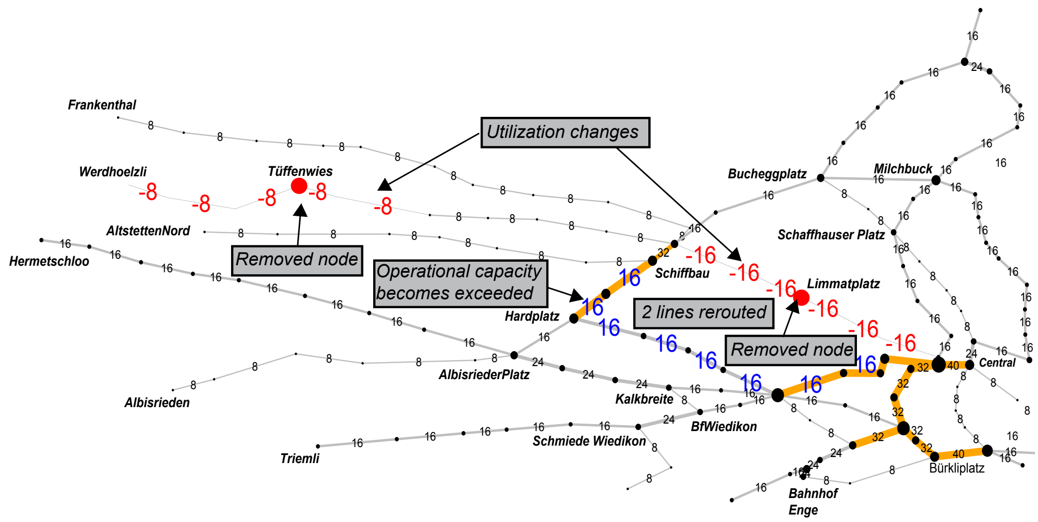
Table 72 Operational robustness results for case study 1 (*Zurich tramway 2025*)

	No capacities considered		Considering operational capacity thresholds	
q_1 : Served stations	195 / 205	0.951	195 / 205	0.951
q_2 : Giant cluster size	195 / 205	0.951	195 / 205	0.951
q_3 : Mean distance	13.39 / 13.34 [hops]	0.996	13.39 / 13.34 [hops]	0.996
q_4 : Changing processes	1.779 / 1.8 [lines]	1	1.788 / 1.8 [lines]	1
Connectivity value	Product	**0.901**	Product	**0.901**
q_5 : Track-km	144.1 / 143.9 [km]	0.999	141.6 / 143.9 [km]	1
q_6 : Vehicles	122 / 121	0.992	119 / 121	1
q_7 : Operational capacity	Additional edges: 6	0.973	No additional edge	1
q_8 : Theoretical capacity	No additional edge	1	No additional edge	1
Capacity value	Product	**0.964**	Product	**1**
Operational robustness	Formula	**0.865**	Formula	**0.901**
Line parts per operated line	= 14 / 14	1	= 15 / 14	1.071

A comparison with the results in Table 70 shows that the calculated *operational robustness* value is less reduced indicating robustness improvements from an operational point of view.

The results further indicate significant increases of the *connectivity values*, i.e. the degraded network sustains in a giant cluster containing more nodes than for *Zurich tramway 2006*. It hence becomes possible to reroute lines instead of truncating them. Simultaneously, the *capacity value* is decreased since for some additional edges the specified operational capacity thresholds are exceeded (Figure 81).

Figure 81 Capacity utilization changes for case study 1 (*Zurich tramway 2025*)



In the capacity-restricted case where for no additional edge the specified operational capacity threshold shall be exceeded, the procedures illustrated in Figure 41 are applied and a different solution is calculated (lines are now dispatched in order of their lengths in [km]):

- ***Line 8:*** Operated between *Rehalp - Hardturm* → Degraded line path does not contain stops outside the original line path → *Line 8* is truncated.
- ***Line 13:*** Rerouted between *Hauptbahnhof – Escher Wyss Platz* via *Bucheggplatz* → Degraded line path includes stops outside original line path → *Line 13* is rerouted.
- ***Line 4:*** Split into two distinct line parts operating between *Bahnhof Tiefenbrunnen - Hauptbahnhof* and *Escher Wyss Platz – Bahnhof Altstetten* → *Line 4* is truncated.

Line 4 cannot longer be rerouted since the potential alterative routes do not have enough capacity left such that the specified values of the operational capacity thresholds (30 trains per hour) are exceeded.

Figure 82 Capacity-restricted solution for case study 1 (*Zurich tramway 2025*)

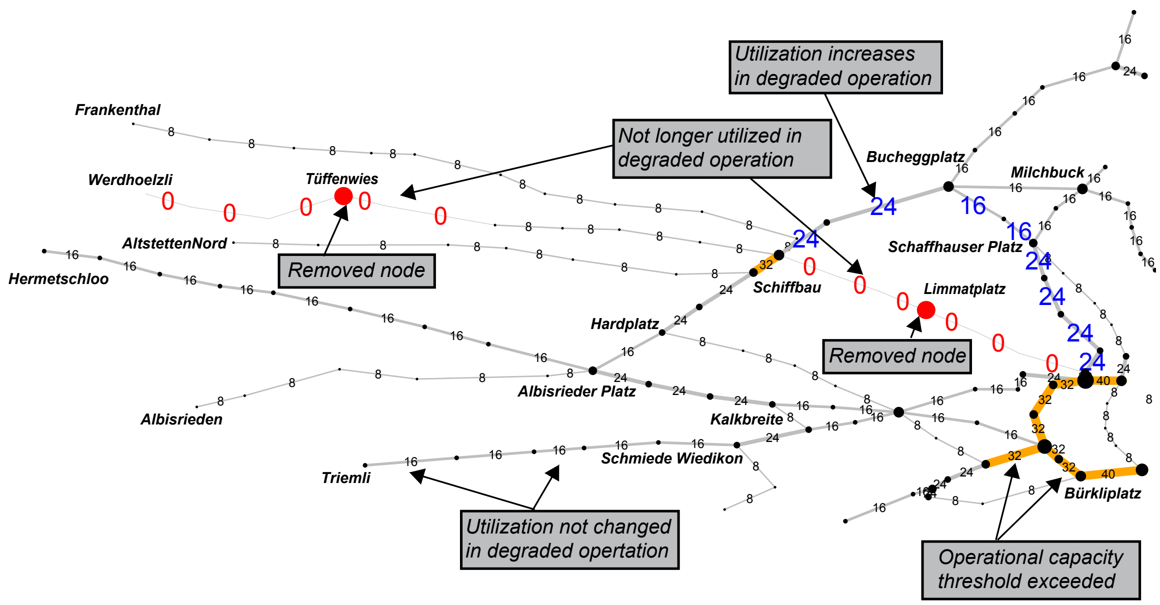


Table 73 compares the calculated *structural robustness* value of the degraded topology with the degraded operated network. A pure topological analysis would give wrong results deviating 3 % from each other.

Table 73 Structural robustness results for case study 1 (*Zurich tramway 2025*)

	Degraded topology		Degraded operated network	
q_a: Giant cluster size	200 / 205	0.976	195 / 205	0.951
q_b: Average shortest path length	13.31 / 13.34 [hops]	0.998	13.39 / 13.34 [hops]	0.996
Structural robustness	**Product**	**0.974**	**Product**	**0.948**
Relation between both	0.974 / 0.948 = 1.027			

The correct application of the implemented line disposition framework introduced in Figure 36 can also be analysed by measuring the number of calculated steps for each branching path, denoted by the numbers in the circles.

Table 74 shows the results for both, *Zurich tramway 2006* and *Zurich tramway 2025* for the restricted (based on the operational capacity thresholds) and non-restricted case. The numbers in the first row coincide with those in the line disposition framework (Figure 36) and capacity-restricted rerouting scheme (Figure 41).

Table 74 Distribution of steps for case study 1 analysis

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
*	2	11	2	-	4	-	-	-	-	4	4	-	-	-	-	-	-	-	-	-	-	-	-	-
**	2	11	2	-	4	-	-	-	-	4	4	-	-	-	-	-	-	-	-	-	-	-	-	-
***	3	11	3	-	1	2	-	-	-	1	1	-	2	-	-	-	-	-	-	2	-	-	-	-
****	3	11	3	-	1	2	-	-	-	1	1	-	1	-	-	-	-	-	1	1	-	1	-	-

* *Zurich tramway 2006*, no capacities considered
** *Zurich tramway 2006*, capacity-restricted, operational capacity thresholds
*** *Zurich tramway 2025*, no capacities considered
**** *Zurich tramway 2025*, capacity-restricted, operational capacity thresholds

Table 74 verifies the correct implementation due to the following observations:

- The values in the first two columns sum up to the number of lines represented in the *Traffic Operation and Management* subsystem.

- The sum of the values in column 3 and 4 sum up to the number of lines affected by the node removals, i.e. the value in column 1.

- Column 5 indicates the number of line parts that are analysed within the *Truncation module*, column 6 shows the corresponding value for line parts analysed in the *Re-routing module*. Since lines can be split into multiple parts, the sum of both columns may be larger than the number of affected lines, i.e. the value within column 3. For *Zurich tramway 2025*, the values in column 5 and column 6 sum up to the value in column 3 indicating that lines are not split into multiple parts. For *Zurich tramway 2006*, two lines are split such that the value in column 5 doubles that in column 3.

- Since *Case study 1* considers the removal of nodes, columns 7 and 8 are zero.

- The values of column 9 and 10 sum up to the number in column 5 since either all stations in the corresponding cluster are served or not. For all networks, there remain stations within the same cluster, but which are not served yet. Hence, it is checked whether other turnaround alternatives can be used such that the number of stations served by the line in regular and degraded operation increases. In all cases this does not hold, i.e. the values in column 11 equal those in column 10.

- For the capacity-restricted rerouting in *Zurich tramway 2025*, one line can be rerouted and another one cannot. The values of columns 19 and 20 sum up to that in column 6.

- The calculated rerouting path is of feasible length, and hence used for rerouting the line: The values in column 13 and 20 coincide.
- For a single line within *Zurich tramway 2025*, rerouting is not longer possible due to the operational capacity restrictions (column 19). Since some parts of the original line path can still be operated, the line is truncated indicated by the value in column 22.

7.3 Case study 2: *Swiss railway* network

7.3.1 Introduction

The second case study analyses the importance of the corridor *Bern – Belp – Thun* in the *Swiss railway* network. In planned operation, no represented line traverses this corridor. However, the simulation results showed, that the corridor has influences on the robustness of the entire network since it is used for rerouting lines, especially if capacity thresholds are considered. The corridor hence provides necessary rerouting alternatives. The second case study illustrates how the importance of a specific corridor can be assessed and verifies the correct application of the implemented procedures if also nodes from the *Control-command and Signalling* or *Energy* subsystem are removed.

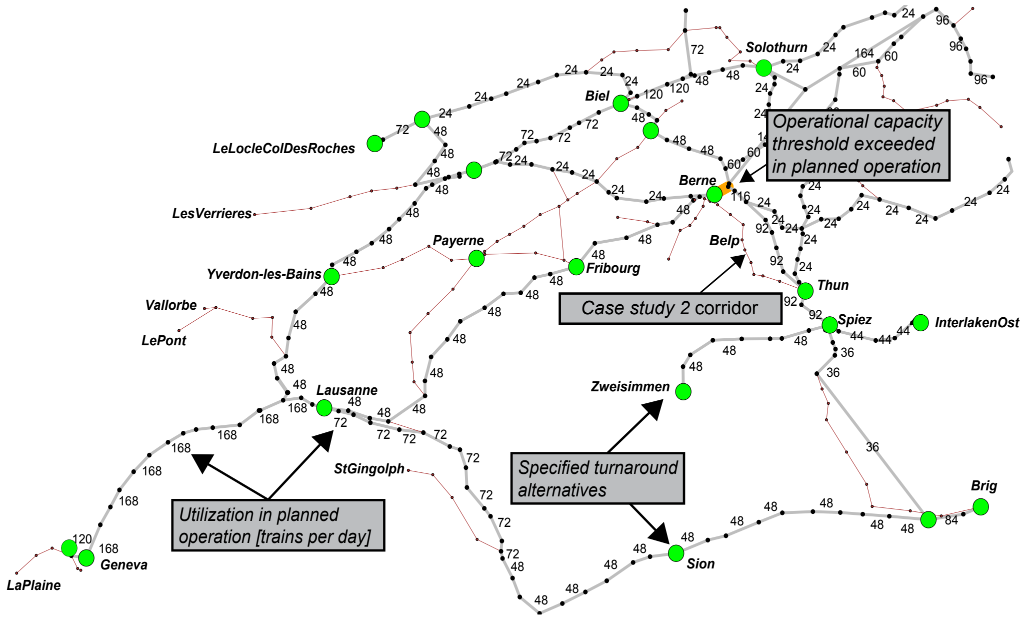
7.3.2 Utilization in planned operation state

The analysed corridor *Bern – Belp - Thun* contains nodes representing the stations *Ausserhol-ligen*, *Fischermättli*, *Weissenbühl*, *Wabern*, *Kehrsatz*, *Belp*, *Toffen*, *Kaufdorf*, *Thurnen*, *Bur-gistein*, *Seftigen*, *Uetendorf* and *Thun*. Figure 83 shows the capacity utilization and the location of the corridor in the *Swiss railway* network. Even though the represented lines do not traverse the analysed corridor, in real-world operation the corridor is utilized by urban railway lines.

Since some parts of the corridor can only be served along single tracks, the following capacity utilization thresholds are considered (see Table 39):

- Operational capacity threshold: 80 trains per day
- Theoretical capacity threshold: 120 trains per day

Figure 83   Location and capacity utilization of the *Case study 2* corridor



7.3.3 Structural importance in the *Infrastructure* subsystem

For each node within the analysed corridor, Table 75 lists the values calculated for assessing the structural importance of the corridor stations for the *Swiss railway* topology.

Table 75   Structural importance of the *Case study 2* nodes

Station	Class	Betweenness	Rank	q_a	Rank	Distances	Rank	*Str. robustness*	Rank
Ausserholligen	*B1*	0.205	17	0.999	222	0.972	46	0.971	58
Fischermättli	*C2*	0.028	276	0.992	66	0.994	193	0.987	130
Weissenbühl	*C1*	0.014	425	0.999	233	0.997	299	0.996	328
Wabern	*C1*	0.011	461	0.999	232	0.998	370	0.996	398
Kehrsatz	*C1*	0.009	520	0.999	231	0.998	460	0.997	485
Belp	*C1*	0.007	582	0.999	230	0.999	548	0.998	565
Toffen	*C1*	0.005	645	0.999	229	0.999	646	0.998	655
Kaufdorf	*C1*	0.003	688	0.999	228	1	714	0.998	719
Thurnen	*C1*	0.002	725	0.999	227	1	729	0.998	732
Burgistein	*C1*	0.003	697	0.999	226	1	702	0.998	707
Seftigen	*C1*	0.005	656	0.999	225	0.999	614	0.998	627
Uetendorf	*C1*	0.007	590	0.999	224	0.999	521	0.998	539
Thun	*A1*	0.114	57	0.999	197	0.903	3	0.902	17

The *structural system performance* results for the station *Thun* coincide with the findings in Table 48, stating that removing the node from the topology significantly increases the average shortest path length in the giant cluster.

7.3.4 Operational importance of the corridor

Traffic Operation and Management subsystem analysis

Table 76 presents the results of quantifying the values of the *operational system performance*, the *capacity value* and the *connectivity value* in degraded operation if a specific corridor node is removed from the analysed railway network. The results calculated for the station *Thun* match those presented in Table 59. With exception of the stations *Ausserholligen* and *Thun* the values for the *operational system performance* are not reduced in degraded operation. The last column denotes the differences between the *structural system performance* calculated for the degraded topology and the corresponding values for the degraded operated network. For the stations *Thun* and *Ausserholligen* both values differ significantly.

Table 76 Operational importance of the *Case study 2* nodes

Station	*Capacity value*	*Connectivity value*	*Operational robustness*	*Structural robustness (Degraded topology) / (Degraded operated network)*
Ausserholligen	0.989	0.911	0.9	1.053
Fischermättli	1	1	1	0.987
Weissenbühl	1	1	1	0.996
Wabern	1	1	1	0.996
Kehrsatz	1	1	1	0.997
Belp	1	1	1	0.998
Toffen	1	1	1	0.998
Kaufdorf	1	1	1	0.998
Thurnen	1	1	1	0.998
Burgistein	1	1	1	0.998
Seftigen	1	1	1	0.998
Uetendorf	1	1	1	0.998
Thun	1	0.762	0.762	1.120

Table 77 reveals in which cases a rerouting solution is found using the corridor *Bern – Belp – Thun*. The numbers indicate how many trains traverse the corridor links per day. If for instance the node representing *Münsingen* is removed, the corridor is for rerouting lines and hence utilized by 56 trains daily if operational capacity restrictions are considered.

Table 77 Cases in which corridor *Bern – Belp – Thun* is used for rerouting

	No thresholds		Theoretical capacity		Operational capacity	
Removed node and utilization of the corridor in [trains per day]	*Sion* *Bern* *Wankdorf* *Ostermundigen* *Gümligen*	48 48 48 24 92	*Sion* *Bern* *Wankdorf* *Ostermundigen* *Gümligen*	48 48 96 24 92	*Sion* *Bern* *Wankdorf* *Ostermundigen* *Gümligen* *Rubigen* *Münsingen* *Wichtrach* *Uttigen*	48 48 60 56 68 56 56 56 56

Figure 84 shows the calculated degraded operation state if the node representing *Münsingen* is removed and rerouting measures do not consider the specified capacity thresholds. Four lines are affected and need disposition efforts (*Brig – Romanshorn, Brig – Basel SBB, Interlaken Ost – Basel SBB* and *Zweisimmen – Bern*). The lines are rerouted along *Thun – Konolfingen – Gümligen* exceeding the specified operational capacity thresholds of 80 trains daily.

Figure 85 visualizes the calculated degraded operation state if for no additional edges the specified operational capacity threshold is exceeded. Not all the lines can still use the previously found rerouting alternative, but are rerouted along the case study 2 corridor, i.e. *Bern – Belp – Thun*.

Figure 84 Degraded *Swiss railway* network if node *Münsingen* is removed (capacity restrictions are neglected)

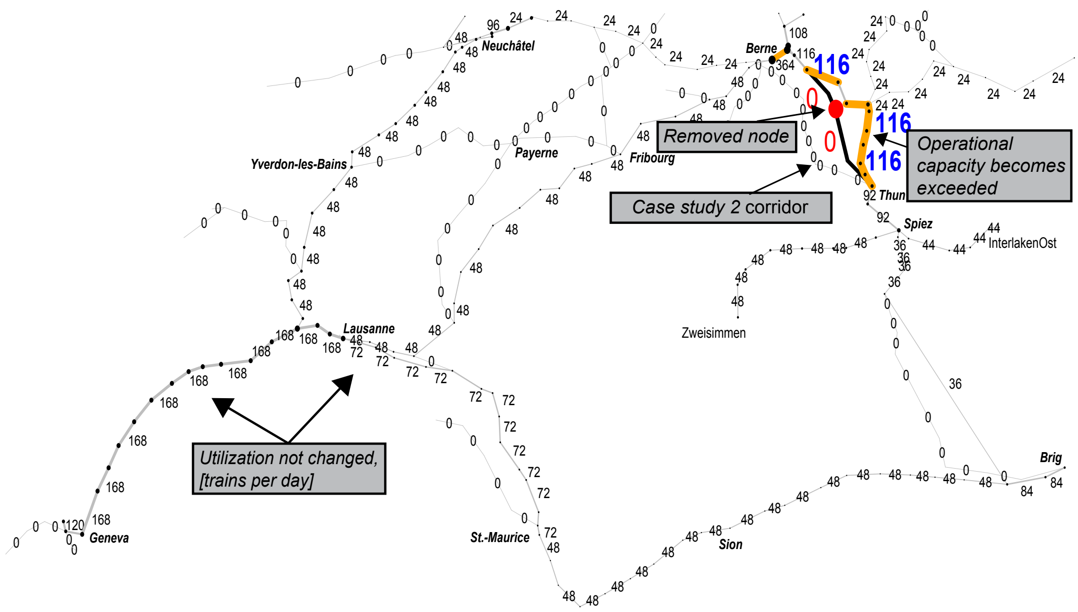
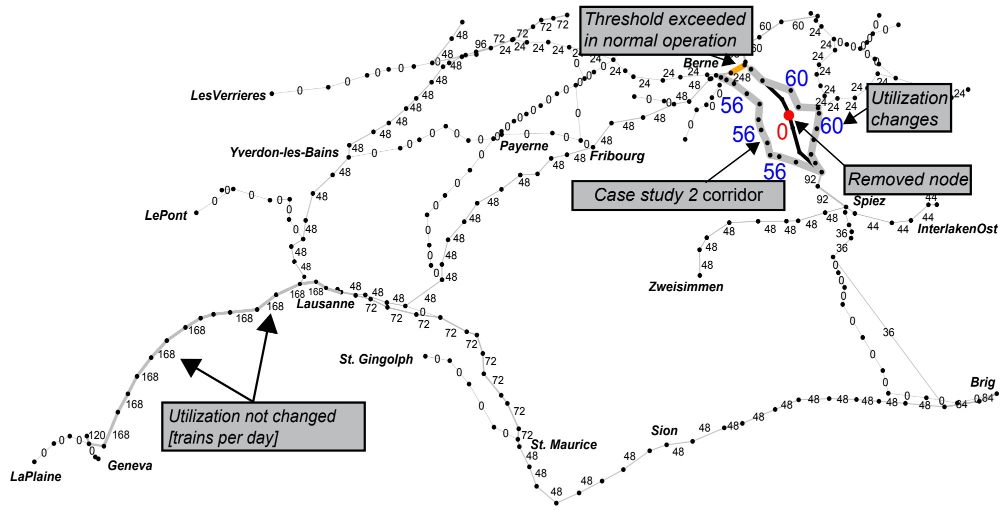


Figure 85 Degraded *Swiss railway* network if node *Münsingen* is removed considering the specified operational capacity thresholds



If now the corridor *Bern – Belp – Thun* is not longer available for rerouting, i.e. due to construction work or blockades along the tracks, two lines cannot longer be rerouted and are truncated:

- *Line 17: Basel SBB – Bern – Thun – Interlaken Ost* is split into two distinct branches operating along *Basel SBB - Bern* and *Thun – Interlaken Ost*
- *Line 41: Zweisimmen – Thun - Bern* is truncated, serving *Zweisimmen – Thun*

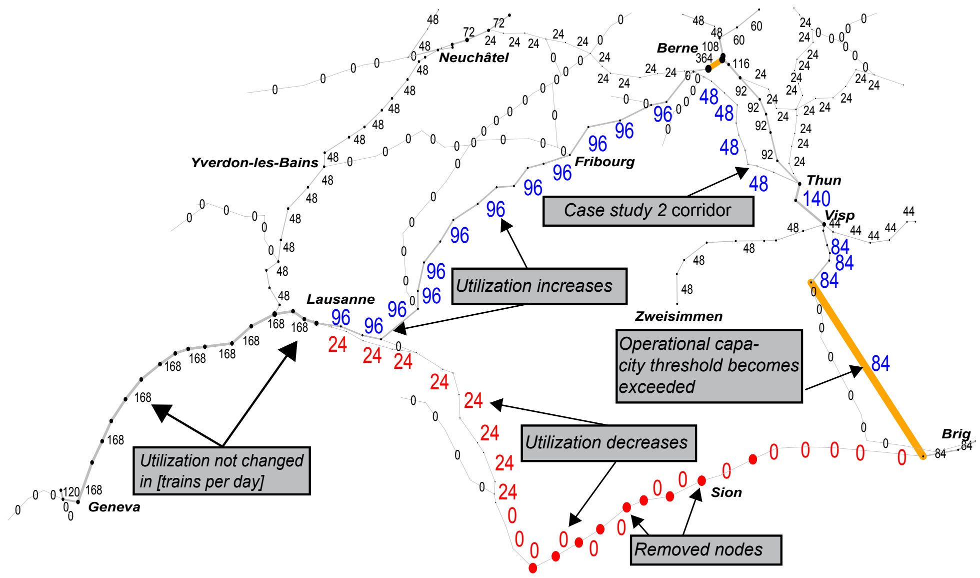
Failures originating in the Control-command and Signalling subsystem

It was found that the implemented line disposition framework routes the line *Lausanne - Brig* along this analysed corridor if the *Control-command and Signalling* node *Sion* fails. Removing all the stations that are remotely controlled from Sion represents this.

The calculated degraded operation state is displayed in Figure 86 assuming that no capacity restrictions are considered. The values along the edges reveal the absolute capacity utilization in degraded operational state. The calculated rerouting exceeds the operational capacity threshold specified for the link *Frutigen – Visp*[20].

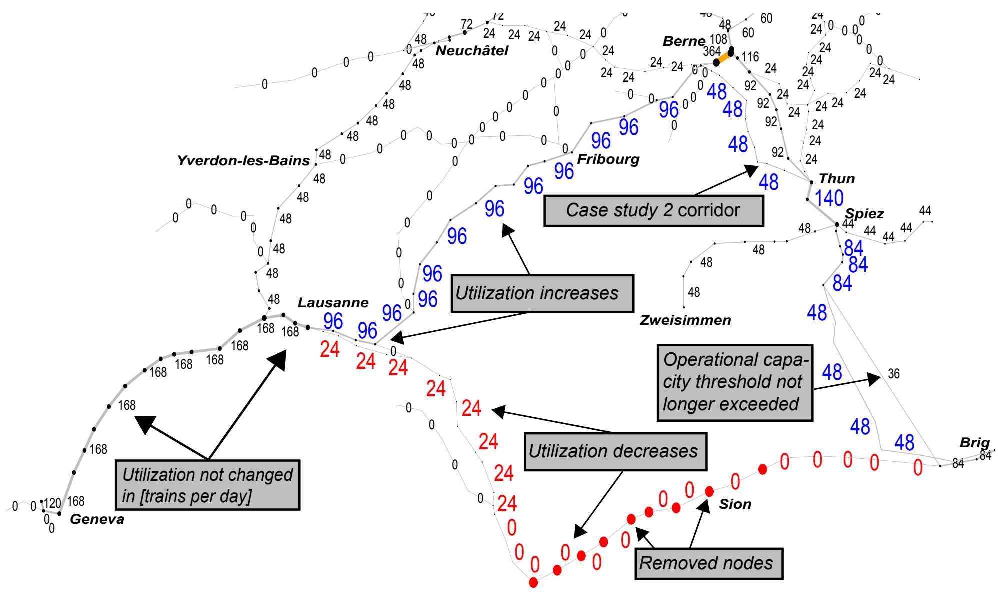
[20] Actually, the corridor has higher capacity thresholds since it only contains a small part with single tracks.

Figure 86 Degraded operation of the *Swiss railway* network calculated for the removal of stations remotely controlled from *Sion* (capacity restrictions are neglected)



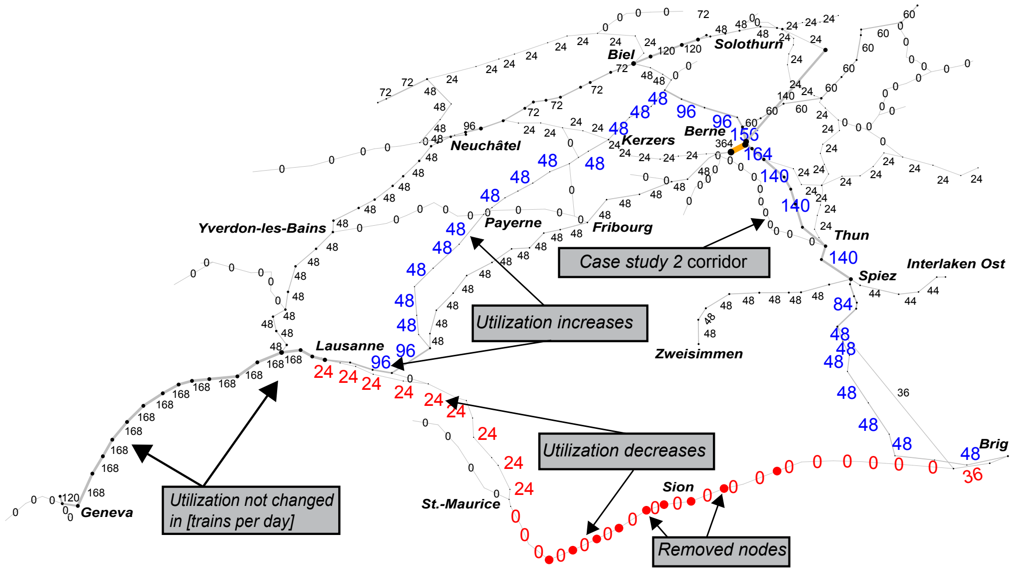
In case of rerouting lines such that the operational capacity thresholds are not exceeded for additional links, a different solution is calculated, depicted in Figure 87.

Figure 87 Degraded *Swiss railway* network if the stations remotely controlled by *Sion* are removed considering operational capacity thresholds



Recalculating the previous degraded operation state and assuming that the corridor is no longer available is suitable for assessing the operational importance of the corridor. Hence, the capacity thresholds for the corridor links are set to zero such that they cannot be used for rerouting lines. Then a different solution is found depicted in Figure 88. The line path lengths are severely increased if the corridor *Bern – Belp – Thun* is not longer available.

Figure 88 Degraded *Swiss railway* network removing stations remotely controlled by *Sion* considering operational capacity thresholds, corridor is not longer available



Failures originating in the Energy subsystem

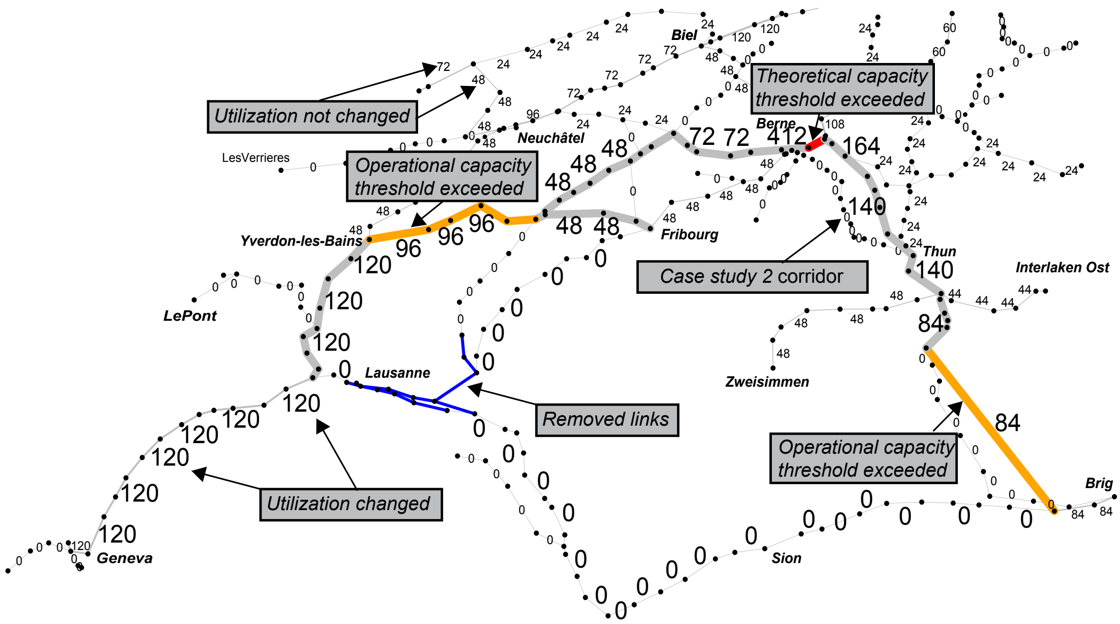
The analysed corridor is utilized for rerouting lines if the following *Energy* substations fail:

- **No capacity restrictions:** corridor utilized if substation *St. Leonhard* fails
- **Rerouting considers theoretical capacity thresholds:** corridor utilized if substation *St. Leonhard*, *Biel* or *Puidoux* fails
- **Rerouting considers operational capacity thresholds:** corridor utilized if substation *St. Leonhard* or *Biel* is removed

In the following, the calculated degraded operational states for removing the substation *Puidoux* from the *Energy* subsystem is analysed in more detail. If capacity thresholds of rerouting alternatives are not considered, the following degraded operational states are calculated (illustrated in Figure 89):

- *Line 3: Geneva Airport – St. Gallen* rerouted between *Morges* and *Fribourg* via *Yverdon-les-Bains* and *Payerne*

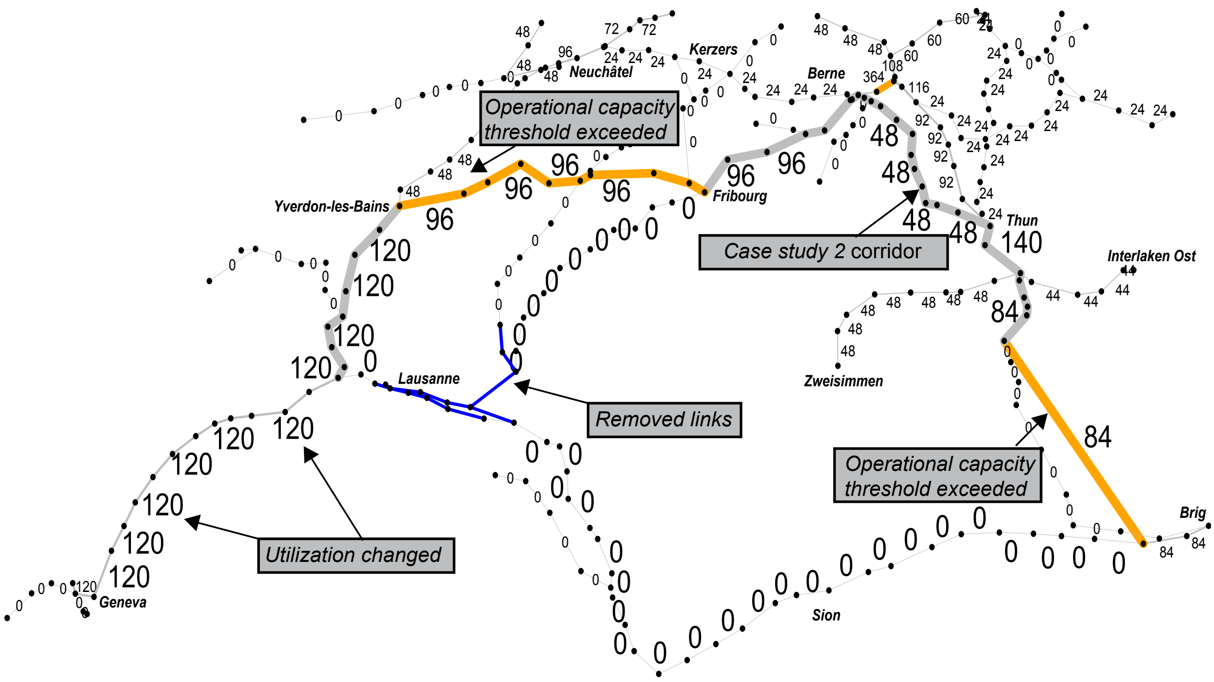
Figure 89 Degraded operation of the *Swiss railway* network calculated for the removal of the *Energy* node *Puidoux* (capacity restrictions are neglected)



- *Line 4: Geneva Airport – Lucerne* rerouted between *Morges* and *Fribourg* via *Yverdon-les-Bains* and *Payerne*
- *Line 5: Geneva Airport – Brig* rerouted between *Morges* and *Visp* via *Yverdon-les-Bains, Kerzers, Bern* and *Thun*
- *Line 6: Geneva – Lausanne* not operated anymore
- *Line 7: Lausanne – Basel SBB* operated between *Yverdon-les-Bains – Basel SBB*
- *Line 8: Lausanne – St. Gallen* operated between *Yverdon-les-Bains – St. Gallen*
- *Line 42: Geneva - Lausanne* not operated anymore
- *Line 44: Lausanne – St. Maurice* not operated anymore

Figure 89 shows that in degraded operation, the specified operational capacity thresholds along *Yverdon-les-Bains – Payerne* and *Frutigen - Visp* are exceeded, as well as the theoretical capacity threshold of the link *Bern – Wankdorf*. The case study corridor is not utilized for rerouting. Figure 90 shows the recalculated solution if for no additional edge the specified theoretical capacity threshold is exceeded.

Figure 90 Degraded operation of the *Swiss railway* network calculated for the removal of the *Energy* node *Puidoux* considering the specified theoretical capacity thresholds



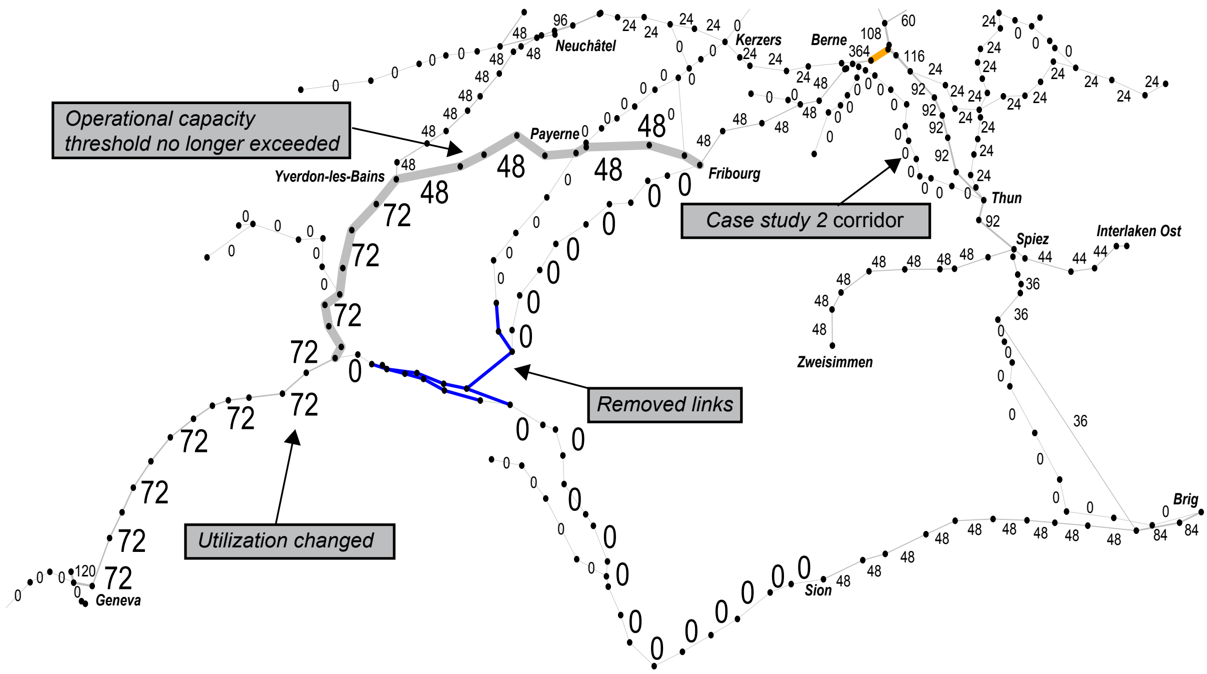
For the solution depicted in Figure 90 the capacity utilization between *Bern* and *Wankdorf* is below the specified theoretical capacity threshold. The following changes compared to the previous solution traversing the corridor *Bern – Belp – Thun* are calculated*:*

- *Line 4: Geneva Airport – Lucerne* rerouted between *Morges* and *Fribourg* via *Yverdon-les-Bains* and *Payerne*
- *Line 5: Geneva Airport – Brig* rerouted between *Morges* and *Visp* via *Yverdon-les-Bains, Payerne, Fribourg, Belp* and *Thun*

The calculated solution still exceeds the operational capacity thresholds for the edges along *Yverdon-les-Bains – Payerne - Fribourg* and between *Frutigen - Visp*. It is also possible to calculate a solution such that no additional edge is utilized above the operational capacity threshold (see Figure 91). In this case, rerouting all the affected lines is no longer possible such that *Line 5* is truncated due to the capacity restrictions of the rerouting alternatives:

- *Line 5: Geneva Airport – Brig* split into two truncated line parts *Geneva Airport - Geneva* and *Sion - Brig*

Figure 91 Degraded operation of the *Swiss railway* network calculated for the removal of the *Energy* node *Puidoux* considering the specified operational capacity thresholds



8 Robustness enhancements

8.1 Overview

This chapter collects measures for improving the operational robustness of railway networks and shows for which of them the evaluated methodology. The implemented robustness analysis tool is used for quantitatively assessing the benefits of three concrete enhancing measures:

- Adding a new link to the represented *Infrastructure* subsystem
- Offering a new turnaround alternative in the represented network
- Reconstructing the overlapping between the *Control-command and Signalling* and *Energy* subsystem.

This chapter extends the verification of the tool. Table 78 shows the contents of this chapter.

Table 78 Structure and contents of chapter 8

Section	Contents	Purpose
8.1	Overview	Introduction, goals and purpose of this chapter
8.2	Potential measures	Collection of potential measures to improve the robustness, i.e. increase the *structural* and *operational system performances* in degraded operation states
8.3	Analysis results	Application of the implemented procedures and quantitative assessment of the benefits when adding new links and turnaround alternatives to the network

8.2 Potential measures

This section gives examples of measures suitable to enhance the structural and operational robustness of railway networks. Generally, these measures can either focus on single subsystems or on multiple ones including the location of interconnections.

Table 79 shows some measures suitable for improving the robustness of railway networks focussing on those that can be represented in the evaluated methodology. This means that the measures are chosen such that they can be modelled in the implemented robustness analysis procedures. Three of the suggested robustness enhancing measures are applied to the case study networks in section 8.3.

Table 79 Potential measures for enhancing the robustness of railway networks

Subsystem	Measure	Representation in the evaluated methodology
Infrastructure	Building new tracks and stations	Adding links and nodes to the *Infrastructure* topology → section 8.3.1
	Add redundancies for most important corridors	Identify most important nodes and links from structural point of view → section 6.3
Traffic Operation and Management	Additional turnaround alternatives	Existing *Infrastructure* nodes may offer turnaround alternative → section 8.3.2
	Increase number of parallel tracks and other capacity enhancements	Increasing capacity thresholds for all or some specific links
	Optimization of line path routing in normal operation	Analyse and compare different line path routings
	Increase headway times for specific lines	Check whether the reduction of frequencies of (specific) lines improves the robustness
	Add redundancies for most important corridors	Identification of most important nodes and links from operational point of view → section 6.4
	Change the edge weights	Reduce track lengths or time needed for travelling along them (increase speed)
Control-command and Signalling	Optimize integration of stations remotely controlled from others	Analyse and improve the allocation of *Infrastructure* nodes into *CCS* regions
Energy	Optimize integration of stations and traction current areas	Analyse and improve the allocation of *Infrastructure* nodes into *Energy* regions
Others	Redesign *Control-command and Signalling* and *Energy* regions to increase overlapping	Compare regions in the *Control-command and Signalling* and *Energy* subsystems → section 8.3.3
	Improve understanding the operational robustness	Improve the level of detail of the elements representing railway networks (→ section 3.2 - 3.7)
		Improve the methodology for measuring the structural and operational robustness (→ section 5.5 and 5.6)
		Improvements of the implemented line disposition framework (→ section 5.7)
		Integrate other transport modes, i.e. urban railway lines and freight transport

8.3 Analysis results

For three potential robustness enhancements, the evaluated methodology is applied in order to verify that the implemented robustness analysis tool is also useful for quantifying the implied robustness improvements. This sections analyses the benefits gained from adding new links to the *Infrastructure* topology, offering new turnaround alternatives in the *Traffic Operation* *and Management* subsystem and reconstructions of the *Control-command and Signalling – Energy* subsystem overlapping.

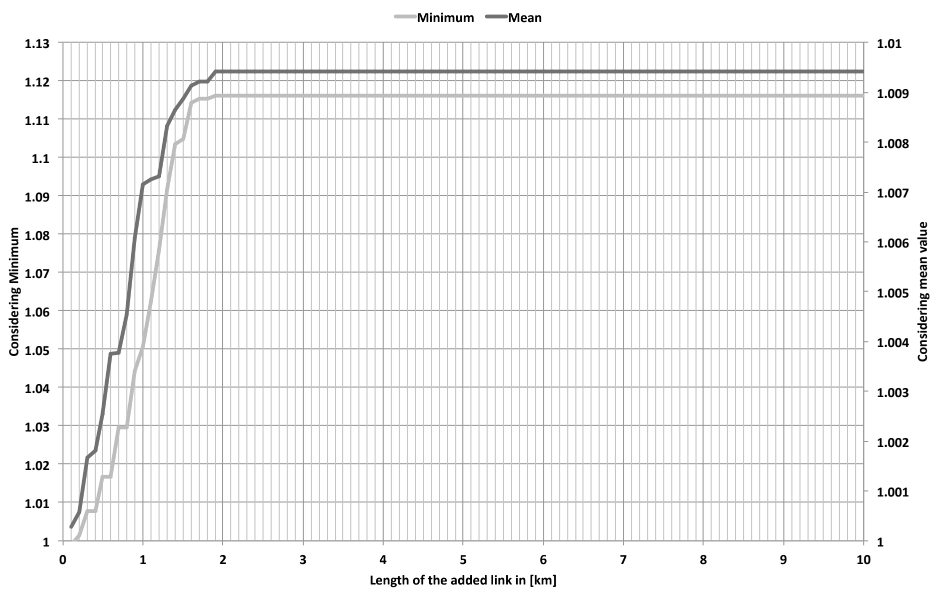
8.3.1 Adding links to the *Infrastructure* topologies

For a first assessment of the benefits of adding links to the *Zurich tramway 2006* network, the increases of the structural robustness are measured if a single link is added between any pair of nodes that is not adjacent in the current topology, i.e.:

1. A new link is added to the *Infrastructure* subsystem representing a potential robustness enhancing measure.
2. Each single node is removed from the enhanced network and the *structural robustness* values are calculated according to the scheme introduced in section 5.5.
3. The results of the mean and the minimal *structural robustness* values are divided by the corresponding values in *Zurich tramway 2006* without the enhancements.

Adding a new link can hence either increase or decrease the minimal and mean *structural robustness* values since on the one hand the giant cluster size is likely to be increased. On the other hand, especially for new long-distance edges many shortest paths contain the new link such that the average shortest path length is likely to increase as well if nodes are removed from the network. Figure 92 shows the improvements of the mean and minimal *structural resiliencies* if only links shorter than a specific value are considered.

Figure 92 Edge length and structural improvements for *Zurich tramway 2006*

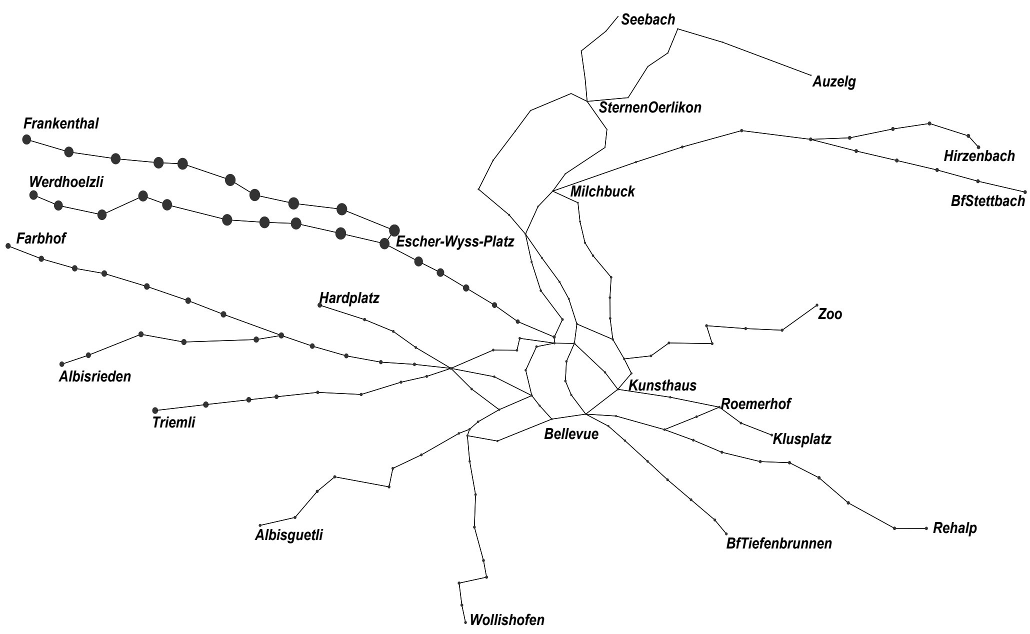


The calculation showed that in about 78.8 % of cases, adding a new link improves the mean *structural robustness*. The minimal *structural robustness* value is increased in only 8.5 % of all cases where a new link is added. The figure shows that the maximal improvements of the mean *structural robustness* is 1 %, a small value compared to the enhancements of the minimal one, which can be improved by up to 12 %. The values of both quantities depend on the length of the added link.

The results further show that both curves have similar shapes indicating ranges of edge lengths for which the largest improvements can be observed, lying between 0.6 and 1.3 kilometres. In other words, it is most beneficial to add links to the *Infrastructure* subsystem with lengths in this interval. Longer edges do not further increase the benefits while smaller lengths do not significantly improve the calculated values of the *structural robustness*. Long-distance connections are extensively contained in many shortest paths and important for network integrity in degraded state. Hence, removals of this edge increase the average shortest path lengths significantly or increase the giant cluster size.

Figure 93 shows for which nodes the highest mean improvements of the mean *structural system performances* are measured if new links are added that are incident with a specific node. This means that the results were gained by calculating the mean value of the changes of the *structural resiliencies* if edges are added that are incident with a specific node.

Figure 93 *Zurich tramway 2006* nodes with highest mean improvement of the mean *structural system performance*



Larger nodes indicate that the enhancements are more beneficial from a topological point of view. Adding new links should be biased towards them. The results show that enhancements should focus on the western part of Zurich. The largest benefits are observed if enhancements are established for *Wipkinger Platz* or *Escher-Wyss-Platz*, i.e. where the extensions for *Zurich tramway 2025* actually focus on.

The addition of six specific edges and the measured effects on the *connectivity value*, the *capacity value* and the *operational system performance* are shown in Table 80. The edges were added to the *Zurich tramway 2006* network and can be used for rerouting lines according to the implemented line disposition framework illustrated in Figure 36. These edges were chosen such that some of them represent exactly those edges that are newly added in the *Zurich tramway 2025* network (links 1 – 3). Two new edges are incident with the node representing *Escher-Wyss-Platz* since the results illustrated in Figure 93 showed that enhancing measures should be biased towards it.

Table 80 Operational benefits from adding *Infrastructure* links to *Zurich tramway 2006*

Added link	*Connectivity value*	*Capacity value*	*Operational robustness*
Zurich tramway 2006	0.9124	0.9901	0.9025
1 *Hardplatz – Escher-Wyss-Platz*	0.9185	0.9869	0.9055
2 *Bucheggplatz – Escher-Wyss-Platz*	0.9182	0.9871	0.9054
3 *Milchbuck – Bucheggplatz*	0.9131	0.9899	0.9030
4 *Klusplatz – Hegibachplatz*	0.9140	0.9897	0.9037
5 *Utobrücke – Schmiede Wiedikon*	0.9141	0.9890	0.9032
6 *Wollishofen – Bahnhof Tiefenbrunnen*	0.9129	0.9878	0.9007

The other additional links were chosen such that both short and long-range connections are added. Figure 94 shows where the added links are located in the *Zurich tramway 2006* network. The numbers along the highlighted new edges correspond to those in the first column in Table 80.

Adding each of the considered links increases the *connectivity value*. However, the *capacity value* decreases in all analysed cases, such that the *operational system performance* in degraded state can either increase or decrease. Added links offer rerouting alternatives that may often be used for degraded operation, likely to decrease the *capacity value* and the *operational system performance.* Those corridors actually established for *Zurich tramway 2025* are highly beneficial, i.e. the corridors *Hardplatz – Escher-Wyss-Platz* and *Bucheggplatz – Escher-Wyss-Platz.*

Figure 94 Location of the additional links in the *Zurich tramway 2006* network

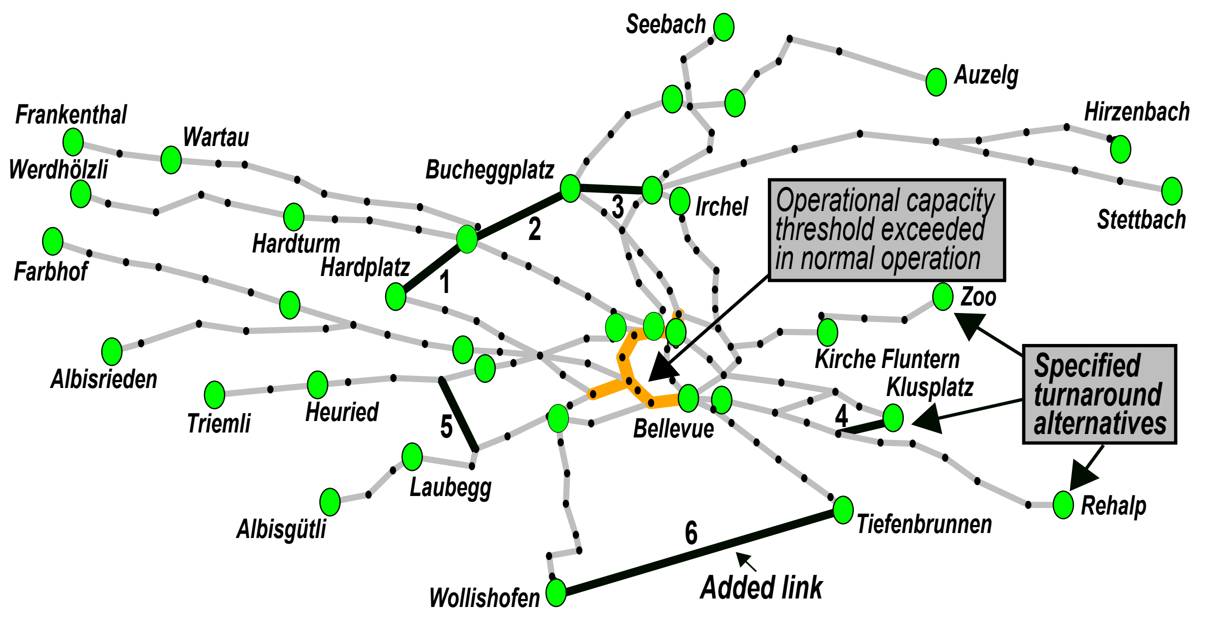
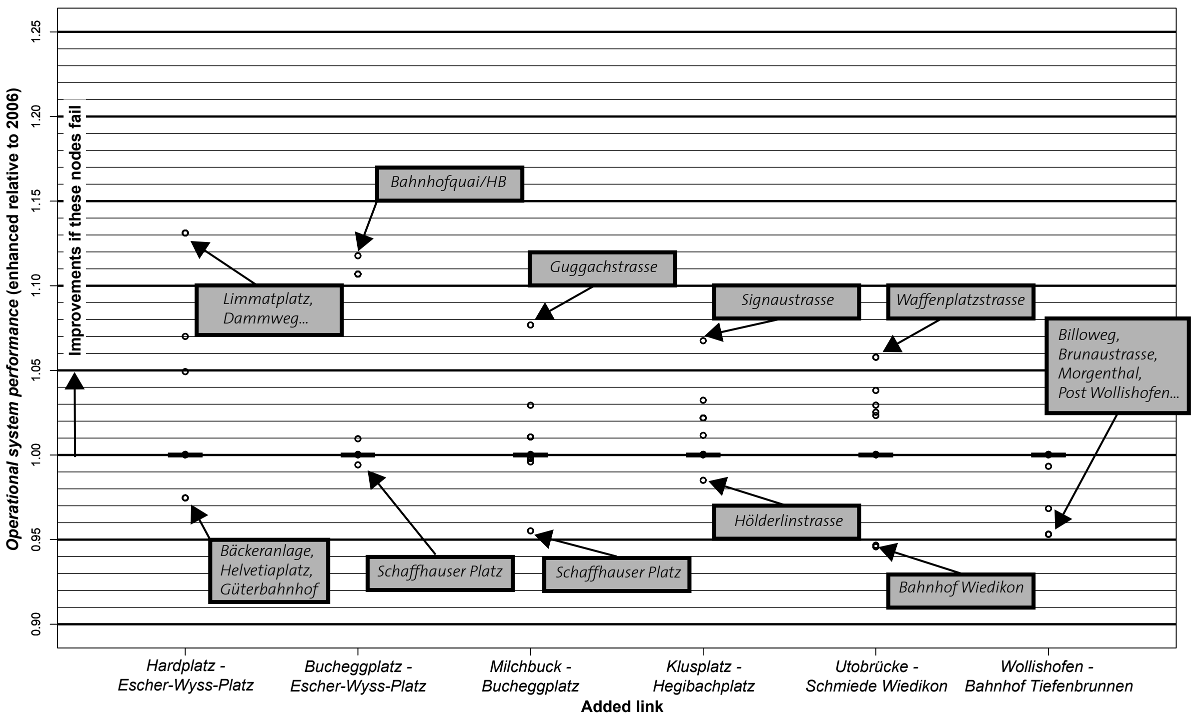


Figure 95 shows in which cases the *operational robustness* is improved due to the addition of a single link. This means that those nodes are identified for which the operational system performances in degraded operation increase if they are removed from the enhanced network. The results are calculated as follows:

- A specific node is removed from the enhanced *Zurich tramway 2006* network and the values of the *operational robustness*, the *connectivity value* and the *capacity value* are calculated.
- The same analysis is done in the original, non-adapted *Zurich tramway 2006* network.
- The results calculated for both networks are compared, by dividing the value in the enhanced network by the corresponding value in the original network. → Values larger than one are measured if the operational robustness is improved.
- This is done for all nodes in the *Zurich tramway 2006* network.

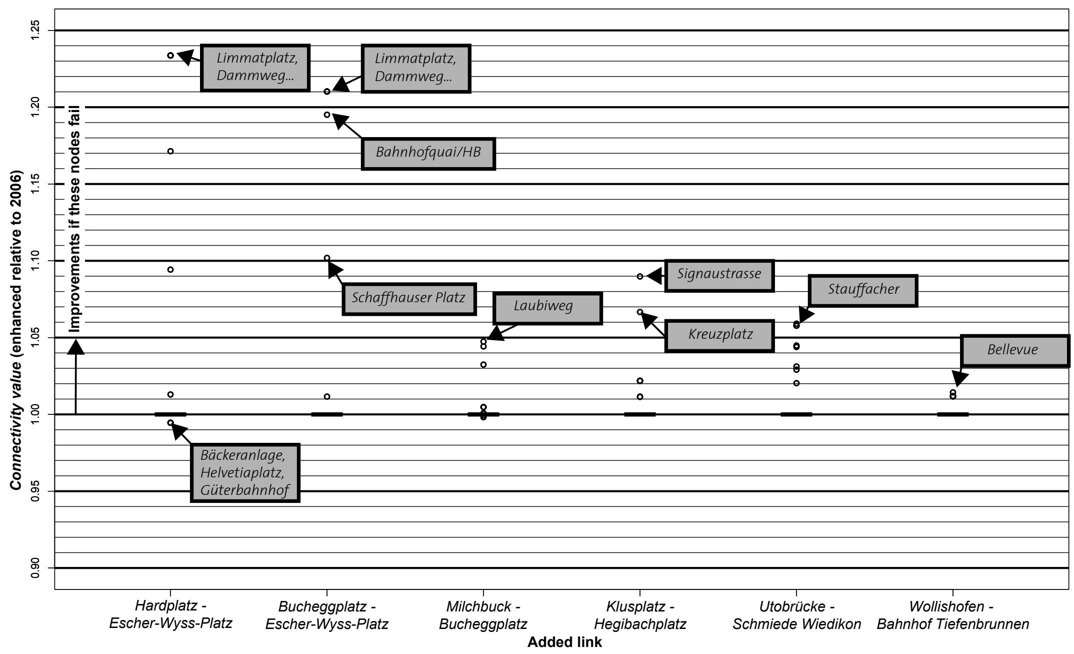
Figure 95 shows that for the majority of such node removals, the value of the *operational system performance* remains constant in degraded operation. This means that for the majority of such removals, no improvements of the *operational robustness* are measured, i.e. the majority of measured values equal to 1. If a link between *Hardplatz* and *Escher-Wyss-Platz* is added, for the removal of the stations *Limmatplatz* or *Dammweg* improvements of the *operational resiliencies* are calculated. In other words, in cases where these nodes are removed benefits are realized from adding the link. The results also show, that all enhancements are beneficial. In a few cases, also values smaller than one are calculated indicating that adding a link decreases the calculated *operational robustness* value. One reason for this observation is that the new link now offers rerouting alternatives that exceed the capacity threshold of some links such that the *capacity value* is reduced (see Figure 97).

Figure 95 Changes of the *operational system performance* in degraded operation if links are added to the *Zurich tramway 2006* network



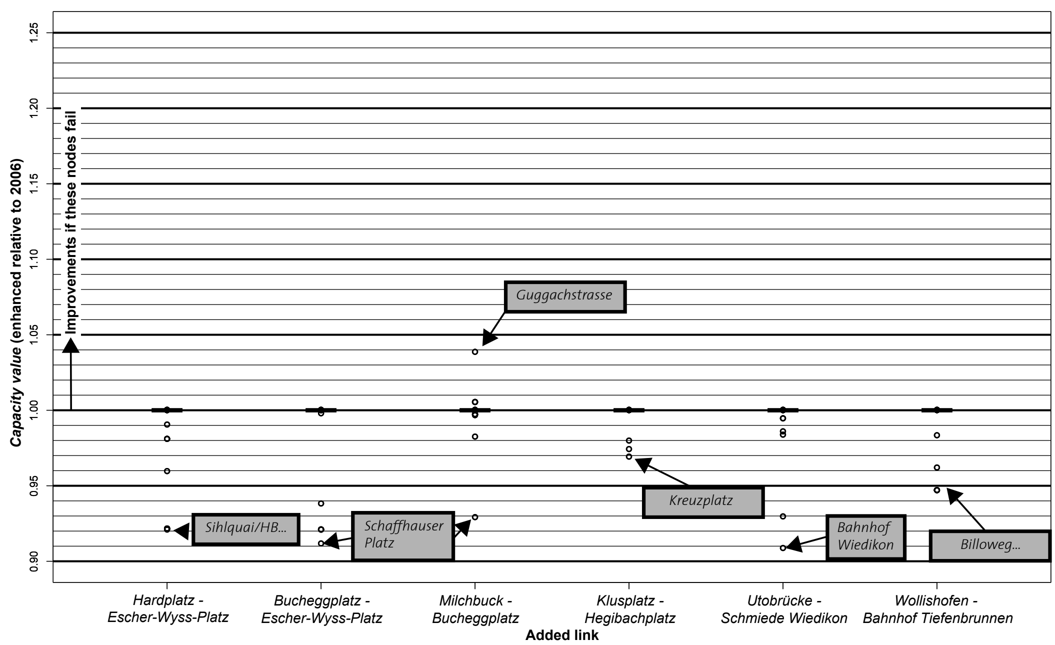
The corresponding results for changes of the *connectivity value* are shown in Figure 96. Adding a link connecting *Hardplatz* and *Escher-Wyss-Platz* increases the *connectivity value* by more than 20 % for removals of the nodes representing *Dammweg* and *Limmatplatz* and is hence beneficial for the connectivity of the network in degraded operation not only in cases where this nodes are removed. Connecting the stations *Wollishofen* and *Bahnhof Tiefenbrunnen* only slightly increases the *connectivity value* for a few cases.

Figure 96 Changes of the *connectivity value* in degraded operation if links are added to the *Zurich tramway 2006* network



The dynamics of the *capacity value* in case of adding the introduced links to the Zurich tramway 2006 network are shown in Figure 97.

Figure 97 Changes of the *capacity value* in degraded operation if links are added to the *Zurich tramway 2006* network



In most cases, adding links decreases the *capacity value*. This indicates that the new edges are actually used for degraded operation, which can increase the line path length such that additional vehicles become necessary. It is also possible that the specified theoretical or operational capacity thresholds are exceeded for some further edges.

8.3.2 Offering new turnaround alternatives

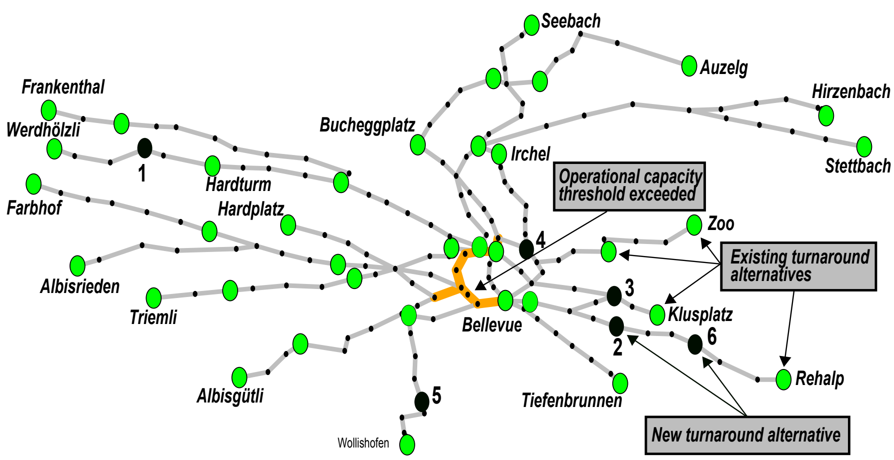
This sections analyses how the operational robustness of railway networks can be increased by adding new turnaround alternatives. Table 81 shows how the values for the *connectivity value*, the *capacity value* and the *operational system performance* change if a single stations offers a new turnaround alternative in the *Zurich tramway 2006* network. The stations were arbitrarily chosen.

Table 81 Robustness improvements by adding turnaround alternatives to the *Zurich tramway 2006* network

New turnaround alternative	*Connectivity value*	*Capacity value*	*Operational system performance*
Zurich tramway 2006	0.9124	0.9901	0.9025
1 *Tüffenwies*	0.9131	0.9901	0.9033
2 *Hegibachplatz*	0.9135	0.9901	0.9036
3 *Römerhof*	0.9124	0.9901	0.9025
4 *ETH/Universitätsspital*	0.9124	0.9901	0.9025
5 *Bahnhof Wollishofen*	0.9139	0.9901	0.9041
6 *Burgwies*	0.9139	0.9901	0.9040

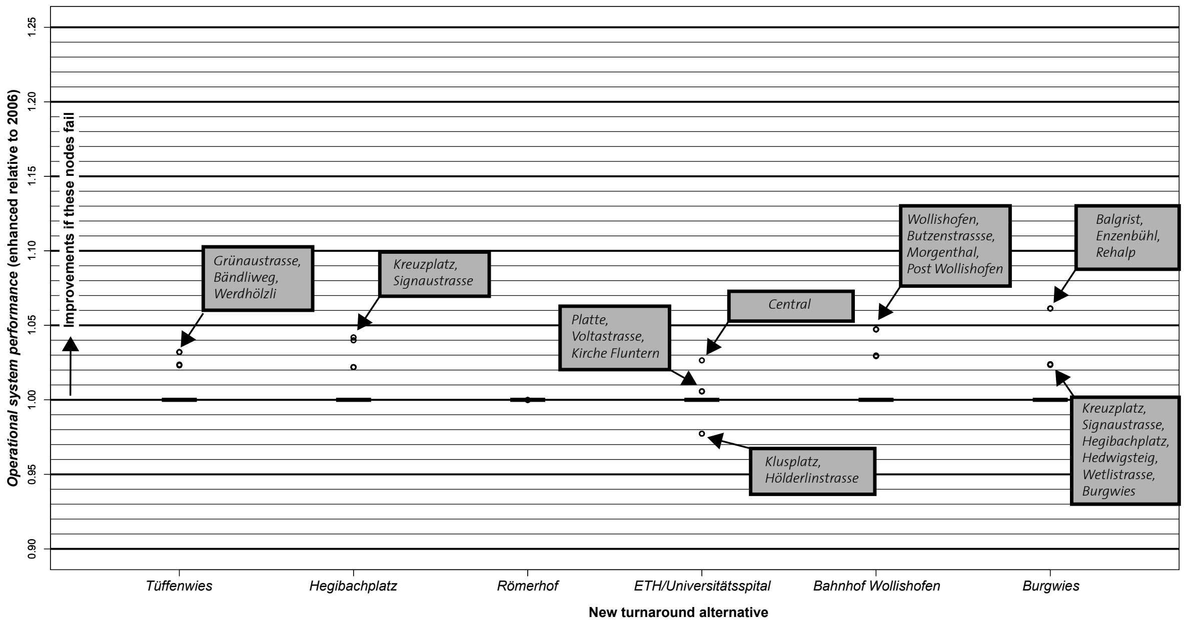
Figure 98 shows where the new turnaround alternatives are located in *Zurich tramway 2006.*

Figure 98 Location of the new turnaround alternatives in the *Zurich tramway 2006* network



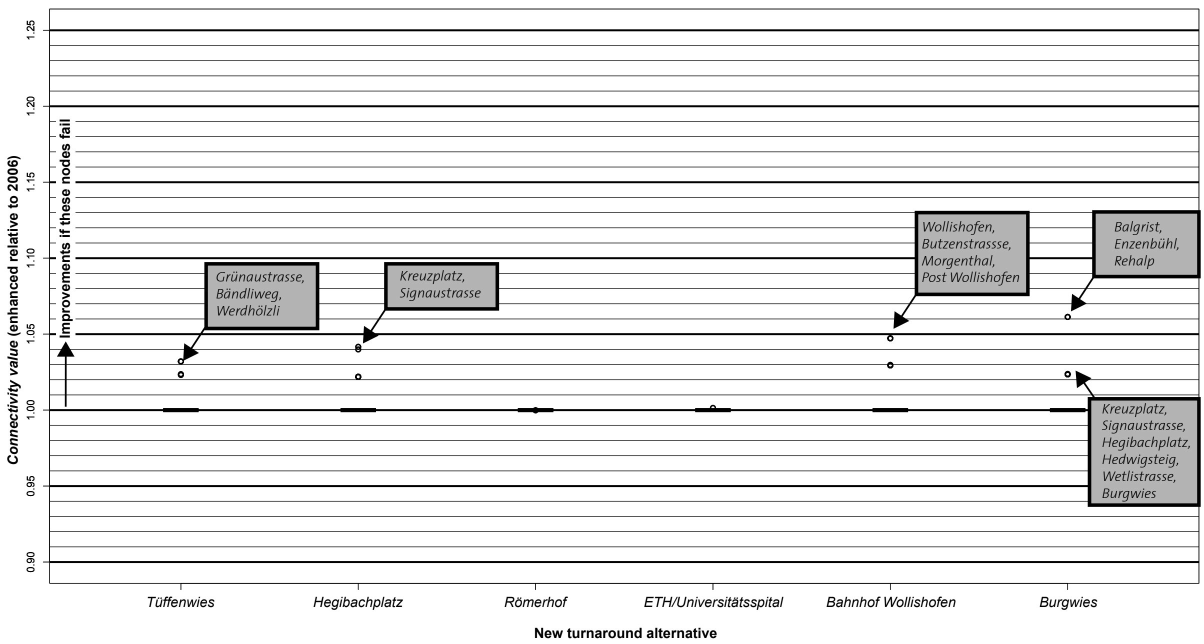
Black circles represent stations offering new turnaround alternatives. The numbers in Figure 98 correspond with those in the first column in Table 81. Figure 99 shows for which node removals the measured *operational system performances* actually change. The values were calculated according to the procedures described in the previous section. The results show that fewer improvements are measured if turnaround alternatives are added to the *Zurich tramway 2006* network. If for instance the station *Tüffenwies* offers a turnaround alternative, the *operational system performance* in degraded operation can be improved by about 3 % if the stations *Grünauweg*, *Bändliweg* or *Werdhölzli* are removed. The largest improvements of the *operational resiliencies* are measured if the station *Burgwies* offers a turnaround alternative.

Figure 99 Changes of the *operational system performances* in degraded operation if turnaround alternatives are added to the *Zurich tramway 2006* network



Those node removals for which the *connectivity value* changes if the new introduced turnaround alternatives are established are identified in Figure 100. For all analysed enhancements the *connectivity values* increase or remain constant if new turnaround alternatives are established. The results show that for offering a turnaround alternative at the stations *Römerhof* or *ETH/Universitätsspital* only slightly changes the *connectivity value* in a very few cases. The main reason for this observation is that other turnaround alternatives are available within short distances such that almost no improvements of the *connectivity values* are measured.

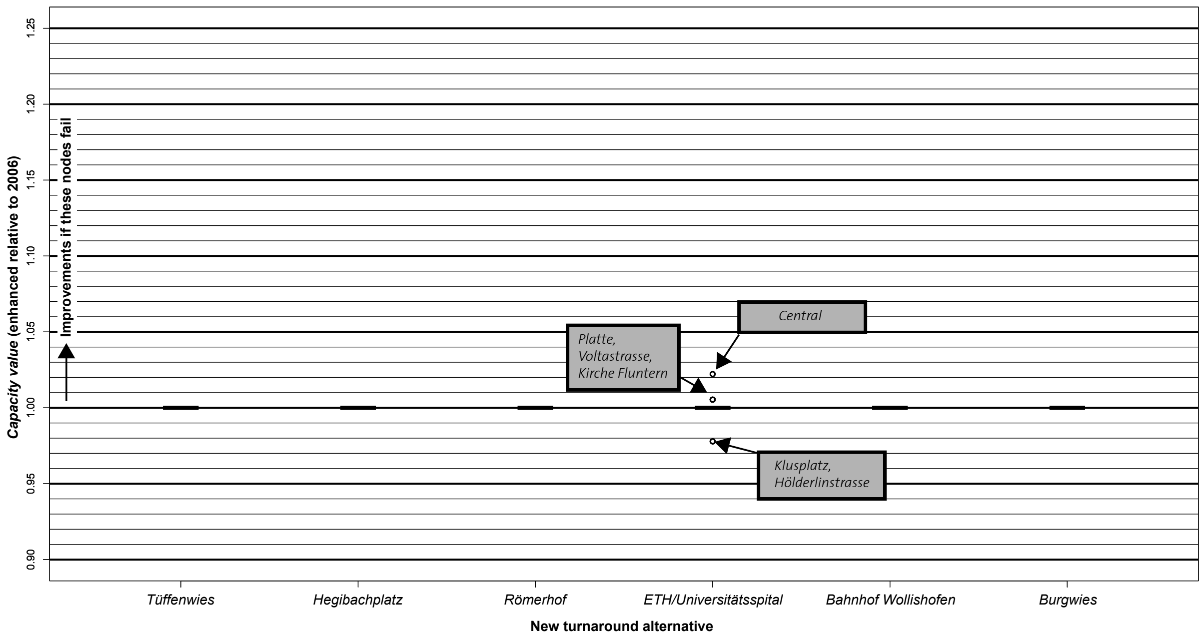
Figure 100 Changes of the *connectivity value* in degraded operation if turnaround alternatives are added to the *Zurich tramway 2006* network



The changes of the *capacity value* are shown in Figure 101 if the new turnaround alternatives are established. For *Zurich tramway 2006*, the calculated *capacity values* change only in a very few cases if the station *ETH/Universitätsspital* offers a turnaround alternative. In more detail, in case of removing the stations *Central, Platte, Voltastrasse* or *Kirche Fluntern* the availability of a turnaround alternative at *ETH/Universitätsspital* allows to calculate degraded operation states for which the capacity values is improved since for less edges the specified capacity thresholds are exceeded.

Altogether, the results show that only small improvements for the removals of a few nodes are realized by offering new turnaround alternatives and enhancements efforts should rather focus on building new tracks in the analysed *Zurich tramway 2006* network. The implemented tool can give useful information about where to offer new turnaround alternatives and its contributions to robustness improvements.

Figure 101 Changes of the *capacity value* in degraded operation if turnaround alternatives are added to the *Zurich tramway 2006* network

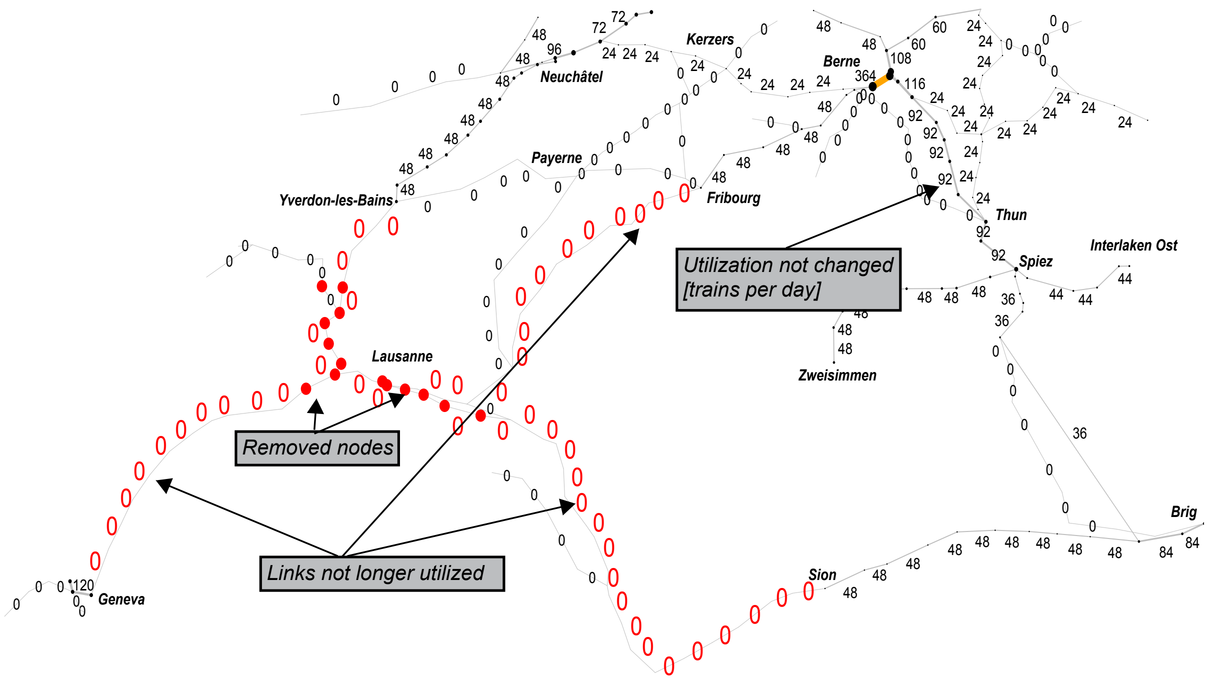


8.3.3 Reconstructing the overlapping between *Control-command and Signalling* and *Energy* regions

The third analysed robustness enhancement addresses to the overlapping of *Control-command and Signalling* regions (nodes that are remotely controlled from a specific device) and regions in the *Energy* subsystem (stations and links within specific traction current areas). The results show that the implemented procedures can also be used to find ineffectiveness of their integration or overlapping. This section shows how the operational robustness can be improved be redesigning the *Control-command and Signalling* or the *Energy* regions respectively their overlapping for a concrete case. The analysis refers to [Schneider et al., 2011] showing that *«with small changes in the network structure [...] the robustness of diverse networks can be improved dramatically, whereas their functionality remains unchanged.»*

Figure 102 shows the degraded operation state of the *Swiss railway* network if all nodes are removed that are remotely controlled from *Lausanne* in the *Control-command and Signalling* subsystem. In the calculated degraded operation states, all affected lines are either truncated or entirely not operating anymore (Table 82). Rerouting alternatives do not exist. Table 82 also shows the calculated operational robustness values: Removing all nodes remotely controlled from *Lausanne* significantly decreases the *operational system performance* by 30 per cent. 13 % of lines are truncated and about 6 % i.e. three lines are not longer operated.

Figure 102 Calculated degraded operation state if the CCS node *Lausanne* is removed from the *Swiss railway* network[21]



The set of stations that is remotely controlled by *Lausanne* overlaps with two different *Energy* subsystem regions, i.e. the nodes remotely controlled from *Lausanne* receiving traction current from the substations *Puidoux* and *Bussigny*. If the area of stations remotely controlled from *Lausanne* would contain the nodes and links receiving traction current from the substation *Puidoux* many lines could be rerouted (see Figure 90) and the calculated *operational robustness* values could be improved (see Table 82).

Operational robustness improvements can also be measured if the area of stations remotely controlled from *Lausanne* would contain the nodes and tracks receiving traction current from the substation *Bussigny*. Also in this case, the *operational system performance* in degraded operation is improved and the number of lines that cannot longer be operated decreases and more lines can be rerouted (Table 82). The degraded operation state as calculated by the implemented robustness analysis tool is visualised in Figure 103.

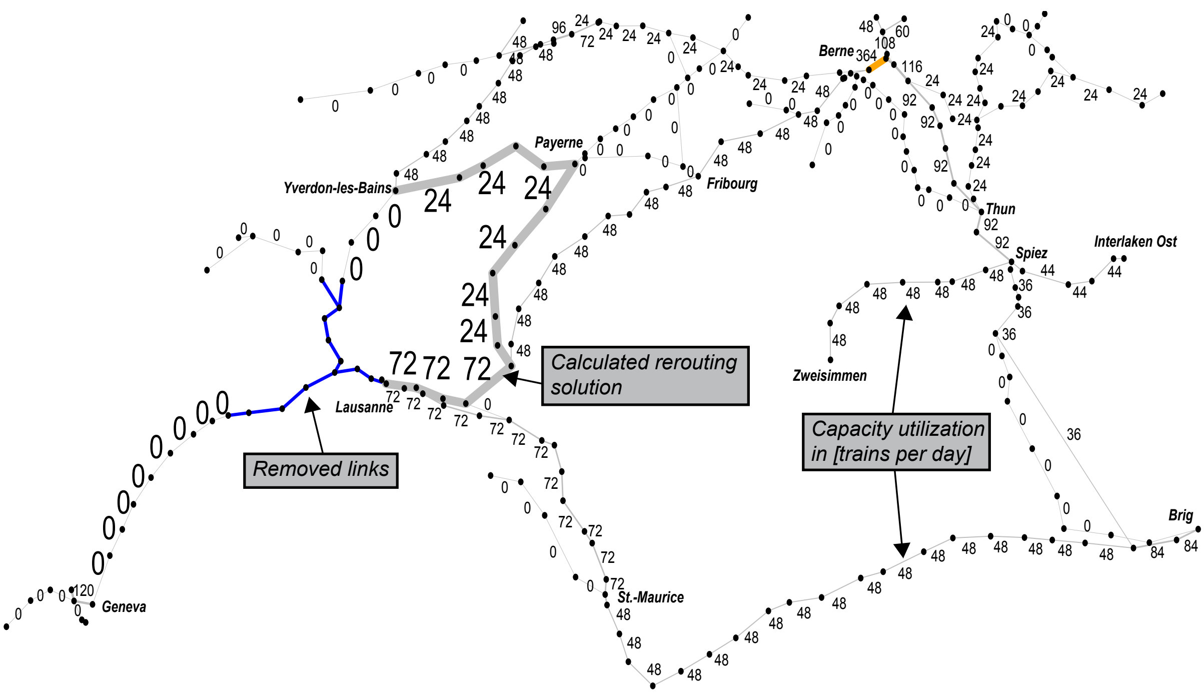
[21] In 2010, the *Control-command and Signalling* region remotely controlled from *Lausanne* was adapted.

Table 82 Benefits from adaptations of the *Control-command and Signalling* subsystem

Subsystem	*Control-command and Signalling*	*Energy*	
Removed node	*Lausanne*	*Puidoux*	*Bussigny*
Operational system performance	0.6946	0.7764	0.861
Connectivity value	0.6946	0.7845	0.861
Capacity value	1	0.9919	1
Line not changed [%]	80.8	84.6	82.7
Line not longer operated [%]	5.8	5.8	3.8
No stops outside the original line path [%] → Truncation	13.5	3.8	9.6
Stops outside the original line path [%] → Rerouting	-	5.8	3.8

A comparison of all three cases shows that reconstructing the *Control-command and Signalling* subsystem region remotely controlled from *Lausanne* can significantly increase the operational robustness, i.e. if the size of the overlapping area decreases. This means that the set of stations remotely controlled from *Lausanne* should more coincide with the distinction of the traction currents in the *Energy* subsystem.

Figure 103 Calculated degraded operation state if the *Energy* node *Bussigny* is removed



9 Conclusions

9.1 Overview

The last chapter summarizes the main insights gained in this study and discusses the strengths and weaknesses of the evaluated methodology and the implemented procedures. The structure of this chapter is described in Table 83.

Table 83 Structure and contents of chapter 9

Section	Contents	Purpose
9.1	Overview	Introduction, goals and purpose of this chapter
9.2	Strengths and weaknesses	Identification of strengths and weaknesses of the developed robustness analysis method and the implemented robustness analysis tool
9.3	Synopsis and hypothesis verification	Statements about the hypothesis made and the calculated results, summarization of the main benefits and insights gained in the study
9.4	Adaptability and extendibility	Statements about how the implemented tool can be adapted and extended, remaining questions, further research potentials

9.2 Strengths and weaknesses of the developed method

This section discusses the strengths and weaknesses of the evaluated methodology and shows for which questions useful information is provided and in which cases the results of the implemented procedures have to be interpreted carefully. In the following grading of the study, scientific aspects and practical impacts of the study are discussed separately.

9.2.1 Scientific aspects

→ Strengths of the introduced methods

Introducing methods for calculating degraded operation states extends the current knowledge about the resilience of railway networks.

The evaluated methodology introduces a methodology that focuses on the operational impacts of threatening events on railway networks and hence extends the current knowledge about the resilience of railway systems, which mainly focuses on the topological features of the analysed networks. Many studies that analyse the resilience of critical infrastructures with both stationary and dynamic models are available, either focussing on the dynamics of shortest path lengths and network integrity or on epidemiological models used for simulating the spreading of failures in network structures. For analysing the robustness of railway networks, this study introduces a methodology that calculates degraded operation states in which lines are truncated, rerouted or entirely put out of service. The developed methods can be applied in other scientific disciplines assessing the robustness of complex systems in which lines are not routed along shortest paths but along specific line paths in planned and degraded state.

The developed methodology considers a multi-level approach analysing not on the infrastructure topology but integrating other subsystems.

The developed methodology analyses not only the topology of railway networks, but integrates other subsystems such as the *Traffic Operation and Management,* the *Control-command and Signalling* and the *Energy* subsystem. Especially considering operational data such as line path restrictions and capacity thresholds of rerouting alternatives are new concepts and significantly contribute to increasing the level of detail of the simulated impacts of threatening events on railway operation. Failures of locally operated or remotely controlled signal boxes and the non-availability of traction current areas can also be simulated.

Degraded operation states are calculated and the amounts of degradations are quantified for measuring the impacts of threatening events on railway operation.

The introduced and implemented line disposition framework allows systematically simulating and calculating realistic degraded operation states that consider line path routing aspects and mimic the degraded operation states in real-world scenarios. While recent studies focus on shortest path flows in both, normal and degraded operation, specific line paths are considered which is essential for measuring the robustness of railway networks. The developed methodology simulates degraded operation states and introduces a scheme for quantifying the amount of degradation of railway networks that integrates connectivity-related and capacity-related measures into a single quantity.

The level of degradation is expressed by measuring multiple quantities that are suitable to distinguish between the connectivity of the network in degraded operation and aspects of the capacity utilization. This allows comparing the simulated impacts of failures on railway operation.

The evaluated methodology allows distinguishing between the impacts of threatening events on the connectivity and capacity utilization of railway networks in degraded operation. In degraded operation, the connectivity may be reduced, capacity problems may occur or even both simultaneously. The introduced procedures allow systematically assessing and quantifying connectivity and capacity-related aspects.

The structural and operational consequences of removing specific nodes or links from the network on the degraded topology and the degraded operation state may significantly deviate.

The study shows that there are nodes whose removals significantly degrade the network topology but whose deletion only slightly decrease railway operation and vice versa. Existing studies identifying the most critical elements from a topological point of view are not suitable for finding all the nodes whose removals have the most drastic operational impacts.

The study shows how the structural and operational robustness results of removing a specific node or link are correlated, i.e. how information about the structural impacts of such removals can be used for assessing the operational consequences.

The study introduces a classification scheme that subdivides the nodes according to the impacts of their removals on the degraded topology and integrates the giant cluster size and the average shortest path length within. The study shows that information about the classification of a node can be used for anticipating the operational impacts of their removals. This means that for the introduced node classes, specific dispositive measures are more likely to be taken such as rerouting or truncating lines.

The most critical elements of railway networks can be identified, i.e. the nodes and links whose removal induces the most severe degradations of railway operation. Also the bottlenecks in degraded operation can be calculated, i.e. the nodes and links extensively utilized in degraded state.

The developed methodology can be used for identifying the nodes and links with smallest operational robustness, i.e. the elements whose removals induce the most severe degradations of the system performance in degraded operation. Also the nodes and links can be determined that are bottlenecks in degraded states, i.e. the nodes and links offering rerouting alternatives.

The developed methods are modular and can be adapted or extended.

The developed procedures and introduced methods such as the line disposition framework or the scheme used for quantifying the system performance of railway networks in either planned or degraded operation can be adapted or extended as shown in section 9.4. Additional dispositive measures can be included or further measures can be integrated in the system performance value. Also the level of detail can be improved, increasing the computation times.

→ *Weaknesses of the developed methodology*

Railway networks are represented on a macroscopic level.

Railway transport systems are represented on a macroscopic level, which may give wrong or misleading results in some cases. For instance, in the *Infrastructure* subsystem representation it is assumed that all paths can actually be used for operation. However, not all switches and routing possibilities actually have to exist. Increasing the level of detail when representing the Infrastructure subsystem may circumvent this problem, but this also increases the time needed for specifying and implementing the input data and calculation times. The introduces macroscopic representation allows systematically calculating and quantifying degraded operational states within reasonable amount of time and relying on manageable data sets.

The developed methodology introduces a stationary model that calculates ad-hoc degraded operation states.

The methodology considers two states of the network topology and railway operation, the planned and degraded one. When threatening events occur, degraded operation states are established immediately. Aspects such as the time needed for establishing degraded operation states by rerouting or truncating lines and other operational requirements for establishing them such as the number of trains that are in a degraded component are neglected.

Data about real-world scenarios is rare and hence only a single real-world scenario is analysed for the model verification.

The study focuses on rare events that are represented by removing entire links and stations from railway networks. Partial failures of single tracks along double-track connections are not analysed even though they occur much more often in real-world operation.

Not all the aspects that are contained in real-world decisions about degraded operation states are represented.

The implemented procedures calculate realistic degraded operation states in many cases. These solutions can be assumed to mimic real-world ones. However, the implemented line disposition framework does not display the entire set of operational measures for establishing degraded operation states. This means that for instance combining multiple lines into a single one, or the experience of the decision makers are not simulated. Also some operational conditions for running degraded operation states are neglected: For instance, there may not be enough trains within a component in the degraded network for maintaining the frequencies of the affected lines. The implemented tool is no expert system.

9.2.2 Practical relevance

→ *Strengths*

The developed methodology visualizes degraded operation states even in case of multiple simultaneous failures and supports the decisions about operational measures. The results identify bottlenecks in degraded operation (important rerouting corridors).

The developed method and the implemented robustness analysis tool can be used for anticipating the operational consequences of removing stations and tracks, i.e. to assess the impacts of threatening events causing that stations or links cannot longer be used for operation. For single events, codes of action exist providing all information about the degraded operation states. However, if multiple failures occur simultaneously, the developed method may contribute to establish degraded operation states, to improve the preparedness and to decrease the response time by visualising degraded operation states and hence to identify the stations that cannot longer be served. This information is essential in complex situations that are time critical. The results quantify the impacts of such events and the amount of degradation and hence allow comparing multiple failure scenarios. The information can be used to locate bottlenecks in degraded operation and to find locations where protection efforts should concentrate on.

The results provide valuable quantitative information for robustness enhancements and the consequences of reconstructions on the robustness of the railway network.

The methodology is suitable for measuring the benefits gained from several investments and network extensions or reconstructions. The tool can be used for quantifying the changes of the robustness if new tracks are added, tracks are removed from the topology or line paths are adapted.

→ *Weaknesses*

Railway networks are represented in a simplified way: For instance line paths are assumed to be symmetric. Hence, solutions may be calculated that are not feasible in real-world operation.

The representation of railway networks contains simplifications such that degraded operation states are calculated, that cannot be operated in all cases. For instance, the method assumes that line paths are equal for travelling in both directions. This may not always hold in real-world operation. These simplifications have to be considered when interpreting the calculated results.

The represented railway networks are sharply demarcated. This can influence the quality of the calculated results in some cases. For instance, other transport modes are neglected and not included in the developed methodology.

The represented railway systems are closed one such that connections and rerouting alternatives outside the represented system are not considered. It may for instance be possible to drive around blocked parts along tracks that are not represented in the model. In some cases, rerouting alternatives for truncated lines may exist, outside the represented network.

Focussing on a single transport mode can give misleading results: In some cases the calculated rerouting solutions may not mimic real-world decisions since transport operators may prefer to establish services using other transport modes such as bus services, especially if the calculated rerouting solutions are too long (the factor for the maximal length may be changed) or short and fast bus services give better results than rerouting a tram line.

The developed line-dispatching framework contains only a basic set of dispatching measures and may hence reduce the applicability for real-world operation.

There are only a few basic dispatching measures considered in this study, i.e. truncating lines, rerouting lines or putting lines out of service. Real-world solutions can also be to establish new lines for degraded operation, combine multiple truncated line paths into new lines during the impacts of threats and putting lines out of service such that enough capacities are available for rerouting lines that are considered to be more important. Hence, the line disposition framework illustrated in Figure 36 and Figure 41 may have to be extended (see section 9.4).

9.3 Synopsis and hypothesis verification

9.3.1 Synopsis

The evaluated methodology and implemented procedures can be used for assessing the structural and operational robustness of railway networks. The developed robustness analysis methodology and the implemented tool improve knowledge about the robustness of transport networks in general, especially for railway transports with pre-defined line path routings.

The set of existing mathematical methods for assessing the topological features of networks representing complex systems such as social or router networks is extended such that the structural and operational impacts of severe events threatening railway networks can be simulated and quantitatively assessed.

The developed method allows to systematically manipulate railway networks and to measure the effects on the connectivity of the network in degraded operation and the capacity utilizations of the traversed links. Realistic degraded operation states can only be calculated if procedures are developed specifying how to dispatch lines traversing a blockaded element. The amount of degradation from planned to degraded operation state is quantified in a single value. Hence, the developed methods make it possible to compare degraded operational states, to identify the most critical elements on the system and subsystem level and to visualize and compare the impacts of threatening events on railway operation, which is of high practical importance for both, the transport operators and their customers: The results can be used to anticipate the consequences of adaptation measures for transport networks, to prioritize investments and to improve the preparedness and the customer information if threatening events occur. From the operator's point of view the results give useful information for evaluating rules of action how to deal with hazardous events threatening operation.

The implemented procedures are applied to three case study networks, representing the Swiss railway system and the tramway network in Zurich. The analysis verified that all networks are highly robust towards removing elements with equal probability. If these threatening events are biased towards specific *important* system elements, the networks may disintegrate very fast into many isolated components. In this sense, the analysed railway systems share the characteristics of many other complex systems that were successfully shown to have scale-free topologies. Considering operational aspects, the study showed that at least for small number of initially failing elements, the majority of lines do not traverse blockaded elements such that dispatching measures do not have to be taken only for a few lines. Lines traversing a failing element can be rerouted to drive around removed elements or are truncated if this is not possible. Putting entire lines out of service is necessary only in very few cases, even for large numbers of simultaneous failures.

While recent studies solely assess the structural robustness of railway networks and hence focussing on the changes of topological key parameters and neglecting any operational requirements for degraded operation, this study shows that this can give misleading results. Even the known structural robustness quantification procedures in some cases fail to find the most critical topology elements, since the degraded topology and the degraded operated network can significantly differ.

For entirely assessing the operational robustness of railway networks, dispositive measures have to be modelled for simulating degraded operation states. Instead of focussing on the node degree, the betweenness often gives better results for identifying the most critical network elements, whose removals has most severe structural impacts. The evaluated classification scheme integrating two topological measures is most suitable for quickly determining the nodes and links whose removal has most severe topological impacts. This often induces first indications for dispositive measures such as line path truncation or the existence of rerouting alternatives.

The implemented robustness analysis tool can simulate failures of multiple nodes representing stations remotely controlled from a specific *Control-command and Signalling* device. It is also possible to consider removals of several edges if specific traction current areas fail. Dispatching measures distinguish between line path adaptions such that specific capacity threshold values are not exceeded or neglect these restrictions (capacity-related measures quantify the amount of capacity thresholds that are exceeded).

The study showed that the evaluated methodology is additionally suitable for quantifying and comparing the benefits from robustness enhancements such as building new tracks, offering new turnaround possibilities or redesigning regions in the *Control-command and Signalling* and the *Energy* subsystem such that they overlap to a greater extent. The implemented procedures verified that even nodes and links with minor importance for planned operation are important for the stability and robustness of the network. This means that even corridors not extensively used in planned operation can be important for offering rerouting alternatives for specific scenarios and hence contribute to the robustness and resilience on the network level.

9.3.2 Hypothesis verification

The evaluated methodology and the implemented robustness analysis tool is suitable for verifying the hypotheses denoted in section 1.2. The results of this study concerning the formulated hypotheses are summarized in Table 84.

Table 84 Verification of the hypotheses

Hypotheses	Contents	Result
Hypotheses 1	Railway networks have scale-free topologies.	(✓)
Hypotheses 2	The topological and operational importance of elements can deviate.	✓
Hypotheses 3	It is possible to systematically simulate degraded operation states.	✓
Hypotheses 4	Impacts depend on various characteristics such as the locations of failing elements.	✓
Hypotheses 5	Even rarely used elements can be of high importance for the robustness of the system.	✓
Hypotheses 6	The robustness of railway networks can be enhanced.	✓

In the following, the results for the formulated hypotheses (see section 1.2) are summarized.

Hypotheses 1 → Verified to a large extent

The structures of railway networks share the topological features of the so-called *scale-free networks*: The network remains in a large connected component even if many nodes are removed at random choice. On the contrary, for biased-removal strategies focussing on the most important nodes, networks disintegrate fast.

Scale-free networks are introduced in section 2.4.5. Many real-world systems were shown to have scale-free topologies. This knowledge implies first information about the (structural) robustness of the analysed networks, since for scale-free networks characteristic degradations of the topologies are known for both, non-biased removals of randomly chosen nodes or biased strategies focussing on the most important nodes (illustrated in Figure 11). It was shown that the topology of scale-free networks deteriorate fast in the latter cases, while the networks are highly robust if the removed nodes are chosen with equal probability among all nodes.

The structural properties of the analysed networks (the *Swiss railway* network, the *Zurich tramway 2006* network and the *Zurich tramway 2025* network) are measured in section 6.3.2. The non-adapted topologies were all shown to be small-worlds (Table 44) with node-degree distributions decaying as a power law (Table 45, Figure 104). Both, the number of nodes and the range of the node degrees are comparatively small, maybe too small for detecting that the networks are scale-free. Many other networks that were shown to have scale-free topologies contain much more nodes than the analysed networks (Table 42). The Infrastructure topologies of railway networks are adapted into functional topologies as shown in Figure 31 and Figure 32. This eliminates many of the triangles present in the networks and changes the analysed topology such that an essential ingredient for detecting small-world networks is likely to vanish. However, the degradation of network integrity, i.e. the dynamics of the giant cluster sizes (Figure 50) and the dynamics of the average shortest path lengths (Figure 52) share the observations made for scale-free networks.

Hypotheses 2 → Verified

The structural and operational consequences of removing a specific node can significantly differ, i.e. the topological importance and the operational one do not necessarily coincide. Hence, existing structural robustness analysis methods are not suitable for assessing the operational robustness of railway networks.

Figure 66 and the further results presented in section 6.4 showed that the structural and operational robustness for removing a specific node may significantly deviate. This means that there are nodes whose removal implies severe degradations of railway operation, but whose structural degradation is much less significant.

Hypotheses 3 → Verified

Railway systems can be modelled and it is possible to systematically calculate degraded operation states and hence to simulate and quantify the impacts of threatening events on railway operation.

In this study, railway networks are modelled as multi-level networks as illustrated in Figure 25. The considered subsystems and their representations are described in chapter 3. Removing nodes and links from railway networks induces that all lines have to be dispatched traversing the removed elements. Figure 36 shows how degraded operation states are calculated in this study. If in the degraded case the specified capacity thresholds shall not be exceeded for additional edges, the procedures illustrated in Figure 41 are included in the line disposition framework. Chapter 7 shows that feasible solutions are calculated that change if the input data is adapted. For specific cases (case study 1 for the *Zurich tramway 2006* network), the results were discussed with the VBZ.

Hypotheses 4 → Verified

Both, the structural and operational robustness of railway networks depend on the number of simultaneously removed nodes, the locations of the deleted elements and the existence of potential rerouting alternatives and their capacity utilizations.

The level of the structural robustness depends on the location of the removed elements in the analysed topology (Figure 47) such as the centrality of the removed node (Table 49) or its classification (Table 53). Also the results for the operational robustness and the distributions of dispatching measures depend on the removed node (Table 59, Figure 60), the classification of the removed node (Figure 64, Figure 65), the centrality values (Table 59) and the number of simultaneously removed nodes (Table 62, Table 63, Figure 71).

Hypotheses 5 → Verified

There are routes not heavily used in planned operation, which are important bottlenecks in degraded operation by offering rerouting alternatives. These corridors contribute to the structural and operational robustness of the entire network.

Even routes that are not extensively used in normal operation can be of major importance for offering rerouting alternatives in degraded operation. This is verified for the corridor *Bern – Belp – Thun* in the *Swiss railway* network in section 7.3.

Hypotheses 6 → Verified

The robustness of railway networks can be enhanced and the gained benefits can be quantified with the evaluated and implemented methodology.

Chapter 8 summarizes potential robustness enhancements and contains analysis results in case of adding links, adding turnaround alternatives and reconstructing the overlapping of the *Control-command and Signalling* and *Energy* subsystem (areas of stations that are remotely controlled from the same station and which lie within a specific traction current area). These measures are suitable to increase the values of the calculated operational robustness such that the *operational system performances* can be improved in degraded state.

9.4 Adaptability, extendibility and limitations

This section shows how the developed methods can be extended in further research projects. Also the limitations of the methodology are discussed.

9.4.1 Adaptations

The developed methods and implemented procedures for assessing the structural and operational robustness of railway networks can be adapted in various ways, including:

→ Adaptations of quantifying the system performance in degraded operation states

The methodology of quantifying the system performance in degraded operation is defined in section 5.6 (Figure 35). Beside the *connectivity value* and the *capacity value* additional or different values can be included, potentially using different weights. It may also be beneficial to define further measures measuring additional aspects (number of affected customers, estimated costs…).

→ Change the values used for calculating the results in chapter 6, 7 and 8

The values used for calculating the operational robustness of the analysed networks can be changed. For instance, it is possible to change the capacity threshold values used in this study (see Table 39 and Table 40) or to consider edge-specific values, depending for instance on the number of parallel tracks. In this study, for each edge is specified whether there are single or double tracks are between two stations but other values may also be suitable. It may also be beneficial to consider different values for the maximal length of rerouting alternatives, relative to the length of the rerouted line. In this study the value 2 was taken (section 5.7).

→ Include other lines, freight transports and single trains in the *Traffic Operation and Management* subsystem

Considering urban railway lines, freight transports and additional trains increases the level of detail of the calculated results and gives more realistic results. This increases the calculation times.

→ Represent capacity limitations of nodes and turnaround loops

Capacity thresholds can also be specified for stations and turnaround alternatives.

→ Consider the removal of turnaround alternatives while the node remains present

The developed method can be adapted such that it is also possible to represent cases in which only the turnaround loops cannot be used any longer while the corresponding station can still be traversed (especially for tramway networks).

9.4.2 Extensions

The evaluated methodology can be extended in order to improve the quality of the robustness results and the calculated degraded operation states in various ways such as:

→ Extension or adaptation of the line disposition framework used for calculating degraded operation states

The method for calculating degraded operation states is introduced in Figure 36. For the capacity-restricted case, Figure 41 shows how to calculate dispatching solutions if for no additional edge specific capacity threshold shall not be exceeded. The procedures and steps can be extended (or adapted) to give more realistic solutions such as integrating two truncated line paths into a single one, or considering cases in which the frequency of line is reduced such that the capacity thresholds are not longer exceeded.

→ Increase the level of detail for representing the *Infrastructure* topology

A more detailed (macroscopic) representation of the *Infrastructure* subsystem is possible with the developed method and can eliminate solutions that are not operable in real-world scenarios, for instance due to missing switches. It may also be beneficial to consider separate nodes for stops traversed in different directions.

→ Include quantification of financial aspects and number of affected customers

The method can be extended such that the induced direct and indirect costs of disposition efforts for establishing stable degraded operation states are estimated (using estimates for the duration of degraded operation states). Railway operators are interested in these values. If the numbers of customers travelling between any pair of stations or using a line are known, also the number of affected customer can be estimated.

→ Allow failures to change its locations

Some threatening events cause the removal of a set of nodes that is not static but dynamic. For instance, in case of demonstrations the set of affected nodes may change.

→ Integration of time-relevant aspects and quantification of other resilience elements such as the resourcefulness and rapidity

Integrating temporal aspects such as the duration of time spans with reduced system performances allows entirely assessing the resiliencies of railway networks and the system performance curves displayed in Figure 33. This takes much effort for turning the developed stationary model into a dynamic one.

→ Consider partial removals and directed edges

In many real-world scenarios, only one of multiple parallel tracks is blocked and cannot longer be used for operation. In the developed model, reducing the capacity of the specific link can represent this. The model can also be extended to consider cases in which a line path has to be changed in only a single direction of travel while for the other one the planned train path can be maintained.

→ Integrate probabilities of occurrence for threatening events

If occurrence probabilities for threatening events in specific parts of the system or for specific locations were available, a full risk assessment would become possible.

→ Integration of other transport modes

The method can be extended such that additional transport modes such as bus transport are included in the model. Modelling the subsystems of the transport modes separately can do this, connecting the *Infrastructure* topologies and specifying for each Infrastructure link which transport mode can travel along a link. This means that for each Infrastructure link has to be specified whether busses or trains can travel along the link.

→ Search and simulate real-world scenarios to improve the model verification

Degraded operation states and robustness results for other cases of real-world scenarios can be compared with calculated simulation results gained by the implemented robustness analysis tool. This would improve the model verification and may improve the developed model.

9.4.3 Limitations of the evaluated methodology

The evaluated methodology is not believed to be suitable for including optimization procedures determining the best solution with respect to specific conditions or requirements such as resource optimizations.

Turning the stationary model into a dynamic one may not be possible. The introduced methodology calculates ad-hoc solutions for degraded operation states and time aspects are not modelled. However, it may take some time to establish degraded operation states since additional trains and drivers are needed. Maybe epidemiological models can be used for simulating the dynamic aspects of hazard consequences on railway operation.

10 Bibliography

[Achermann, 2009] Achermann, D. (2009) *Mit Rail Control das Netz im Griff*, BY RAIL.NOW!2009, p. 71 – 72. (in German).

[Ahrens et al., 2009] Ahrens, G.-A., H. Baum, K.J. Beckmann, W. Brilon, A. Eisenkopf, H. Fricke, I. Göpfert, C. von Hirschausen, G. Knieps, S. Oeter, F.-J. Radermacher, W. Rothengatter, V. Schindler, B. Schlag, J. Siegmann, W. Stölzle (2009) *Zuverlässigkeit der Verkehrssysteme*, Wissenschaftlicher Beirat beim Bundesminister für Verkehr, Bau und Stadtentwicklung, Zeitschrift für Verkehrswissenschaft, **80** (1), p. 1 – 28. (in German)

[Albert et al., 2000] Albert, R., J. Hawoong, A.-L. Barabasi (2000) *Error and attack tolerance of complex networks*, Nature, **406**, p. 378 – 381.

[Albert et al., 2002] Albert, R., A.-L. Barabasi (2002) *Statistical mechanics of complex networks*, Reviews of Modern Physics, **74**, p. 47 – 97.

[Amaral et al., 2000] Amaral, L.A.N., A. Scala, M. Barthélémy, H.E. Stanley (2000) *Classes of small-world networks*, Proceedings of the National Academy of Sciences of the United States of America (PNAS), **97**, p. 11149 – 11152.

[Amaral et al., 2003] Amaral, L.A.N., J.M. Ottino (2003) *Complex systems and networks: challenges and opportunities for chemical and biological engineers*, Chemical Engineering Science, **59**, p. 1653 – 1666.

[Amaral et al., 2004a] Amaral, L.A.N., J.M. Ottino (2004) *Complex networks – Augmenting the framework for the study of complex systems*, European Physical Journal B, **38**, p. 147 – 162.

[Amaral et al., 2004b] Amaral, L.A.N., J.M. Ottino (2004) *Complex systems and networks: challenges and opportunities for chemical and biological engineers*, Chemical Engineering Sciences, **59,** p. 1653 – 1666.

[Anderhub et al., 2008] Anderhub, G., R. Dorbritz, U. Weidmann (2008) *Leistungsfähigkeitsbestimmung öffentlicher Verkehrssysteme*, IVT – Schriftenreihe **139**, Institute for Transport Planning and Systems, ETH Zurich, Zurich. (in German)

[Anthonisse, 1971] Anthonisse, J. M. (1971) *The rush in a directed graph*, Technical Report BN 9 / 71, Stichting Mathematisch Centrum, Amsterdam.

[ARE, 2007] Bundesamt für Raumentwicklung ARE (2007) *Risikoprävention- Voraussetzungen für eine nachhaltige Raumentwicklung*, Informationsheft, forum Raumentwicklung, 3/2007, UVEK, 2007. (in German)

[Barabasi et al., 1999] Barabasi, A.-L., R. Albert (1999) *Emergence of Scaling in Random Networks*, Science, **286**, p. 509 – 512.

[Barrat et al., 2004] Barrat, A., M. Barthélemy, A. Vespignani (2004) *The architecture of complex weighted networks*, Proceedings of the National Academy of Sciences, **101**, p. 3747 – 3752.

[Barthélemy, 2004] Barthélemy, M. (2004) *Betweenness centrality in large complex networks*, European Physical Journal B; **38**, p. 163 – 168.

[BAV, 2010] Bundesamt für Verkehr BAV (2010) *Schnellübersicht – Was muss dem BAV gemeldet werden?, in German, downloaded via http://www.lsy.ch/documents/Meldevorschriften_d.pdf, February 2010.*

[Bearman et al., 2004] Bearman, P.S., J. Moody, K. Stovel (2004) *Chains of affection: The structure of adolescent romantic and sexual networks*, American Journal of Sociology, **110**, p. 44 – 91.

[Boguna et al., 2004] Boguna, M., R. Pastor-Satorras, A. Diaz-Guilera, A. Arenas (2004) *Models of social networks based on social distance attachment*, Physical Review E, **70**, p. 056122.

[Bruneau et al., 2003] M. Bruneau, S.E. Chang, R.T. Eguchi, G. C. Lee, T.D. O'Rourke, A.M. Reinhorn, M. Shinozouka, K. Tierney, W. A. Wallace, D. von Winterfeldt. (2003) *A Framework to Quantitatively Assess and Enhance the Seismic Resilience of Communities*, Earthquake Spectra, **19** (4), p. 733-752.

[Buzna et al., 2006] Buzna, L., K. Peters, D. Helbing (2006) *Modelling the dynamics of disaster spreading in networks*, Paper Physica A, **363**, p. 132 – 140.

[Buzna et al., 2008] Buzna, L, K. Peters, H. Ammoser, C. Kühnert and D. Helbing (2008) *Efficient Response to Cascading Disaster Spreading*, arXiv:physics/0611244v2.

[Caimi, 2009] Caimi, G. C. (2009) *Algorithmic decision support for train scheduling in a large and highly utilised railway network*, Dissertation ETH, 18581, ETH Zurich, Zurich.

[Caldarelli et al., 2004] Caldarelli, G., R. Pastor-Satorras, A. Vespignani (2004) *Structure of cycles and local ordering in complex networks*, European Physical Journal B, **38**, p. 183 – 186.

[CH, 2009] Schweizerische Eidgenossenschaft, Der Bundesrat (2009) *Grundstrategie des Bundesrates zum Schutz Kritischer Infrastrukturen*. (in German)

[Clauset et al., 2009] Clauset, A., C. R, Shalizi, M. E. J. Newman (2009) *Power-law distributions in empirical data*, arXiv: 0706.1062v2, 02.02.2009.

[Cohen et al., 2000] Cohen, R., K. Erez, D. Ben-Abraham, S. Havlin (2000) *Resilience of the Internet to Random Breakdowns*, Physical Review Letters, **85** (21), p. 4626 – 4628.

[Crawley, 2008] Crawley, M.J. (2008) *The R Book*, ISBN 978-0-470-51024-7, John Wiley & Sons Ltd.

[Csardi et al., 2006] Csardi, G., T. Nepusz (2006) *The igraph software package for complex network research*, InterJournal, Complex Systems 1695. http://igraph.sf.net

[Davis et al., 2003] Davis, G-F-. M. Yoo, W.E. Baker (2003) *The small world of the American corporate elite,* 1981 – 2001, Strategic Organisation, **1**, p. 301 – 326.

[Denzler, 2009] Denzler, L. (2009) *Gefahren einschätzen*, TEC 21, **31-32**, p. 3. (in German)

[Ebel et al., 2002] Ebel, H., L.I. Mielsch, S. Bornholdt (2002) *Scale-free topology of e-mail networks*, Physical Review E, **66**, p. 035103.

[EC, 2005] European Commission (2005) *Green Paper on a European Program for Critical Infrastructure Protection*, COM (2005), **576**, Brussels.

[EPJB, 2004] European Physical Journal B (2004) *Virtual Round Table on ten leading questions for network researc*h, European Physical Journal B, **38**, p. 143 – 145.

[ERA, 2007] European Railway Agency (2007) ERA-REC-02-2007-SAF, *Recommendation on the 1st set of common safety methods*.

[EU, 2001a] Official Journal of the European Union (2001) *Directive 2001/16/EC of the European Parliament and the Council of 19th March 2001 on the interoperability of the trans-European conventional rail system*.

[EU, 2001b] Official Journal of the European Union (2001) *Directive 2001/14/EC of the European Parliament and of the Council of 26 February 2001 on the allocation of railway infrastructure capacity and the levying of charges for the use of railway infrastructure and safety certification*.

[EU, 2002] Official Journal of the European Union (2002) *Commission decision of 30 May 2002 concerning a technical specification for interoperability relating to the Control-command and signalling subsystem of the trans-European high-speed rail system*, Official Journal of the European Union, 2002/731/EC.

[EU, 2004] Official Journal of the European Union (2004) *Directive 2004/49/EC of the European Parliament and the Council of 29th April 2001 on safety on the Community's railways and amending Council Directive 95/18/EC on the licensing of railway undertakings and Directive 2001/14/EC on the allocation of railway infrastructure capacity and the levying of charges for the use of railway infrastructure and safety certification*.

[EU, 2006a] Official Journal of the European Union (2006) *Commission regulation concerning the technical specification for interoperability relating to the telematic applications for freight subsystem of the trans-European conventional rail system*, 2006/62/EC.

[EU, 2006b] Official Journal of the European Union (2006) *Commission Decision concerning the technical specification of interoperability relating to the subsystem "Traffic Operation and Management" of the trans-European conventional rail system*, 2006/920/EC.

[EU, 2006c] Official Journal of the European Union (2006) *Commission decision concerning the technical specification for interoperability relating to the control-command and signalling subsystem of the trans-European conventional rail system*, 2006/679/EC.

[EU, 2007] Official Journal of the European Union (2007) *Directive 2008/163/EC concerning the technical specification of interoperability relating to 'safety in railway tunnels' in the trans-European conventional and high-speed rail system*, 2008/163/EC.

[EU, 2008a] Official Journal of the European Union (2008) *Directive of the European Parliament and of the Council on the interoperability of the rail system within the Community*, 2008/57/EC.

[EU, 2008b] Official Journal of the European Union (2008) *Commission decision concerning a technical specification for interoperability relating to the operation subsystem of the trans-European high-speed rail system*, Official Journal of the European Union, 2008/231/EC.

[EU, 2008c] Official Journal of the European Union (2008) *Commission decision concerning a technical specification for interoperability relating to the "infrastructure" subsystem of the trans-European high-speed rail system*, Official Journal of the European Union, 2008/217/EC.

[EU, 2008d] Official Journal of the European Union (2008) *Commission decision of 6 March 2008 concerning a technical specification for interoperability relating to the "energy" subsystem of the trans-European high-speed rail system*, 2008/284/EC.

[EU, 2009] Official Journal of the European Union (2009) *Commission Directive amending Directive 2004/49/EC of the European Parliament and of the Council as regards Common Safety Indicators and common methods to calculate accident costs,* 2009/149/EC.

[EU, 2011] Official Journal of the European Union (2011) *Commission Decision concerning a technical specification for interoperability relating to the "energy" subsystem of the trans-European conventional rail system*, 2011/274/EU.

[Eurostat, 2006] Eurostat (2006) *Statistics in focus, Rail transport accidents in the European Union in 2004*, ISSN 1562-1324, European Communities.

[Ferrer I Cancho et al., 2001] Ferrer I Cancho, R., C. Janssen, R.V. Solé (2001) *Topology of technology graphs: Small world patterns in electronic circuits*, Physical Review E, **64**, p. 046119.

[Freeman, 1977] Freeman, L.C. (1977) *A set of measures of centrality based upon betweenness*, Sociemetry, **40**, p. 35 – 41.

[Garrison et al., 1961] Garrison, W.L., D.F. Marble (1961) *The Structure of Transportation Networks*, Unpublished report for the U.S. Army Transportation Research Command, by the Transportation Center at Northwestern University, p. 140.

[Germroth, 2009] Germroth, H. (2009) *Automatisierung für mehr Sicherheit und Effizienz*. BY RAIL.NOW!, p. 68 – 69. (in German)

[Ghim et al., 2004] Ghim, C.-M., E. Oh, K.-I. Goh, B. Kahng, D. Kim (2004) *Packet transport along the shortest pathways in scale-free networks*, European Physical Journal B, **38**, p. 193-199.

[Gribble, 2001] Gribble, S.D. (2001) *Robustness in complex systems*, Proceedings of the 8th Workshop on Hot Topics in Operating Systems, p. 21 – 26.

[Guillelmon et al., 2004] Guillelmon, B., A. Marti, J.-P. Pfander, J. Riatsch (2004) *Geschäftseinheit Energie und Bahnstromversorgung der SBB AG – Teil 1*, Elektrische Bahnen, **102(**1-2), p. 50 – 57. (in German)

[Harrald, 2007] Harrald, J.R. (2007) *Restoring the National Response System, Fixing the flaws exposed by hurricane Katrina*, TR News, Transportation Research Board on the National Academies, **250**, May-June 2007, p. 9 – 13.

[Helbing et al., 2003] Helbing, D., C. Kühnert (2003) *Assessing interaction networks with applications to catastrophe dynamics and disaster management*, Paper Physica A, **328**, p. 584 – 606.

[Helbing et al., 2005] Helbing, D., H. Ammoser, C. Kühnert, S. Albeverio, V. Jentsch, H. Kantz (Eds.), (2005) *The Unimaginable and Unpredictable: extreme Events in Nature and Society*, Springer, Berlin.

[Helbing, 2007] Helbing, Dirk (2007) *Die Katastrophe verstehen*, ETH Globe, Ausgabe 4/2007, p. 32. (in German)

[Hess et al., 2008] Hess, S., A. Erath, K.W. Axhausen (2008) *Zeitwerte im Personenverkehr: Wahrnehmungs- und Distanzabhängigkeit*, Bundesamt für Strassen (ASTRA), **1322**, Bern. (in German)

[Hornik, 2011] Hornik, K. (2011) *The R FAQ*, ISBN 3-900051-08-9, http://CRAN.R-project.org/doc/FAQ/R-FAQ.html, 16.August 2011.

[Huxham et al., 1996] Huxham, M., S. Beaney, D. Raffaeli (1996) *Do parasites reduce the chances of triangulation in a real food web?*, Oikos, **76**, p. 284 – 300.

[IEC, 2002] International Electrotechnical Commission IEC (2002) *Railway applications: Specification and demonstration of reliability, availability, maintainability and safety (RAMS)*, International standard, IEC 62278.

[IRGC, 2007] IRGC (2007) *White Paper No. 3: Managing and reducing social vulnerabilities from coupled critical infrastructures*, International Risk Governance Council.

[Jansen, 1999] Jansen, D. (1999) *Einführung in die Netzwerkanalyse – Grundlagen, Methoden, Anwendungen*, Leske + Budrich, ISBN 3-8100-2262-4. (in German)

[Jeong et. al., 2001] Jeong, H., S. Mason, A.-L. Barabasi, Z.N. Oltvai (2001) *Lethality and centrality in protein networks*, Nature, **411**, p. 41 – 42.

[Kansky, 1963] Kansky, K.J. (1963) *Structure of Transportation Networks: Relationships Between Network Geometry and Regional Characteristics*, University of Chicago, Chicago.

[KATARISK, 2009] KATARISK (2009) *Katastrophen und Notlagen in der Schweiz – eine Risikobeurteilung aus der Sicht des Bevölkerungsschutzes*. (in German)

[Keegan et al., 2000] Keegan, T., B. Abbot, M. Ruel (2000) *A Risk Management for Ground Hazards along Canadian National Railways*, Conference proceedings, AREMA – American Railway Engineering and Maintenance-of-Way, downloaded via http://www.arema.org/eseries/scriptcontent/custom/e_arema/library/2000_Conference_Proceedings/00045.pdf, February 2010.

[Kooij et al., 2009] Kooij, R., A. Jamakovic, F. van Kesteren, T. de Koning, I. Theisler, P. Veldhoven (2009) *The Dutch Soccer Team as a Social Network*, Connections, **29**, p. 4 – 14.

[Kröger, 2008] Kröger, W. (2008) *Critical infrastructures at risk: A need for a new conceptual approach and extended analytic tools*, Reliability Engineering and System Safety, **93**, p. 1781 – 1787.

[Kröger et al., 2008] Kröger, W., I. Eusgeld, D. Henzi (2008) *Comparative Evaluation of Modelling and Simulation Techniques for Interdependent Critical Infrastructures*, Scientific Report, Laboratory for Safety Analysis, Institute for Energy Technology, ETH Zurich, Zurich.

[Latora et al., 2001] Latora, V., M. Marchiori (2001) *Efficient Behavior of Small-World Networks*, Physical Review Letters, **87**(19), p. 198701-1-198701-4.

[Latora et al., 2002] Latora, V., M. Marchiori (2002) *Is the Boston subway a small-world network?*, Physica A, **314** (2002), p. 109 – 113.

[Leemann, 2005] Leemann, R. (2005) *Stellwerktechnologie und Automation – Rückblick und Stand bei den SBB*, Bulletin SEV / VSE 19/05, in German, p. 3 – 18.

[Leskovec et al., 2007] Leskovec, J., E. Horvitz (2008) *Planetary-scale views on an instant-messaging network*, Microsoft Research Technical Report, MSR-TR-2006-186.

[Leveson, 2001] Leveson, N.G. (2001) *Safeware, System Safety and Computers*, ISBN 0-201-11972-2.

[Liebchen et al., 2009] Liebchen, C., M. Lübbecke, R. Möhring, S. Stiller (2009) *The Concept of Recoverable Robustness, Linear Programming Recovery, and Railway Applications*, Lecture Notes in Computer Science, **5868**, p. 1 – 27.

[Linger et al., 2000] Ellison, R.J., N.R. Mead, T.A. Longstaff, R.C. Linger (2000) *The Survivability Imperative: Protecting Critical Subsystems*, The Journal of Defence Software Engineering, **13**(10), p. 12 – 15.

[Maier, 2010] Maier, C. (2010) *Neues Betriebsleitsystem für BVB und BLT*, Interview with Tobias Beck, Facts 03/2010, p. 17. (in German)

[Martinez, 1991] Martinez, N.D. (1991) *Artifacts or attributes? Effects of resolution on the Little Rock Lake food web*, Ecological Monographs, **61**, p. 367 – 392.

[Milgram, 1967] Milgram, S. (1967) *The small-world problem,* Psychology Today, **2**, p. 60 – 67.

[Moreno et al., 2004] Moreno, Y, A. Vazquez (2003) *Disease spreading in structured scale-free networks*, European Physical Journal B, **31**, p. 265 – 271.

[Moser, 2010] Moser, S. (2010) *Klar, exakt, dynamisch*, Panorama, 03/2010, p. 16-17. (in German)

[Murray-Tuite et al., 2004] Murray-Tuite, P.M., H.S. Mahmassani (2004) *Methodology for Determining Vulnerable Links in a Transportation Network*, Transportation Research Record: Journal of the Transportation Research Board, **1882**, TRB, National Council, Washington, D.C., p. 88 – 96.

[Nagurney et al., 2010] Nagurney, A., Q. Quiang (2010) *Fragile Networks – Identifying Vulnerabilities and Synergies in an Uncertain World*, Wiley.

[Newman et al., 1999] Newman, M.E.J., D.J. Watts (1999) *Scaling and percolation in small-world network model*, Physical Review E, **60** (6), p. 7332 – 7342.

[Newman et al., 2001] Newman, M.E.J., S.H. Strogatz, D.J. Watts (2001) *Random graphs with arbitrary degree distributions and their applications*, Physical Review E, **64**, p. 026118.

[Newman, 2001] Newman, M.E.J. (2001) *The structure of scientific collaboration networks*, Proc. National Academic Sciences USA, **98**, p. 404 – 409.

[Newman, 2003] Newman, M.E.J. (2003) *Mixing patterns in networks*, Physical Review E, **67**, p. 026126.

[Newman, 2010] Newman, M.E.J. (2010) *Networks – An Introduction*, Oxford University Press.

[PCCIP, 1997] President's Commission on Critical Infrastructures (1997) *Critical Foundations: Protecting America's Infrastructures*, The Report of the President's Commission on Critical Infrastructures, Washington D.C., from http://*www.fas.org/sgp/library/pccip.pdf.*

[Perrow, 1984] Perrow, C. (1984) *Normal Accidents – Living with High-Risk Technologies*, Princeton University Press.

[Petermann et al., 2004] Petermann, T., P. De Los Rios (2004) *Exploration of scale-free networks: Do we measure the real exponents?*, European Physical Journal B, **38**, p. 201 – 204.

[Petermann et al., 2011] Petermann, T., H. Bradke, A. Lüllmann, M. Poetzsch, U. Riehm (2011) *Was bei einem Blackout geschieht – Folgen eines langandauernden und grossräumigen Stromausfalls,* Studien des Büros für Technikfolgen-Abschätzung beim Deutschen Bundestag. (in German)

[SBB, 2005] Schweizerische Bundesbahnen SBB (2005) *Der Blackout bei den SBB*, Eisenbahntechnische-Revue 8-9/2005, p. 373-379. (in German)

[SBB, 2010] Schweizerische Bundesbahnen SBB (2010) *Codeliste ErZu*, internal document, not published. (in German)

[Schneider et al., 2011] Schneider, C.M., A.A. Moreira, J.S. Andrade Jr., S. Havlin and H.J. Herrmann (2011) *Mitigation of malicious attacks on networks*, Applied Physical Sciences, www.pnas.org/cgi/doi/10.1073/pnas.1009440108

[Sen et al., 2003] Sen, P., S. Dasgupta, A. Chatterjee, P.A. Sreeram, G. Mukherjee, S.S. Manna (2003) *Small-world properties of the Indian railway network*, Physical Review E, **67**, p. 036106.

[Strogatz, 2001] Strogatz, S.H. (2001) *Exploring complex networks*, Nature, **410**, p. 268 – 276.

[Stutz, 2007] Stutz, M. (2007) *Wenn die Natur den Fahrplan ändert*, via, 08/2007. (in German)

[Tierney et al., 2007] Tierney, K., M. Bruneau (2007) *Conceptualizing and Measuring Resilience: A key to Disaster Loss Reduction*, TR News, Transportation Research Board on the National Academies, **250**, May-June 2007, p. 14 – 17.

[TRB, 2009] National Cooperative Highway Research Program (2009) *Transportation's Role in Emergency Evacuation and Re-entry, A Synthesis of Highway Practice*, NCHRP synthesis, **392**, Transportation Research Board, Washington D.C.

[UNEP, 2009] United Nations Environment Programme (UNEP) (2009) *Maps and Graphics*, http://maps.grida.no/, November 2009.

[Valvoda et al., 2010] Valvoda, W., K. Marschall (2010) *Errichten von Betriebsführungszentralen für die ÖBB*, Signal + Draht, **102**(9), p. 35 – 40. (in German)

[Wägli, 1998] Wägli, H.G. (1998) *Schienennetz Schweiz – Ein technisch-historischer Atlas*, AS Verlag & Buchkonzept AG, Zurich. (in German)

[Wang et al., 2007] Wang, J.-Z., Z.-R. Liu, J. Xu (2007) *Epidemic spreading on uncorrelated heterogeneous networks with non-uniform transmission*, Physica A, **382**, p. 715 – 721.

[Watts et al., 1998] Watts, D.J., S.H. Strogatz (1998) *Collective dynamics of "small-world" networks*, Nature, **393**, p. 440 – 442.

[WEF, 2011] World Economic Forum (2011) *A vision for managing natural disaster risk – Proposals for public/private stakeholder solutions*, World Economic Forum, January 2011.

[Weidmann, 2007] Weidmann, U. (2007) *Betrieb öffentlicher Verkehrssysteme, Band 3.2*, Lecture Notes, Institute for Transport Planning and Systems, ETH Zurich, Zurich. (in German)

[Weidmann, 2008a] Weidmann, U. (2008) *Systemdimensionierung und Kapazität, Band 2.1,* Lecture notes, Institute for Transport Planning and Systems, ETH Zurich, Zurich. (in German)

[Weidmann, 2008b] Weidmann, U. (2008) *System- und Netzplanung, Band 1.1,* Lecture notes, Institute for Transport Planning and Systems, ETH Zurich, Zurich. (in German)

[Weidmann, 2009] Weidmann, U. (2009) *Systemdimensionierung und Kapazität, Band 2.2*, Lecture notes, Institute for Transport Planning and Systems, ETH Zurich, Zurich. (in German)

[Weidmann, 2011] Weidmann, U. (2011) *System- und Netzplanung, Band 1.1,* Lecture notes, Institute for Transport Planning and Systems, ETH Zurich, Zurich. (in German)

[Welt, 2007]: Die Welt Online, (2007) *Wo der Streik Bahn und Wirtschaft hart trifft*, Die Welt Online, http://www.welt.de/wirtschaft/article1340761/Wo_der_Streik_Bahn_und_Wirtschaft_hart_trifft.html. (in German)

[Wittwer, 2010] Wittwer, J. (2010) *Die gefährlichsten Orte der Welt*, Tagesanzeiger, 14.September 2010. (in German)

[Xu et al., 2008] Xu, X.-J., Zhi-Xi W., Yong C., Ying-Hai W. (2008) *Steady States of Epidemic Spreading in Small-World Networks*, Institute of Theoretical Physics, Lanzhou University, Lanzhou Gansu, China.

[Zhu, 2000] Zhu, P.L. (2000) *Betriebliche Leistung von Bahnsystemen unter Störungsbedingungen*, Dissertation, TU Braunschweig, Braunschweig. (in German)

[Ziegler, 2010] Ziegler, R. (2010) *Analyse sozialer Netzwerke – die strukturelle Perspektive, Konzepte, Methoden, Anwendungen*, Lecture Notes, ETH Zurich, Zurich. (in German)

[Zio et al., 2008] Zio, E., G. Sansavini (2008) *A systematic procedure for analysing network systems*, International Journal for Critical Infrastructures, **4**, p. 172 – 184.

11 Glossary

A

Accident [EU, 2004] An unwanted or unintended sudden event or a specific chain of such events which have harmful consequences; accidents are divided into the following categories: collisions, derailment, level-crossing accidents, accidents to persons caused by rolling stock in motion, fires and others.

Accident [Perrow, 1984] Involve damage to subsystems or the system as a whole, stopping the intended output or affecting it to the extent that it must be stopped.

Accident [Leveson, 2001] An undesired and unplanned (but not necessarily unexpected) event that results in (at least) a specified level of loss.

Accident [Linger et al., 2000] Accidents describe a broad range of randomly occurring and potentially damaging events (such as natural disasters), which usually originate outside a system.

Accident to persons caused by Rolling Stock in motion [EU, 2009] Any accident to one or more persons that are either hit by a railway vehicle (or part of it) or hit by an object detached from the vehicle. Persons that fall from railway vehicles are included, as well as persons that fall or are hit by loose objects when travelling on-board vehicles.

Algebraic connectivity [Kooij et al., 2009] The algebraic connectivity is the second smallest eigenvalue of the Laplacian matrix. The Laplacian matrix of a graph g is defined as the difference between a diagonal matrix with the degree of each node on the diagonal minus the adjacency matrix of the graph. The algebraic connectivity serves as a measure for the overall connectivity of a graph. The higher the algebraic connectivity, the more difficult it is to cut a graph into independent components.

Armed conflict [KATARISK, 2009] Event that endangers personal livelihood and cultural heritage through military operations or armed conflict and threatens Switzerland's existence and identity.

Assortativity coefficient [Kooij et al., 2009] A metric that quantifies the correlation between pairs of nodes is the assortativity coefficient. Networks with an assortative coefficient being smaller than zero are disassortative, which means that the nodes connect to other nodes with various degrees. Networks with assortativity coefficient larger than one are called assortative networks. In assortative networks the nodes are more likely to connect to nodes with similar degree.

Attack [Linger et al., 2000] A series of potentially damaging steps taken by an intelligent adversary to achieve an unauthorized result.

Attack [PCCIP, 1997] A discrete malicious action of debilitating intent inflicted by one entity upon another. A threat might attack a critical infrastructure to destroy or incapacitate it.

Automatic train protection (ATP) [EU, 2009] A system that enforces obedience to signals and speed restrictions by speed supervision, including automatic stop at signals.

Availability [EN 50126] Ability of a product to be in a state to perform a required function under given conditions at a given instant of time (or over a given time interval) assuming that the required external resources are provided.

Avalanche [KATARISK, 2009] All types of damage caused by rapid downhill flow of snow or ice in mountainous regions.

B

BA-model (Barabasi-Albert model) [Petermann et al., 2004] Network growth model as new nodes are added at a constant rate and they are connected to existing nodes in the network according to the preferential attachment rule.

Bearer [EU, 2008c] Sleeper designed for use in switches and crossings.

Betweenness centrality [Ghim et al., 2004] Accumulated fraction of total number of shortest paths passing on a vertex over all pairs. A quantification of the centrality especially used in social sciences.

Broken rails [EU, 2009] Any rail which is separated in two (or more) pieces or any rail from which a piece of metal becomes detached, causing a gap of more than 50 mm in length and more than 10 mm in depth on the running surface.

Broken wheels and broken axes [EU, 2009] A break affecting the essential parts of the wheel or the axle and creating a risk of accident (derailment or collision).

Buffers [Liebchen et al., 2009] A good timetable is furnished with buffers to absorb small disturbances, such that they do not affect the planned arrival times at all, or that they cause only few delays in the whole system.

C

Cascading events [Kröger et al., 2008] Situation where an adverse event in one part of an infrastructure snowballs into other parts.

Catastrophic consequence [ERA, 2007] Fatalities and/or multiple severe injuries and/or major damages to the environment resulting from an accident.

Catastrophic hazard [EN 50126] Fatalities and/or multiple severe injuries and / or major damage to the environment.

Causes [EU, 2004] Actions, omissions, events or conditions (or a combination thereof), which led to the accident or incident.

Centrality measure [Ghim et al., 2004] A quantifying measure for the importance of a node especially for transport properties

Chemical accident [KATARISK, 2009] Accident in the production, storage, handling or transport of dangerous chemicals.

Closeness [Kooij et al., 2009] The closeness of a node is the average distance to the other nodes in the graph. Closeness may also be defined as the reciprocal of this quantity. Closeness can be regarded as a measure how long it will take information to spread from a given node to other reachable nodes in the network. The closeness of a node is a measure of centrality. The node with the lowest closeness is called the most central node.

Cluster [Newman, 2010] A connected set of nodes during the percolation process.

Clustering coefficient [Boguna et al., 2004] The clustering coefficient ci of a vertex is given by the ratio between the total number of triangles connected to that vertex e_i, and the total number of possible triangles including it, i.e. where k_i is the number of connections of vertex i (its degree). The clustering coefficient of the network is defined as the average of ci over all the vertices in the network.

Clustering coefficient [Kooij et al., 2009] The clustering coefficient of a node is the proportion of links between the nodes within its neighbourhood divided by the number of edges that could possibly exist between the nodes. The clustering coefficient for the whole network is the average of the clustering coefficient for each node.

Code of practice [ERA, 2007] A written set of rules that, when correctly applied, can be used to close out one or more several particular hazards.

Cold periods [KATARISK, 2009] All types of damage caused by extremely cold weather events including cold temperature, snow and wind damage.

Collision of trains, incl. collisions with obstacles within the clearance gauge [EU, 2009] A front-to-front, front-to-end or a side collision between a part of a train and a part of another train, as well as with shunting stock and fixed (or temporarily present) objects on (or near) the track (except at level crossings if lost by crossing vehicle/user).

Complex interactions [Perrow, 1984] Interactions of unfamiliar sequences (or unplanned and unexpected sequences) and either not visible or not immediately comprehensible.

Complex system [Amaral et al., 2004b] Complex systems typically have a large number of components which may act according to rules that may change over time and that may not be well understood.

Component [Newman, 2010] A connected set of nodes in the underlying network.

Component failure accidents [Perrow, 1984] Involves one (or more) component failures (to a part, unit or a subsystem) that are linked in an anticipated way.

Confined events [Kröger et al., 2008] Occurring failures that have no cascading, escalating or common cause consequences on the considered infrastructures.

Connected graph [Kansky, 1963] The connected graph is a graph that contains no isolated subgraphs.

Contact line system [EU, 2011]: System that distributes the electrical energy to the trains running on the route and transmits it to the trains by means of current collectors.

Control-command and Signalling (Subsystem) [EU, 2008a] All the equipment necessary to ensure safety and to command and control movements of trains authorised to travel on the network.

Coordination [EU, 2001b] The process through which the allocation body and applicants will attempt to resolve situations in which there are conflicting applications for infrastructure capacity.

Costs of damages to the environment [EU, 2009] Costs that are to be met by Railway Undertakings / Infrastructure Managers, appraised on the basis of their experience, in order to restore the damaged area to its state before the railway accident.

Cost of delays as a consequence of accidents [EU, 2009] The monetary value of delays incurred by users of rail transport (passengers and freight customers) as a consequence of accidents, calculated by a model given in [EU, 2009].

Cost of material damage to Rolling Stock or Infrastructure [EU, 2009] The cost of providing new rolling stock or infrastructure with the same functionalities and technical parameters as that damaged beyond repair, and the cost of restoring repairable rolling stock or infrastructure to its state before the accident. Both are to be estimated by Railway Undertakings / Infrastructure Managers on the basis of their experience. Also included costs related to leasing rolling stock, as a consequence of non-availability due to damaged vehicles.

Coupling [Perrow, 1984]

> **Tight coupling:** Mechanical term meaning there is no slack (or buffer or give) between two elements.
>
> **Loose coupling**: Ambiguous (or perhaps flexible) performance standards.

Criticality [EEIG General Glossary] The point at which a failure (or a number of failures) renders the system unusable and / or unsafe.

Critical hazard [EN 50126] Single fatality and/or severe injury and/or significant damage to the environment as well as loss of a major system.

Critical infrastructures [CH, 2009] Infrastructures whose disruption, failure or destruction would have a serious impact on public health, public and political affairs, the environment, security and social and economic well-being.

Critical infrastructures [PCCIP, 1997] Networks of independent, large-scale, man-made systems that function collaboratively and synergistically to produce a continuous flow of essential goods and services.

Current collector [EU, 2011] Equipment fitted to the vehicle and intended to collect current from a contact wire or conductor rail.

--

D

--

Dam break [KATARISK, 2009] Damage caused by fracture failure of dams or flooding, which is at least 10 meters above the low water level and/or ground level, or at least 5 m height above the storage level of a reservoir containing at least 50,000 cubic metres.

Damage indicator [KATARISK, 2009] A measure that allows a fact to be recorded quantitatively.

Danger [Leveson, 2001] Danger is the likelihood of an hazard leading to an accident.

Danger, peril [KATARISK, 2009] (Switzerland) Possible event (or potential development) with a natural, technical or political cause, which threatens the people and their livelihoods, or affects the security interests of Switzerland. (General) Exposure to risk of harm (Encarta World English Dictionary).

Deaths (killed person) [EU, 2009] Any person killed immediately or dying within 30 days as a result of an accident, excluding suicides.

Debilitated [PCCIP, 2007] A condition of defence or economic security characterized by ineffectualness.

Degraded operation [EU, 2008b] Operation resulting from an unplanned event that prevents the normal delivery of train services.

Degree [Kooij et al., 2009] The degree of a node denotes the number of neighbours a node has. The average degree can be easily obtained from the total number of nodes and links.

Degree of a vertex [Ghim et al., 2004] The number of edges connecting to a certain vertex. The vertex degree is a centrality measure.

Degree distribution [Petermann et al., 2004] The histogram of the number of nodes with a given degree.

Degree distribution [Albert et al., 2002] The node degree distribution function P(k) gives the probability that randomly selected node has exactly k edges.

Delay [Liebchen et al., 2009] A delay is any difference between the planned point in time for an event and the time the event actually takes place.

Delay management [Liebchen et al., 2009] The set of operational decisions reacting to concrete disturbances.

Diameter [Kooij et al., 2009] The diameter is the largest distance between any pair of nodes.

Diameter [Newman, 2010] The diameter of a graph is the length of the longest geodesic path between any pair of vertices in the network for which a path actually exists.

Disconnected graph [Kansky, 1963] A graph is disconnected if it contains two or more isolated subgraphs.

Distance (graph theory) [Albert et al., 2002] The distance between two nodes is defined as the number of edges along the shortest path connecting them.

Distance (graph theory) [Kooij et al., 2009] The distance between a pair of nodes is the length of the shortest path between the nodes. The average distance is the distance averaged over all pairs of nodes.

Distance between track centres [EU, 2008c] Horizontal distance between the centres of two adjacent tracks.

Disturbance [Liebchen et al., 2009] Initial changes of planning data.

Driver [EU, 2008b] A person competent and authorized to drive trains.

Dry or hot weather [KATARISK, 2009] All types of damage caused by extremely hot or dry weather.

E

Earthquake [Encarta World English Dictionary] A violent shaking of the Earth's crust resulting from a sudden release of tectonic stress or volcanic activity.

Eccentricity [Kooij et al., 2009] The eccentricity of a node is the largest distance to any other node in the graph. The eccentricity of the graph is the average of all nodes.

Edge [Kansky, 1963] An edge is an element of the graph G such that e lies in G. It is a continuous line between two vertices.

Employees [EU, 2009] Any person whose employment is in connection with a railway and is at work at the moment of the accident. It includes the crew of the train and persons handling rolling stock and infrastructure installations.

Energy (Subsystem) [EU, 2008a] The electrification system, including overhead lines and on-board parts of the electric consumptions measuring equipment.

Epidemic [Encarta World English Dictionary] An outbreak of a disease that spreads more quickly and more extensively than would otherwise be expected.

Error [Leveson, 2001] Design flaw or deviation from a desired or intended state.

Error [EEIG General Glossary] A deviation from the intended design, which could result in unintended system behaviour or failure.

Escalating events [Kröger et al., 2008] An extended result of a cascading event, i.e. an occurred "problem" in one infrastructure may snowball into other infrastructures causing their malfunction or disruption or exacerbating an independent disturbance in another infrastructure or time of recovery. This in turn may affect the restoration of service provided by the initially defective infrastructure.

Essential requirements [EU, 2008a] All the conditions, which must be met by the rail system, the subsystems and the interoperability constituents, including interfaces.

Event class [KATARISK, 2009] Damage scale for any type of indicator. The classes indicate what level of damage a specific event, disaster or emergency causes for an "average" community, region, canton or for the country as a whole

Existing rail system [EU, 2008a] The structure composed of lines and fixed installations of existing rail system plus the vehicles of all categories and origin travelling on that infrastructure.

Extensive disruption to traffic [EU, 2009] Train services on a main railway line are suspended for six hours and more.

Extent of damage [KATARISK, 2009] A quantitative assessment of the level of damage caused by incidents or events using defined indicators.

F

Failure [Leveson, 2001] Non-performance or inability of the system (or component) to perform its intended function for a specified time under specified environmental conditions.

Failure [EEIG General Glossary] Effect of an error on the intended service.

Failure [EN 13306:2001] Termination of the ability of an item to perform a required function.

Failure [Linger et al., 2000] A potentially damaging event resulting from deficiencies in a system or in an external element on which the system depends.

Fault [IEC, 2002] An abnormal condition that could lead to an error in a system. A fault can be random or systematic.

Fault [EN 13306:2001] State of an item characterized by the inability to perform a required function, excluding the inability during preventive maintenance or other planned actions, or due to lack of external resources.

Fault detection time [EEIG General Glossary] Time span that begins at the instant when a fault occurs and ends when the existence of the fault is detected.

Fault negation time [EEIG General Glossary] Time span that begins when the existence of a fault is detected and ends when a safe state is enforced.

Fire [KATARISK, 2009] Fires of all types, except for fires involving dangerous goods.

Fires in Rolling Stock [EU, 2009] Fires and explosions that occur in railway vehicles (including their load) when they are running between the departure station and the destination, including when stopped at the departure station, the destination or the intermediate stops, as well as during re-marshalling operations.

Flood [KATARISK, 2009] All types of damage caused by heavy rainfall events including flooding, riverbank erosion and landslides.

Forecast time [EU, 2006a] Best estimate of arrival, departure or passing time of a train.

Forest fire [KATARISK, 2009] Forest and bush fires.

Frequency, probability [KATARISK, 2009] Expected number of events per time period, often per year. For infrequent events the frequency is expressed as probability.

Frequent hazardous event [EN 50126] Like to occur frequently. The hazard will be continually experienced.

G

Graphs [Kansky, 1963] Graphs, defined sets of systematically organized points and lines, are visual similar representations of abstract concepts and relations.

Ground shift [KATARISK, 2009] This includes all types of ground motion such as avalanches, falling rocks and glacier tailings as well as spontaneous ground motion as long as these are not caused by an earthquake, flood or lighting storm.

H

Hazard [EN 50126] Physical situation with a potential for human injury and/or damage to environment.

Hazard [ERA, 2007] A condition that can lead to an accident.

Hazard [Leveson, 2001] A state or set of conditions of a system (or an object) that, together with other conditions in the environment of the system (or object), will lead inevitably to an accident (loss event).

Hazard identification [ERA, 2007] The process to find, list and characterize hazards.

Hazard log [EN 50126] Document in which all safety management activities, hazards identified, decisions made and solutions adopted are recorded or referenced. Also known as „safety log".

Hub [Terminology on combined transport, 2001] Central point for the collection, sorting, transhipment and distribution of goods for a particular area. The term describes collection and distribution through a single point.

Hub node [Petermann et al., 2004]Nodes with a very high degree compared to the other nodes.

Human error [Leveson, 2004] Any deviation from the performance of a specified or prescribed sequence of actions.

Human factors [IEC, 2002] The impact of human characteristics, expectations and behaviour upon a system.

I

Improbable hazardous event [IEC, 2002] Unlikely to occur but possible. It can be assumed that the hazard may exceptionally occur.

Incapacitation [PCCIP, 2007] An abnormal condition when the level of products and services a critical infrastructure provides its customers is reduced. While typically a temporary condition, an infrastructure is considered incapacitated when the duration of reduced performance causes a debilitating impact.

Incident [EU, 2004] Any occurrence (other than accident or serious accident) associated with the operation of trains and affecting the safety of operation.

Incident [Perrow, 1984] Involved damage to or failures of parts or a part only, even though the failure may stop the output of a system or affect it to the extent that it must be stopped.

Incident (near loss) [Leveson, 2001] An event that involves no loss (or only minor loss) but with the potential for loss under different circumstances.

Incredible hazardous event [IEC, 2002] Extremely unlikely to occur. It can be assumed that the hazard may not occur.

Infrastructure [EU, 2008a] The track, points, engineering structures (bridges, tunnels...) associated station infrastructure (platforms, zones of access, including the needs of persons with reduced mobility etc.), safety and protective equipment.

Infrastructure capacity [EU, 2001b] The potential to schedule train paths requested for an element of infrastructure for a certain period.

Injuries (seriously injured person) [EU, 2009] Any person injured who was hospitalised for more than 24 hours as a results of an accident, excluding attempted suicides.

Insignificant hazard [IEC, 2002] Possible minor injury as well as minor system damage.

Intent [PCCIP, 2007] Demonstrating a deliberate serous of actions with the objective of debilitating defence or economic security by destroying or incapacitating a critical infrastructure.

Interfaces [ERA, 2007] All points of interaction during a system life cycle (including operation and maintenance), where different actors of the rail sector will have to jointly work together in order to manage the risks.

Internet [EU, 2006a]

1. Any large network made up of several small networks.
2. A group of networks that are interconnected so that they appear to be one continuous large network, and can be addressed seamlessly at the OSI model network layer through routers.
3. The industry name for the network, used as a reference resource for e-mail and an online chat room for users around the world.

Interoperability [EU, 2008a] The ability of the trans-European conventional rail system to allow the safe and uninterrupted movement of trains which accomplish the required levels of performance for these lines. This ability depends on all the regulatory, technical and operational conditions, which must be met in order to satisfy the essential requirements.

Interoperability constituents [EU, 2008a] Any elementary component, group of components, subassembly or complete assembly of equipment incorporated or intended to be incorporated into a subsystem, upon which the interoperability of the trans-European conventional rail system depends directly or indirectly. The concept of a "constituent" covers both tangible objects and intangible objects such as software.

Interoperability, Operational [EEIG General Glossary] The ability to enable the international safe running of trains on different European networks without having to stop the train at borders, changing the engine at borders and changing the driver at borders, requiring the train driver to perform any other activity other than the standardized ERTMS operation.

Intolerable risk [IEC, 2002] Risks that shall be eliminated.

L

Latency [Leveson, 2001] Hazard duration.

Level crossing [EU, 2009] Any level intersection between the railway and a passage, as recognized by the infrastructure manager and open to public or private users. Passages between platforms between stations are excluded, as well as passages over tracks for the sole use of employees.

Level crossing [EU, 2008c] An intersection at the same elevation of a road and one or more rail tracks.

Level crossing accident [EU, 2009] Any accident at level crossing involving at least one railway vehicle and one or more road vehicles, other users of the road such as pedestrians or other objects temporarily present at or near the track.

Line-km [EU, 2009] The length, measured in kilometres of the railway network in Member States. For multiple-track railway lines, only the distance between origin and destination is to be counted.

Linear interactions [Perrow, 1984] Interactions in expected and familiar production or maintenance sequence and those that are quite visible even if unplanned.

Link density [Kooij et al., 2009] The link density is the ratio of the number of links and the total number of possible links.

Load [Ghim et al., 2004] The load of a vertex is defined as the total amount of data packets passing through that vertex when all pairs of vertices send and receive one unit of data packets between them. Data packets are sent along shortest paths. If there is more than one shortest path, data packages are equally split among the paths.

M

Maintainability [IEC, 2002] Probability that a given active maintenance action for an item under given conditions of use can be carried out within a stated time interval, when the maintenance is performed under stated conditions and using stated procedures and resources.

Maintainability [EN 13306:2001] Ability of an item under given conditions of use, to be retained in, or restored to, a state in which it can perform a required function, when maintenance is performed under given conditions and using stated procedures and resources.

Maintenance [IEC, 2002] The combination of all technical and administrative actions (including supervisions actions) intended to retain an item in (or restore it to) a state in which it can perform a required function.

Maintenance [EU, 2008a] The procedures, associated equipment, logistics centres for maintenance work and reserves allowing the mandatory corrective and preventive maintenance to ensure the interoperability of the rail system and guarantee the performance required.

Major failure [IEC, 2002] A failure that must be rectified for the system to achieve its specified performance and does not cause a delay or cost greater than the minimum threshold specified for a significant failure.

Marginal hazard [IEC, 2002] Minor injury and/or significant threat to the environment as well as severe system(s) damage.

Means [KATARISK, 2009] Resources available to address an event (including personnel, material, equipment and vehicles).

Meteorite [Encarta World English Dictionary] A meteorite is a piece of rock that has reached the earth from outer space (asteroids, comets, meteors).

Minor failure [IEC, 2002] A failure that does not prevent a system achieving its specified performance and does not meet criteria for significant or major failures.

Minor incident [KATARISK, 2009] A minor incident is an incident that can be solved using local or regional resources.

Mission [IEC, 2002] Objective description of the fundamental task performed by a system.

Mission profile [IEC, 2002] Outline of the expected range and variation in the mission with respect to parameters (such as time, loading, speed, distance, stops, tunnels etc.) in the operational phases of the life cycle.

Most central node [Kooij et al., 2009] The node with the lowest closeness is called the most central node.

N

Negligible risk [IEC, 2002] Acceptable with/without the agreement of the Railway Authority.

Network [EU, 2001b] The entire railway infrastructure owned and / or managed by an infrastructure manager.

Network [EU, 2008a] The lines, stations, terminals and all kinds of fixed equipment needed to ensure safe and continuous operation of the rail system.

Network [Newman, 2010] A network is a simplified representation that reduces a system to an abstract structure capturing only the basics of connection patterns and little else.

Networks (Mathematical) [Kooij et al., 2009] A network is a represented as directed or undirected graphs with a set of nodes that are connected by links.

O

Occasional hazardous event [IEC, 2002] Likely to occur several times. The hazard can be expected to occur often.

Other types of accidents [EU, 2009] All accidents other than train collisions, train derailments, at level crossing, to persons caused by rolling stock in motion and fires in rolling stock.

Others (third parties) [EU, 2009] All persons not identified as “passengers”, “employees”, “level crossing users” or “unauthorized persons on railway premises”.

Overhead contact line [EU, 2011] Contact line placed above (or beside) the upper limit of the vehicle gauge and supplying vehicles with electric energy through the roof-mounted current collection equipment.

P

Part (of a system) [Perrow, 1984] Smallest component of a system that is likely to be identified in analysing an accident.

Passage [EU, 2009] Any public or private road, street or highway (including footpaths and bicycle paths) or other route provided for the passage of people, animals, vehicles or machinery.

Passenger-km [EU, 2009] The unit of measure representing the transport of one passenger by rail over a distance of one kilometre. Only the distance on the national territory of the reporting country shall be taken into account.

Passenger [EU, 2009] Any person, excluding members of the train crew, who makes a trip by rail. For accident statistics, passengers trying to embark / disembark onto / from a moving train are included.

Passenger [EU, 2008b] Person (other than an employee with specific duties on the train) travelling by train or on railway property before or after a train journey.

Passive level crossing [EU; 2009b] A level crossing without any form of warning system and / or protection activated when it is unsafe for the user to traverse the crossing.

Path [EU, 2006a] Path means the infrastructure capacity needed to run a train between any two places over a given time period, i.e. the route is defined in time and space.

Path [Newman, 2010] A path in a network is any sequence of vertices such that every consecutive pair of vertices in the sequence is connected by an edge in the network. The length of a path is the number of edges traversed along the path.

Person killed [Eurostat, 2006] Any person killed immediately or dying within 30 days as a result of an accident, excluding suicides. It includes passengers, employees and other persons (specified or unspecified) involved in a rail injury accident.

Person seriously injured [Eurostat, 2006] Any person injured who was hospitalized for more than 24 hours as a result of an accident, excluding attempted suicides.

Plain line [EU, 2008c] Section of track without switches and crossings.

Preferential attachment [Petermann et al., 2004] An existing network node has a probability to attach to a new occurring node that is proportional to its degree. Preferential attachment is used in the network growth process, especially for deriving scale-free networks.

Preventive maintenance [IEC, 2002] Maintenance carried out at predetermined intervals or according to prescribed criteria and intended to reduce the probability of failure or the degradation of the functioning of an item

Probable hazardous event [IEC, 2002] Will occur several times. The hazard can be expected to occur often.

R

Railway accidents [KATARISK, 2009] Railway accidents are all types, except for accidents involving chemicals.

Railway system [EU, 2004] A railway system is the totality of the subsystems for structural and operational areas as well as the management and operation of the system as a whole.

Rail passenger [Eurostat, 2006] Any person (excluding members of the train crew), who makes a trip by rail. For accident statistics, passengers trying to embark / disembark onto / from a moving train are included.

Rail system (Trans-European conventional Rail System) [EU, 2001a] The structure composed of lines, fixed installations of the trans-European transport network, built or upgraded for conventional rail transport and combined rail transport, plus the rolling stock designed to travel on that infrastructure.

Railway transport [Glossary for Transport Statistics] Railway transport is any movement of goods and/or passenger using a railway vehicle on a given railway network.

RAMS [IEC, 2002] Acronym meaning a combination of Reliability, Availability, Maintainability and Safety.

Rapidity [Tierney et al., 2007] Rapidity is the capacity to restore functionality in a timely way, containing losses and avoiding disruptions.

Recognition [Linger et al., 2000] Recognition is the system's capability to detect attacks as they occur and to evaluate the extent of damage and compromise.

Recovery [Linger et al., 2000] Recovery is the capability to maintain essential services and assets during attack, limit the extent of damage, and restore full services following attack.

Redundancy [Tierney et al., 2007] The extent to which systems, system elements or other units are substitutable, that is, capable of satisfying functional requirements, if significant degradation or loss of functionality occurs.

Redundancy [EEIG General Glossary] The provision of one or more additional elements (usually identical) to achieve or maintain availability if one or more of those elements "malfunctions".

Redundancy [EN 13306:2001] Redundancy describes the existence of more technical means than necessary for the required function.

Region [KATARISK, 2009] A region is an area that includes several towns and/or undeveloped areas of a Canton.

Regular network [Newman, 2010] Regular networks are networks in which all vertices have the same degree.

Reliability [IEC, 2002] Probability that an item can perform a required function under given conditions for a given time interval (t1, t2).

Reliability [Leveson, 2001] Probability that a piece of equipment or component will perform its intended function satisfactorily for a prescribed time and under stipulated environmental conditions.

Reliability [EN 13306:2001] Ability of an item to perform a required function under given conditions for a given time interval.

Renewal [EU, 2008a] Any major substitution work on a subsystem or part subsystem which does not change the overall performance of the subsystem.

Reliability and maintainability program [IEC, 2002] Documented set of time scheduled activities, resources and events serving to implement the organization structure, responsibilities, procedures, activities, capabilities and resources that together ensure that an item will satisfy given reliability performance and maintainability performance requirements relevant to a given contract or project.

Remote hazardous event [IEC, 2002] Likely to occur sometime in the system life cycle. The hazard can reasonably expected to occur.

Repair [IEC, 2002] That part of a corrective maintenance in which manual actions are performed on the item.

Resilience [Tierney et al., 2007] The ability of social units (e.g. organizations, communities) to mitigate hazards, contain the effects of disasters when they occur and carry out recovery activities in ways that minimize social disruption and mitigate the effects of future disasters.

Resistance [Linger et al., 2000] Resistance is the capability of a system to repel attacks.

Resourcefulness [Tierney et al., 2007] The ability to diagnose and prioritize problems and to initiate solutions by identifying and mobilizing material, monetary, informational, technological and human resources.

Restoration [IEC, 2002] The event when the item regains the ability to perform a required function after a fault

Return Circuit [EU, 2011]: All conductors, which form the intended path for the traction, return current and the current under fault conditions.

Risk [IEC, 2002] Probable rate of occurrence of a hazard causing harm and the degree of severity of the harm

Risk [Leveson, 2001] Hazard level combined with the likelihood of the hazard leading to an accident (sometimes called danger) and the hazard exposure or duration (sometimes called latency).

Risk acceptance criteria [ERA, 2007] The terms of reference by which the acceptability of risk is assessed. These are criteria that are used to determine the level of a risk is low enough that it is not necessary to take any immediate action to reduce it further.

Risk acceptance principle [ERA, 2007] The rules used in order to arrive to the conclusion that the risk is related to on or several specific hazards are acceptable.

Risk analysis [ERA, 2007] Systematic use of all available information to identify hazards and to estimate the risk.

Risk analysis [KATARISK, 2009] Risk analysis is the science of risks and their probability and evaluation. It is the most valuable and judgement free part of a safety assessment. It systematically evaluates and describes the risks in any activity using a defined format based on predefined levels of damage and frequency.

Risk assessment [ERA, 2007] The overall process comprising a risk analysis and a risk evaluation.

Risk assessment [KATARISK, 2009] A method for evaluating the risk and acceptability of incidents. Among the characteristics considered are independent versus outside control and usefulness.

Risk aversion [KATARISK, 2009] The aversion to disasters and emergencies. Events that cause significant damage are much more visible and taken more seriously than the much more numerous accidents that do little damage.

Risk aversion factors [KATARISK, 2009] Factors taking into account risk aversion against disasters and emergencies. They take on larger values as the severity of incidents increases.

Risk concept [IEC, 2002] The concept of risk is the combination of two elements: The probability of occurrence of an event or combination of events leading to a hazard, or the consequence of the hazard.

Risk estimation [ERA, 2007] The process used to produce a measure of the level of risks being analysed. Risk Estimation consists of the following steps: Frequency, Consequence Analysis and their integration.

Risk evaluation [ERA, 2007] A procedure based on the risk analysis to determine whether the tolerable risk has been achieved.

Risk management [ERA, 2007] The systematic application of management policies, procedures and practices to the task of analysing, evaluating and controlling risk.

Robustness [Tierney et al., 2007] Ability of systems, system elements and other units of analysis to withstand disaster forces without significant degradation or loss of performance.

Rolling Stock [EU, 2008a] Structure, command and control system for all train equipment, current-collection devices traction and energy conversion units, braking, coupling and running gear and suspension, doors, man/machine interfaces, active or passive safety devices and requisites for the health of passengers and on—board staff.

Route [EU, 2008b] The particular section or sections of line.

Route [EU, 2006a] The geographical way to be taken from a starting point to a point of destination.

S

Safety [IEC, 2002] Freedom from unacceptable risk of harm.

Safety [Leveson, 2001] Freedom from accidents or losses.

Safety case [IEC, 2002] Documented demonstration that the product complies with the specified safety requirements.

Safety integrity [IEC, 2002] Likelihood of a system satisfactorily performing the required safety functions under all the stated conditions within a stated period of time.

Safety measures [ERA, 2007] A set of actions either reducing the rate of occurrence of a hazard or mitigating its consequences in order to achieve and / or maintain an acceptable level of risk.

Safety plan [IEC, 2002] Documented set of time-scheduled activities, resources and events serving to implement the organizational structure, responsibilities, procedures, activities, capabilities and resources that together ensure that an item will satisfy given safety requirements relevant to a given contract or project.

Safety requirements [ERA, 2007] The necessary safety characteristics (qualitative and quantitative) of a system and its operation (incl. operational rules) in order to meet e.g. legal or company safety targets.

Scheduled timetable [EU, 2006a] Chronologically defined occupation of railway infrastructure for a train movement on open line or in stations. Changes to the timetable will be supplied by the infrastructure managers at least two days before the commencement of the day when the train departs from its origin. This timetable applies for a specific day.

Serious accident [EU, 2004] Any train collision or derailment of trains, resulting in the death of at least one person or serious injuries to five or more persons or extensive damage to rolling stock, the infrastructure or the environment, and any other similar accident with an obvious impact.

Serious injury accident [Eurostat, 2006] Any accident involving at least one rail vehicle in motion, resulting in at least one killed or seriously injured person. Accidents in workshops. Warehouses and depots are excluded.

Signals passed at danger [EU, 2009] Any occasion when any part of a train proceeds beyond its authorized movement. Cases in which vehicles without any traction unit attached or a train that is unattended run away past a signal at danger are not included. Cases in which, for any reason, the signal is not turned to danger in time to allow the driver to stop the train before the signal are not included.

Significant failure [IEC, 2002] A failure that prevents train movement or causes a delay to service greater than a specified time and/or generates a cost greater than a specified level.

Significant accident [EU, 2009] Any accident involving at least one rail vehicle in motion, resulting in at least one killed or seriously injured person, or in significant damage to stock, track, other installations or environment, or extensive disruptions to traffic. Accidents in workshops, warehouses and depots are excluded.

Significant damage to stock, track, other installations or environment [EU, 2009] Damage that is equivalent to EUR 150’000 or more.

SIS-model [Moreno et al., 2004] An epidemiological model in which each node can exist in two possible states: susceptible (=healthy) and infected. Individual’s removal due to death or immunization is not allowed.

Small-world network [Albert et al., 2002] The small-world concept in simple terms describes the fact that despite their large size, in most networks there is a relatively short path between any two nodes. The small-world property appears to characterize most complex networks. The small –world concept is not an indication of a particular organizing principle.

Staff [EU, 2008b] Employees working for a railway undertaking or an Infrastructure Manager, or their contractors, undertaking tasks as specified in the TSI’s.

State of emergency [KATARISK, 2009] Situation, caused by social interaction, accident or other incident (e.g. weather) that cannot be effectively addressed using the available procedures because the affected community’s human and material resources are overwhelmed.

Station [EEIG General Glossary] A place where trains stop or where loading and unloading occurs and where assistance may be available. Where there can be points that make it possible for the train to use different routes.

Structure [Garrison et al., 1961] The term structure denotes the layout, geometry, or network pattern of transportation facilities or systems.

Subsystems (of the railway system) [EU, 2008a] The result of the division of the trans-European conventional rail system into structural areas (infrastructure, energy, Control-command and signalling, rolling stock) and operational (traffic operation and management, maintenance, telematics applications for passenger and freight services) areas. These subsystems, for which the essential requirements must be laid down, may be structural or functional.

Subsystem (of systems) [Perrow, 1984] An array of units of a system.

Subsystem [EEIG General Glossary] A combination of equipment, units, assemblies etc., which performs an operational function and is a major subdivision of the system.

Subgraph [Kansky, 1963] A subgraph S is a graph which is contained in the graph G such that every element of the subgraph S is an element of G and some elements of the graph G are elements of the subgraph S.

Suicide [EU, 2009] An act to deliberately injure oneself resulting in death, as recorded and classified by the competent national authority.

Superspreader [Wang et al., 2007] Node with a very high infectivity.

Swing nose [EU, 2008c] A crossing in which the crossing nose can be moved laterally to close the flangeway to provide continuous support to wheelsets.

System [Perrow, 1984] Systems are divided into four levels of increasing aggregation: Units, Parts, Subsystems and System.

System [IEC, 2002] Assembly of subsystems and components, connected together in an organized way, to achieve a specified functionality. A system responds to inputs to produce specified outputs, whilst interacting with an environment.

System [EEIG General Glossary] A composite of equipment, skills and techniques capable of performing or supporting an operational role, or both. A complete system includes all equipment, related facilities; material, software, services and personnel required for its operation and support to the degree that it can be considered a self-sufficient unit in its intended operational environment.

System accident [Perrow, 1984] Involve the unanticipated interaction of multiple failures.

Systematic failures [IEC, 2002] Failures due to errors in any safety life cycle activity, within any phase, which cause it to fail under some particular combination of inputs or under some particular environmental condition.

--

T

--

Technical specification for interoperability (TSI) [EU, 2004] The specifications by which each subsystem or part of the rail system is covered in order to meet the essential requirements and ensure the interoperability of the trans-European high-speed and conventional rail systems.

Technical system [ERA, 2007] A product (or an assembly of products) including the design, implementation and support documentation.

Telematics Applications [EU, 2008a] Subsystem comprising two elements: Applications for passenger services (incl. systems providing passengers with information before and during the journey, reservation and payment systems, luggage management and management of connections between trains and with other modes of transport) and applications for freight services (incl. information systems, marshalling and allocation systems, reservation, payment and invoicing systems, management of connection with other modes of transport and production of electronic accompanying documents).

Terrorism [EU, 2007] A deliberate and premeditated act, which is designed to cause wanton destruction, injury and loss of life.

Threat [PCCIP, 2007] A foreign or domestic entity possessing both the capability to exploit a critical infrastructure's vulnerabilities and the malicious intent of debilitating defence or economic security.

Thunderstorm (Lightning, Hail) [KATARISK, 2009] All damages caused by thunderstorms and hailstorms.

Timetable [EU, 2008b] Document or system that gives details of a train(s) schedule over a particular route.

Tolerable risk [IEC, 2002] Maximum level of risk of a product that is acceptable to the Railway Authority.

Track buckles [EU, 2009] Faults related to the continuum and the geometry of track, requiring track obstruction or reduction of permitted speed immediately to maintain safety.

Track centre [EU, 2008c] The middle point between two rails in the plane of the running surface.

Track gauge [EU, 2008c] Distance between the gauge points of the two opposite rails of a track.

Track-km [EU, 2009] The length measured in kilometres of the railway network in the Member States. Each track of a multiple railway line is to be counted.

Traction Unit [EEIG General Glossary] Vehicle from where a train is operated.

Traffic Operation and Management (subsystem) [EU, 2008a] The procedures and related equipment enabling a coherent operation of the different structural subsystems, both during normal and degraded operation, including in particular marshalling and train driving, traffic planning and management.

Train-km [EU, 2009] The unit of measure representing the movement of a train over one kilometre. The distance used is the distance actually run, if available, otherwise the standard network distance between the origin and destination shall be used. Only the distance on the national territory of the reporting country shall be taken into account.

Train [EEIG General Glossary] A traction unit with or without coupled railway vehicles or a train set of vehicles with train data available.

Train [EU, 2008b] A traction unit(s) with or without coupled railway vehicles, or a self-propelled set of vehicles, with a train data available between two or more defined points of the TEN.

Train [EU, 2009] One or more railway vehicles hauled by one or more locomotives or railcars, or one railcar travelling alone, running under a given number or specific designation from an initial fixed point to a terminal fixed point. A light engine, i.e. a locomotive travelling on its own, is considered to be a train.

Train crew [EU, 2008b] Members of the on-board staff of a train, who are certified as competent and appointed by a Railway Undertaking to carry out specific, designated safety-related tasks on the train, for example the driver or the guard.

Train derailment [EU, 2009] Any case in which at least one wheel of a train leaves the rails.

Train integrity [EU, 2002] The status of completeness of the train according to operational rules.

Train path [EU, 2001b] The infrastructure capacity needed to run a train between two places over a given time-period.

Train path [EU, 2006a] Train route defined in time and space.

Train preparation [EU, 2008b] Ensuring that a train is in a fit condition to enter service, that the train equipment is correctly deployed and the formation of the train matches the train's designated pathway. Train preparation also includes technical inspections carried out prior to the train entering service.

Transportation [PCCIP, 2007] A critical infrastructure characterized by the physical distribution system critical to supporting the national security and economic well-being.

Tree [Kansky, 1963] A tree is a connected graph of at least two vertices such that the graph does not contain any circuit.

TSI (Technical Specification for Interoperability) [EU, 2008a] A specification adopted in accordance with Directive 2008/57/EC by which each subsystem or part subsystem is covered in order to meet the essential requirements and ensure the interoperability of the rail system.

--

U

--

Unauthorized persons on railway premises [EU, 2009] Any person present on railway premises where such presence is forbidden, with the exception of level crossing users.

Undesirable risk [IEC, 2002] Shall only be accepted when risk reduction is impracticable and with the agreement of the Railway Authority or the Safety Regulatory Authority, as appropriate.

Unit (of a System) [Perrow, 1984] A functionally related collection of parts.

Upgrading [EU, 2008a] Any major modification work on a subsystem or part subsystem, which improves the overall performance of the subsystem.

--

V

--

Validation [IEC, 2002] Confirmation by examination and provision or objective evidence that the particular requirements for a specific intended use have been fulfilled.

Value of preventing a casualty (VPC) [EU, 2009] The value society attributes to the prevention of a casualty and as such shall not form a reference for compensation between parties involved in accidents.

Vehicle [EU, 2008a] A railway vehicle that runs on its own wheels on railway lines, with or without traction. A vehicle is composed of one or more structural and functional subsystems or parts of such subsystems.

Vehicle [EU, 2008b] Any single item of rolling stock, for example a locomotive, carriage or wagon.

Verification [IEC, 2002] Confirmation by examination and provision of objective evidence that the specified requirements have been fulfilled.

Vertex [Kansky, 1963] A vertex (or node or point) is an element of a graph and represents a point of intersection of the edges.

Victims [Perrow, 1984]

First-Party Victims: Operators of the system

Second-Party Victims: Victims associated with the systems as suppliers or users, but without influence over it.

Third-Party Victims: Innocent, unaware bystanders.

Fourth-Party Victims: Victims of radiation and toxic chemicals, foetuses being carried out, future victims.

Vigilance [EU, 2002] Vigilance ensures that the driver of a train is sufficiently alert (and by implication sufficiently alert to be aware of the signalling). Vigilance is a safety-related system in the sense that they support the driver and provide protection to the train in the event of human inadequacy.

Vulnerability [EC, 2005] A flaw or weakness in the design, implementation, operation and/or management of an infrastructure or its elements that renders it susceptible to destruction or incapacitation by a threat.

W

Wagon [2006/0278/EC] Any rail vehicle without its own means of propulsion that runs on its own wheels on railway tracks and is used for the carriage of goods.

Web [EU, 2006a] World-Wide Web, i.e. an internet service that links documents by providing hypertext links from server to server so a user can jump from document to related document no matter where it is stored in the internet.

Wind storm [KATARISK, 2009] Any type of damage caused by a windstorm. Hurricanes and cyclones are not considered in Switzerland.

12 Appendix

A 1 Curriculum Vitae

Robert Dorbritz

Born 24th November 1981 in Magdeburg (Germany)
Citizen of Germany

Practical experience

2006 – 2012
Research Assistant at the ETH Zurich,
Institute for Transport Planning and Systems, Chair for Transportation Systems

2006
Internship at the Göttinger Verkehrsbetriebe (GöVB)

2005 – 2006
Student assistant at the University of Kaiserslautern,
Institute for Integrated Communication Systems

2004 – 2006
Student assistant at the University of Göttingen,
Numerical Institute for Applied Mathematics

2000 – 2001
Civilian service at the Hospital of Vogelsang

Higher education

2001 – 2006
Study of Economathematics at the University of Kaiserslautern, focussing on Optimization, Statistics and Optimization in transport networks

1992 – 2000
Grammar school at the Europagymnasium Gommern and Abitur

A 2 Cumulative node-degree distributions

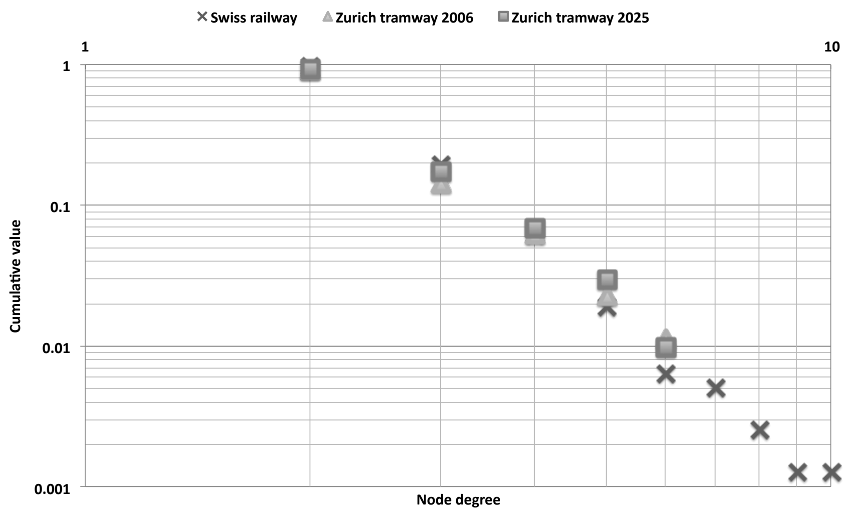
Cumulative degree distribution functions are used for detecting whether the node-degree distribution decays as a power law, i.e. $P(k) \sim k^{-\gamma}$ with P(k) denoting the probability that a node is incident with k edges. According to [Newman, 2010], a *«solution to the problem of visualizing a power-law distribution is to construct the cumulative distribution function, which is defined by: »*

$$P(k) = \sum_{k'=k}^{\infty} p_{k'}$$

where $p_{k'}$ = fraction of nodes with degree k'.

For all analysed networks, Figure 104 shows the curve of the cumulative node-degree distributions for degrees being at least 2. All curves seem to follow straight lines in a plot with both axes being logarithmically scaled. This indicates that the analysed networks are scale-free networks. However, the data set is comparatively small. This means that both the range of different node degrees and the number of nodes are relatively small.

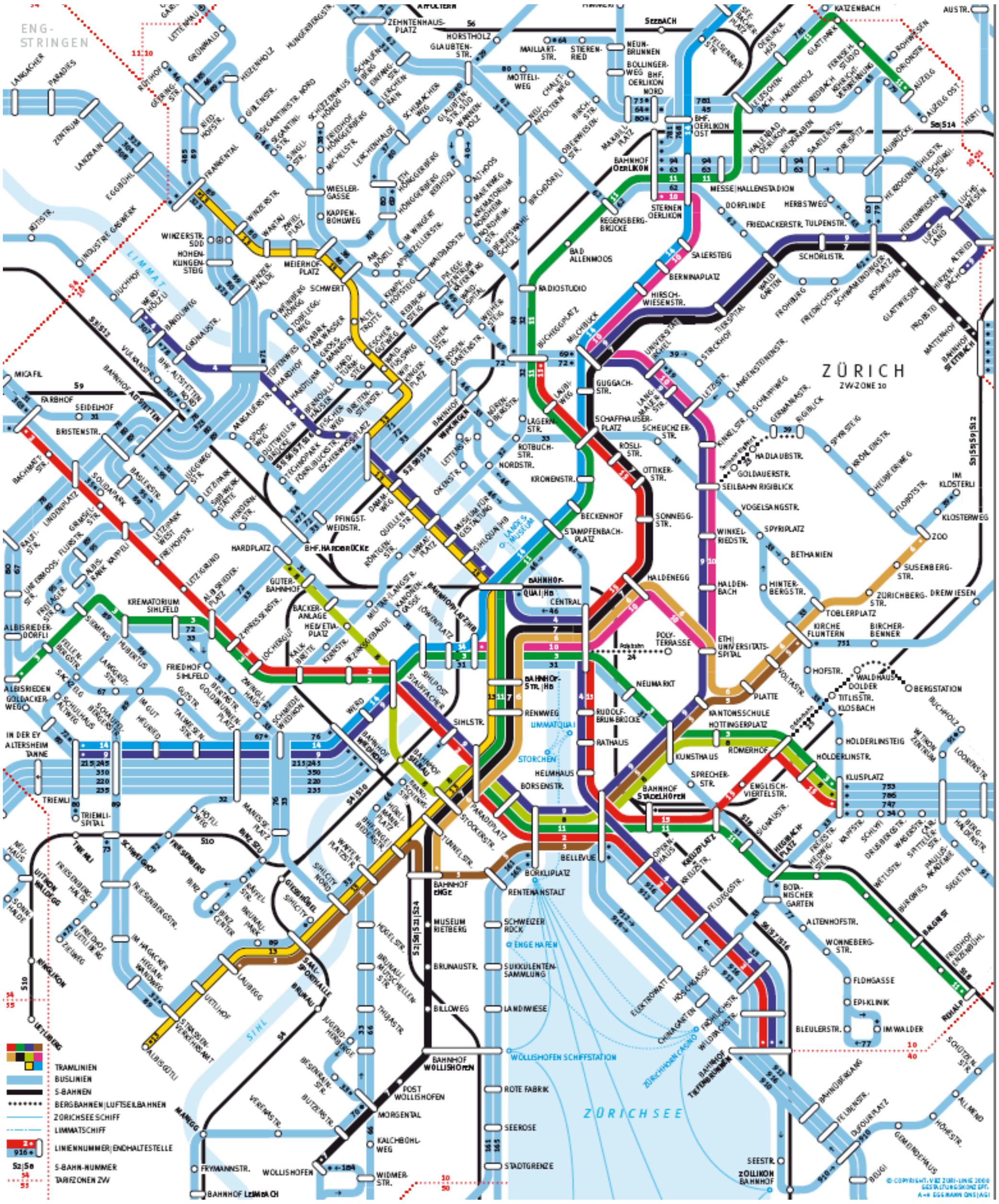
Figure 104 Cumulative degree distributions for determining whether the analysed networks have scale-free topologies



A 3 Maps

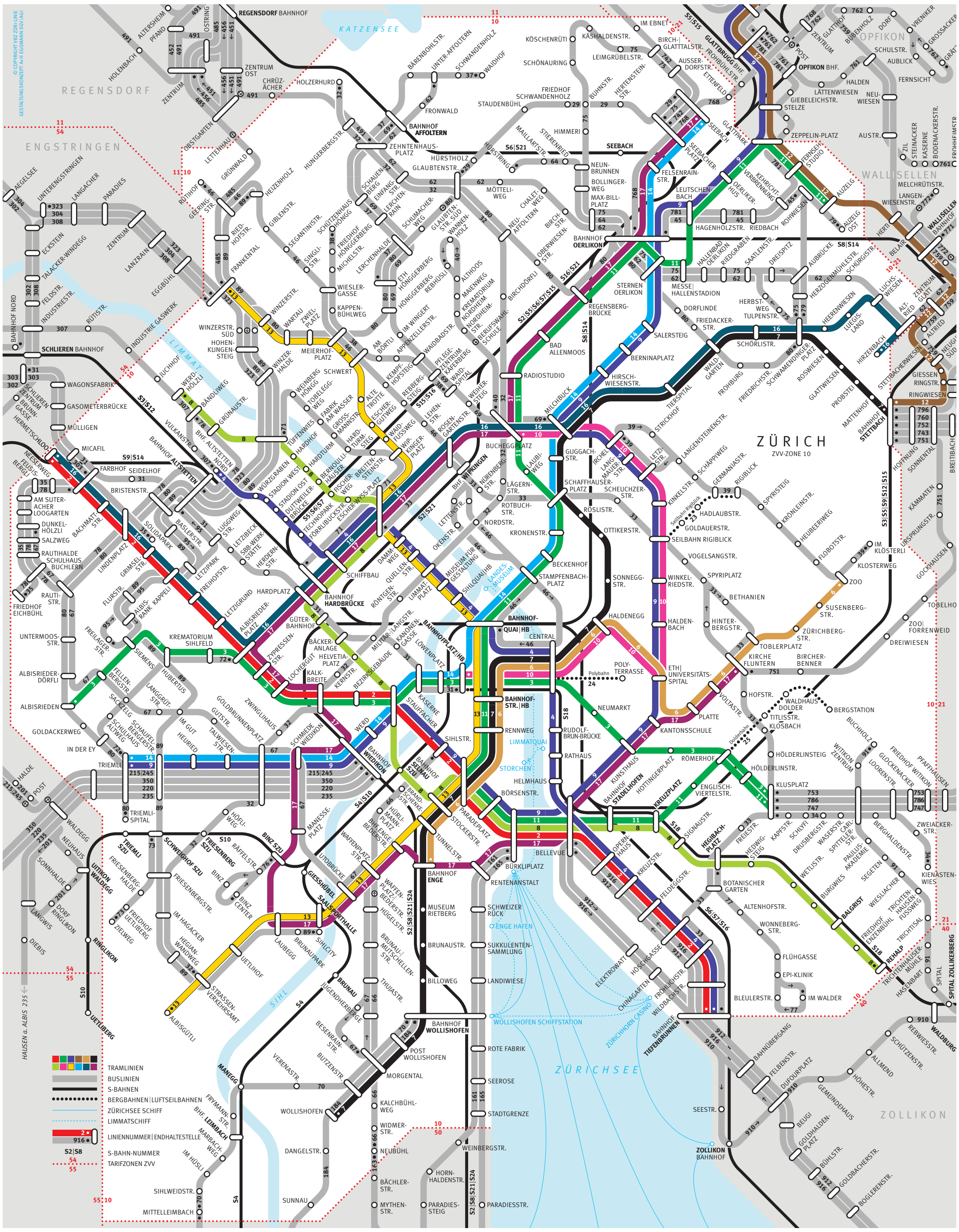
The maps used for representing the *Infrastructure* subsystems of the *Zurich tramway 2006* network, the *Zurich tramway 2025* network and the *Swiss railway* network are shown in Figure 105, Figure 106 and Figure 107.

Figure 105 Map of the *Zurich tramway 2006* network



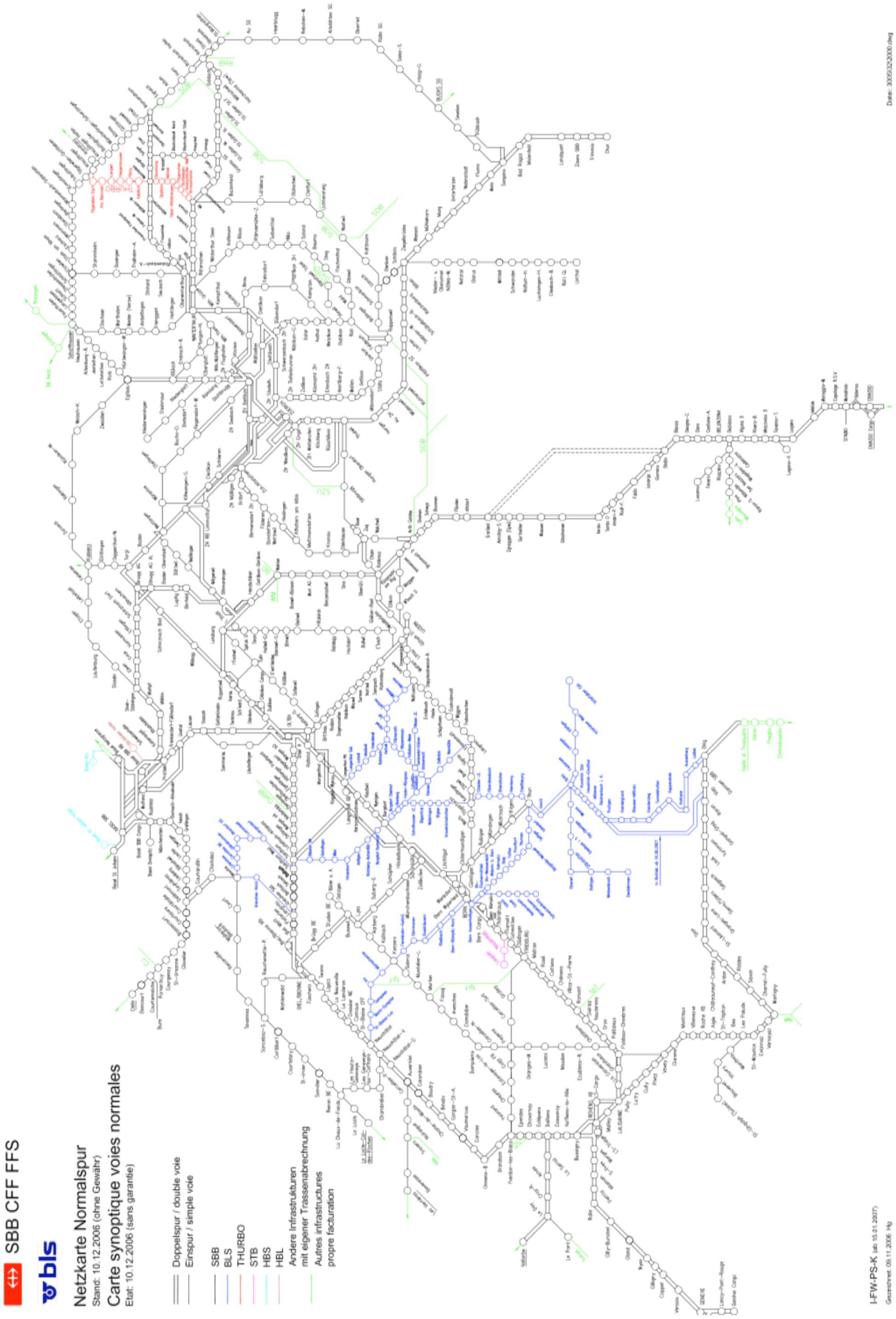
Source: www.vbz.ch

Figure 106 Map of the *Zurich tramway 2025* network



Source: http://www.stadt-zuerich.ch/content/dam/stzh/vbz/Deutsch/Ueber%20das%20Departement/Publikationen%20und%20Broschueren/2025/liniennetz_2025.pdf

Figure 107 Map of the *Swiss railway* network



Source: www.sbb.ch

A 4 *Traffic Operation and Management* data

Table 85 Lines represented in the *Swiss railway network*

Line	Headway in [h]	From	To
Line 1	*0.5*	*Geneva Airport*	*Basel SBB*
Line 2	*0.5*	*Geneva Airport*	*St. Gallen via Solothurn*
Line 3	*1*	*Geneva Airport*	*St. Gallen via Bern*
Line 4	*1*	*Geneva Airport*	*Lucerne*
Line 5	*2*	*Geneva Airport*	*Brig*
Line 6	*1*	*Geneva*	*Lausanne by ICN, IC, IR*
Line 7	*0.5*	*Lausanne*	*Basel SBB*
Line 8	*0.5*	*Lausanne*	*St. Gallen*
Line 9	*1*	*Neuchâtel*	*Bern*
Line 10	*1*	*Berne*	*Lucerne*
Line 11	*2*	*Berne*	*Biel*
Line 12	*1*	*Zurich*	*Berne*
Line 13	*1*	*Berne*	*Olten*
Line 14	*1*	*Zurich*	*Bern via Aarau and Burgdorf*
Line 15	*1*	*Brig*	*Romanshorn*
Line 16	*0.5*	*Basel SBB*	*Brig*
Line 17	*1.5*	*Basel SBB*	*Interlaken Ost*
Line 18	*1*	*Basel SBB*	*Lucerne*
Line 19	*0.5*	*Basel SBB*	*Locarno*
Line 20	*0.5*	*Basel SBB*	*Lugano*
Line 21	*0.5*	*Zurich*	*Locarno*
Line 22	*0.5*	*Zurich*	*Chiasso*
Line 23	*1*	*Zurich*	*Basel SBB*
Line 24	*1*	*Basel SBB*	*Chur by IC, EC or ICN*
Line 25	*1*	*Basel SBB*	*Chur by IR or RE*
Line 26	*1*	*Zurich*	*Basel via Baden*
Line 27	*1*	*Zurich Airport*	*Basel via Baden*
Line 28	*1*	*Chur*	*St. Gallen*
Line 29	*1*	*Romanshorn*	*Lucerne*
Line 30	*1*	*Lucerne*	*Zurich Airport*
Line 31	*1*	*Lucerne*	*Zurich*
Line 32	*1*	*Lucerne*	*Olten*
Line 33	*1*	*Olten*	*Wettingen*
Line 34	*1*	*Konstanz*	*Biel*

Line 35	*0.5*	*Zurich*	*Schaffhausen by IR, ICN or RE*
Line 36	*0.5*	*Zurich*	*Schaffhausen by EC, IC or ICE*
Line 37	*1*	*Aarau*	*Zurich*
Line 38	*1*	*Delle*	*Delemont*
Line 39	*1*	*Solothurn*	*Thun via Burgdorf*
Line 40	*1*	*Neuchâtel*	*Delle*
Line 41	*1*	*Zweisimmen*	*Berne*
Line 42	*1*	*Geneva*	*Lausanne by RE*
Line 43	*1*	*Delle*	*Biel*
Line 44	*1*	*St. Maurice*	*Lausanne*
Line 45	*2*	*Le Locle*	*Neuchâtel*
Line 46	*1*	*Biel*	*La-Chaux-de-Fonds*
Line 47	*0.5*	*Spiez*	*Zweisimmen*
Line 48	*0.5*	*Interlaken Ost*	*Zweisimmen*
Line 49	*0.5*	*Zurich*	*Schwanden*
Line 50	*1*	*La-Chaux-de-Fonds*	*Le Locle*
Line 51	*0.25*	*Zurich*	*St. Margarethen*
Line 52	*1*	*Berne*	*Schaffhausen*

Table 86 Lines represented in the *Zurich tramway 2006* network

Line	Headway in [min]	From	To
Line 2	7.5	*Farbhof*	*Bahnhof Tiefenbrunnen*
Line 3	7.5	*Albisrieden*	*Klusplatz*
Line 4	7.5	*Werdhölzli*	*Bahnhof Tiefenbrunnen*
Line 5	7.5	*Laubegg*	*Kirche Fluntern*
Line 6	7.5	*Bahnhof Enge*	*Zoo*
Line 7	7.5	*Wollishofen*	*Bahnhof Stettbach*
Line 8	7.5	*Hardplatz*	*Klusplatz*
Line 9	7.5	*Triemli*	*Hirzenbach*
Line 10	7.5	*Bahnhofplatz/HB*	*Bahnhof Oerlikon*
Line 11	7.5	*Rehalp*	*Auzelg*
Line 13	7.5	*Albisgütli*	*Frankenthal*
Line 14	7.5	*Triemli*	*Seebach*
Line 15	7.5	*Bucheggplatz*	*Klusplatz*

Table 87 Lines represented in the *Zurich tramway 2025* network

Line	Headway in [min]	From	To
Line 2	7.5	*Hermetschloo*	*Bahnhof Tiefenbrunnen*
Line 3	7.5	*Albisrieden*	*Klusplatz*
Line 4	7.5	*Bahnhof Altstetten Nord*	*Bahnhof Tiefenbrunnen*
Line 6	7.5	*Bahnhof Enge*	*Zoo*
Line 7	7.5	*Wollishofen*	*Bahnhof Stettbach*
Line 8	7.5	*Werdhölzli*	*Rehalp*
Line 9	7.5	*Triemli*	*Zurich Airport*
Line 10	7.5	*Bahnhofquai/HB*	*Bucheggplatz*
Line 11	7.5	*Klusplatz*	*Auzelg*
Line 12	15	*Bahnhof Stettbach*	*Zurich Airport*
Line 13	7.5	*Albisgütli*	*Frankenthal*
Line 14	7.5	*Triemli*	*Seebach*
Line 16	7.5	*Hermetschloo*	*Hirzenbach*
Line 17	7.5	*Kirche Fluntern*	*Seebach*

Table 88 Specified turnaround alternatives in the analysed networks

Network	*Swiss railway*	*Zurich tramway 2006*	*Zurich tramway 2025*
Total number	51	36	39
1	*Aarau*	*Albisgütli*	*Albisgütli*
2	*Arth-Goldau*	*Albisrieden*	*Albisrieden*
3	*Baden*	*Auzelg*	*Altstetten Nord*
4	*Basel SBB*	*Bellevue*	*Auzelg*
5	*Bellinzona*	*Bahnhof Enge*	*Bellevue*
6	*Berne*	*Bahnhof Oerlikon*	*Bahnhof Enge*
7	*Biel*	*Bahnhofquai / HB*	*Bahnhof Oerlikon*
8	*Brig*	*Bahnhofplatz / HB*	*Bahnhofquai / HB*
9	*Brugg AG*	*Bahnhof Stadelhofen*	*Bahnhofplatz / HB*
10	*Chiasso*	*Bahnhof Stettbach*	*Bahnhof Stadelhofen*
11	*Chur*	*Bahnhof Tiefenbrunnen*	*Bahnhof Stettbach*
12	*Delémont*	*Bahnhof Wiedikon*	*Bahnhof Tiefenbrunnen*
13	*Delle*	*Bucheggplatz*	*Bahnhof Wiedikon*
14	*Emmenbrücke*	*Central*	*Bucheggplatz*

15	*Fribourg*	*Escher-Wyss-Platz*	*Central*
16	*Geneva*	*Farbhof*	*Escher-Wyss-Platz*
17	*Geneva Airport*	*Frankenthal*	*Farbhof*
18	*Interlaken Ost*	*Hallenstadion*	*Flughafen Fracht*
19	*Koblenz*	*Hardplatz*	*Frankenthal*
20	*Konstanz*	*Hardturm*	*Hallenstadion*
21	*Kreuzlingen*	*Heuried*	*Hardplatz*
22	*La-Chaux-de-Fonds*	*Hirzenbach*	*Hardturm*
23	*Lausanne*	*Irchel*	*Hermetschloo*
24	*Le Locle – Col des Roches*	*Kalkbreite*	*Heuried*
25	*Lenzburg*	*Kirche Fluntern*	*Hirzenbach*
26	*Locarno*	*Klusplatz*	*Irchel*
27	*Lugano*	*Laubegg*	*Kalkbreite*
28	*Lucerne*	*Letzigrund*	*Kirche Fluntern*
29	*Lyss*	*Milchbuck*	*Klusplatz*
30	*Neuchâtel*	*Rehalp*	*Laubegg*
31	*Olten*	*Seebach*	*Letzigrund*
32	*Payerne*	*Triemli*	*Milchbuck*
33	*Romanshorn*	*Wartau*	*Rehalp*
34	*Sargans*	*Werdhälzli*	*Seebach*
35	*Schaffhausen*	*Wollishofen*	*Triemli*
36	*Schwanden*	*Zoo*	*Wartau*
37	*Sion*		*Werdhölzli*
38	*Solothurn*		*Wollishofen*
39	*Spiez*		*Zoo*
40	*St. Gallen*		
41	*St. Margarethen*		
42	*Thun*		
43	*Visp*		
44	*Weinfelden*		
45	*Wettingen*		
46	*Winterthur*		
47	*Yverdon-les-Bains*		
48	*Ziegelbrücke*		
49	*Zurich*		
50	*Zug*		
51	*Zweisimmen*		

A 5 *Control-command and Signalling* data

Table 89 Represented *Control-command and Signalling* nodes in the *Swiss railway* network

Node	Remotely-controlling	Locally operated
1	*Altstetten*	*Airolo*
2	*Arth-Goldau*	*Altdorf*
3	*Basel SBB*	*Ambri*
4	*Bauma*	*Avenches*
5	*Bellinzona*	*Bäretswil Tobel*
6	*Berne*	*Bärschwil*
7	*Biel*	*Birsfelden Hafen*
8	*Bussnang*	*Bodio*
9	*Chiasso*	*Boveresse*
10	*Chur*	*Courgenay*
11	*Estavayer-le-Lac*	*Court*
12	*Fribourg*	*Dietikon*
13	*Geneva*	*Döttingen*
14	*Göschenen*	*Erstfeld*
15	*Grenchen Nord (BLS 2)*	*Etzgen*
16	*Kollbrunn*	*Felsenau*
17	*Lausanne*	*Fischenthal*
18	*Lavorgo*	*Glarus*
19	*Lucerne*	*Glattbrugg*
20	*Lyss*	*Glovelier*
21	*Magadino*	*Granges*
22	*Moudon*	*Gurtnellen*
23	*Murten*	*Hinwil*
24	*Neuchâtel*	*Koblenz*
25	*Nyon*	*La Plaine*
26	*Oensingen*	*Lachen*
27	*Oerlikon*	*Lancy-Pont Rouge*
28	*Olten*	*Leibstadt*
29	*Payerne*	*Les Verrieres*
30	*Porrentruy*	*Liesberg*
31	*Rapperswil*	*Malleray*
32	*Rorschach*	*Malley*
33	*Sion*	*Mendrisio*

34	*Spiez (BLS 1)*	*Münsingen*
35	*St. Gallen*	*Muntelier*
36	*St.-Maurice*	*Neuchâtel V*
37	*Vallorbe*	*Oberentfelden*
38	*Vernier-Meyrin*	*Pino*
39	*Vevey*	*Ranzo*
40	*Wald*	*Reconvilier*
41	*Wattwil*	*Rekingen*
42	*Wetzikon*	*Renens*
43	*Winterthur*	*Rotkreuz*
44	*Yverdon-les-Bains*	*Rubigen*
45	*Ziegelbrücke*	*Safenwil*
46	*Zurich*	*Schaffhausen*
47		*Sordo*
48		*Suhr*
49		*Tavannes*
50		*Thun*
51		*Trimmis*
52		*Turbenthal*
53		*Uttigen*
54		*Vigana*
55		*Villnachern*
56		*Wichtrach*
57		*Wila*
58		*Zgraggen*
59		*Zizers SBB*
60		*Zurich Mülligen*
61		*Zurich RB Limmattal*
62		*Zurzach*

A 6 *Energy* data

Table 90 Represented *Energy* nodes (substations) in the *Swiss railway* network

Node	Substation	Connected *Infrastructure* edges
1	*Amsteg*	7
2	*Balerna*	6

3	*Berne*	68
4	*Biel*	42
5	*Brugg*	26
6	*Burgdorf*	34
7	*Bussigny*	22
8	*Chur*	5
9	*Courtmaiche*	10
10	*Croy*	7
11	*Deitingen*	16
12	*Delémont*	31
13	*Eglisau*	27
14	*Emmenbrücke*	37
15	*Etzelwerk*	16
16	*Etzwilen*	30
17	*Flüelen*	5
18	*Fribourg*	15
19	*Gampel*	7
20	*Giornico*	6
21	*Giubiasco*	18
22	*Gland*	9
23	*Göschenen*	5
24	*Gossau*	43
25	*Grüeze*	54
26	*Hendschiken*	32
27	*Kerzers*	41
28	*Killwangen*	28
29	*Lavargo*	4
30	*Massaboden*	11
31	*Melide*	8
32	*Muttenz*	35
33	*Neugut*	13
34	*Olten*	44
35	*Others*[22]	69
36	*Payerne*	29
37	*Puidoux*	31
38	*Rapperswil*	21
39	*Ritom*	7

[22] *Others* are connected to *Infrastructure* links for which no SBB data was available. It includes tracks operated by the BLS or SOB for instance.

40	*Rivera*	7
41	*Roche*	19
42	*Romont*	15
43	*Rotkreuz*	27
44	*Sargans*	19
45	*Seebach*	43
46	*Sihlbrugg*	14
47	*St. Leonhard*	9
48	*St. Margarethen*	8
49	*Stein-Säckingen*	21
50	*Steinen*	14
51	*Thun*	24
52	*Tuileries*	11
53	*Vauseyon*	32
54	*Vernayaz*	19
55	*Wanzwil*	14
56	*Wassen*	1
57	*Weinfelden*	13
58	*Wetzikon*	29
59	*Yverdon-les-Bains*	7
60	*Ziegelbrücke*	29
61	*Zurich*	37

A 7 Classification of nodes for *Swiss railway*

Figure 108 shows how the values of the *operational system performance, connectivity value* and *the capacity value* are distributed for the different classes of nodes for the *Swiss railway* network. The corresponding results of the distribution of dispositive measures are illustrated in Figure 109.

As already stated in Table 52, nodes classified as *A3*, *A4*, *B3* or *B4* and *C3*, *C4*, *D3* or *D4* are not present in this network (see Table 52). The results show how the classification of a node correlates with the operational robustness in degraded state. The results meet meet the findings for the *Zurich tramway 2025* network, explained in section 6.4.2.

Figure 108 Calculated *operational system performances* for removals of nodes of different classes from the *Swiss railway* network (capacity restrictions are neglected)

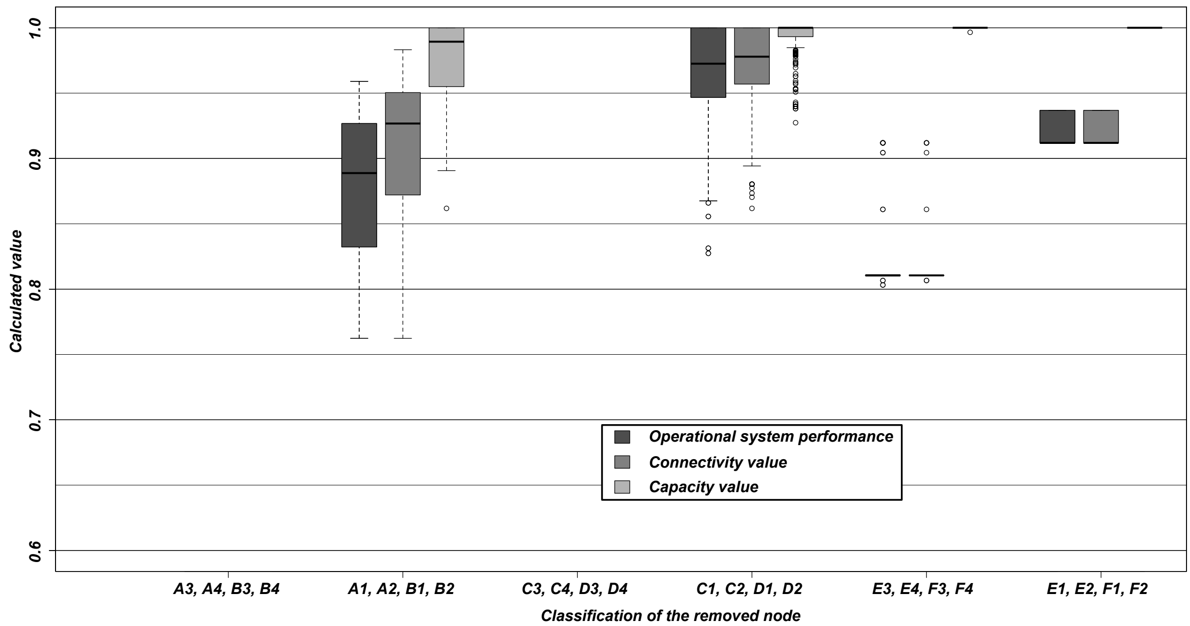
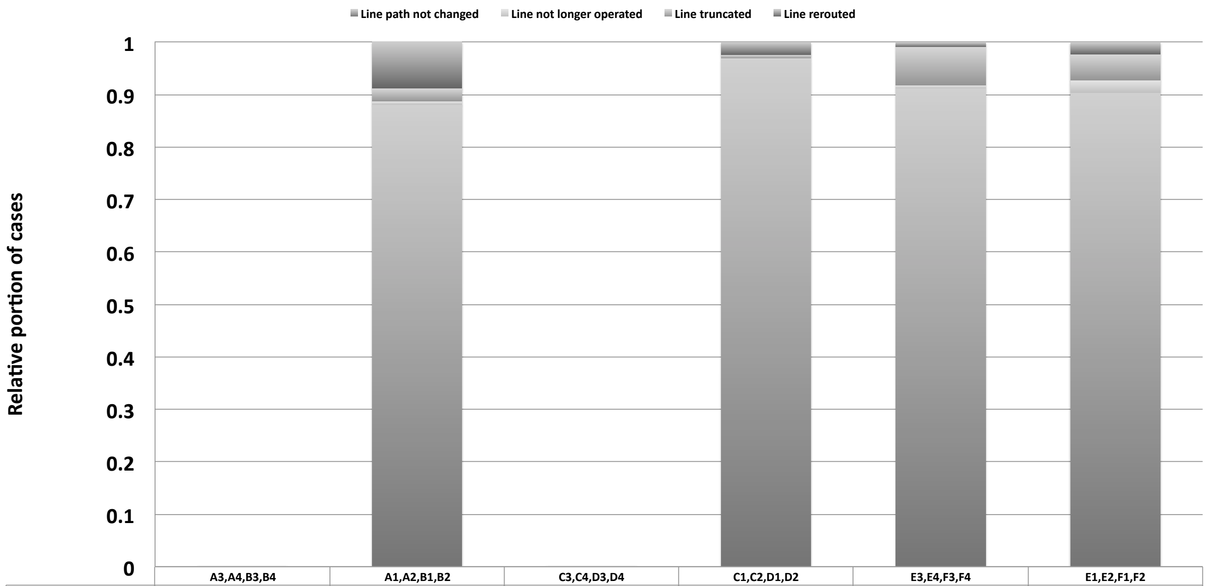


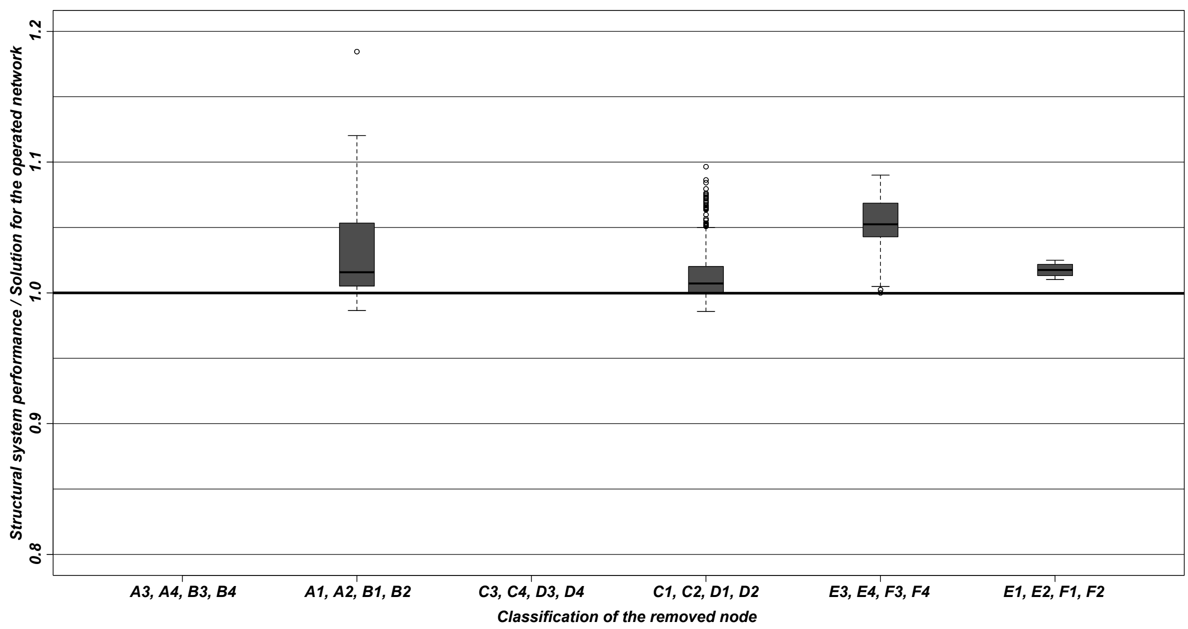
Figure 109 Distribution of dispositive measures for removing nodes of different classes from the *Swiss railway* network (capacity restrictions are neglected)



	A3,A4,B3,B4	A1,A2,B1,B2	C3,C4,D3,D4	C1,C2,D1,D2	E3,E4,F3,F4	E1,E2,F1,F2
Line rerouted	0	0.089	0	0.024	0.009	0.023
Line truncated	0	0.025	0	0.007	0.073	0.05
Line not longer operated	0	0.006	0	0.002	0.006	0.023
Line path not changed	0	0.881	0	0.967	0.912	0.904

Figure 110 shows how the values of the *structural system performances* differ between the degraded topology and the degraded operated network for different node classes. The curves show that the largest differences are measured for nodes classified as *A1*, *A2*, *B1* or *B2*.

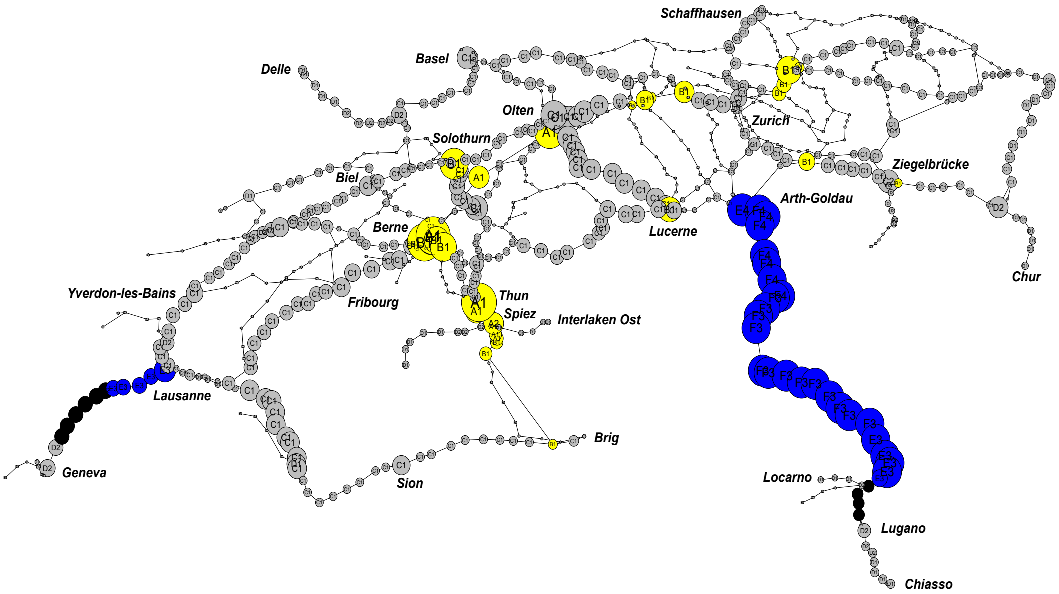
Figure 110 Comparing the *structural system performance* and those for operated networks for different classes of *Swiss railway* nodes



The impacts of removing a single node from the *Swiss railway* network on the *operational system performance* in degraded operation are illustrated in Figure 111. The corresponding results for the *connectivity value* or the *capacity value* are shown in Figure 112 and Figure 113. In all figures, the size of a node depends on the amount of reduction of the measured value. Larger nodes hence indicate more larger reductions and hence more severe impacts.

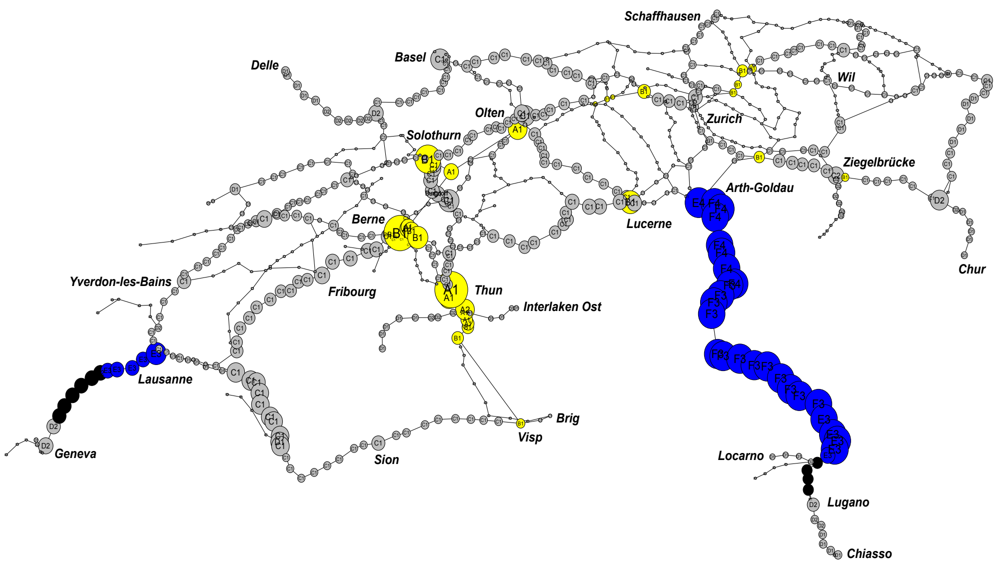
The smallest values of the *operational system performance* are measured for removals of nodes classified as *A1*, *A2*, *B1* or *B2* and *E3*, *E4*, *F3* or *F4*. The removal of nodes classified as *A1*, *A2*, *B1* or *B2* have major impacts on the *capacity value* while removing nodes classified as *E3*, *E4*, *F3* or *F4* have (almost) no consequences on it.

Figure 111 Visualization of the classification of a node and the consequences of its removals on the *operational system performance* for the *Swiss railway* network



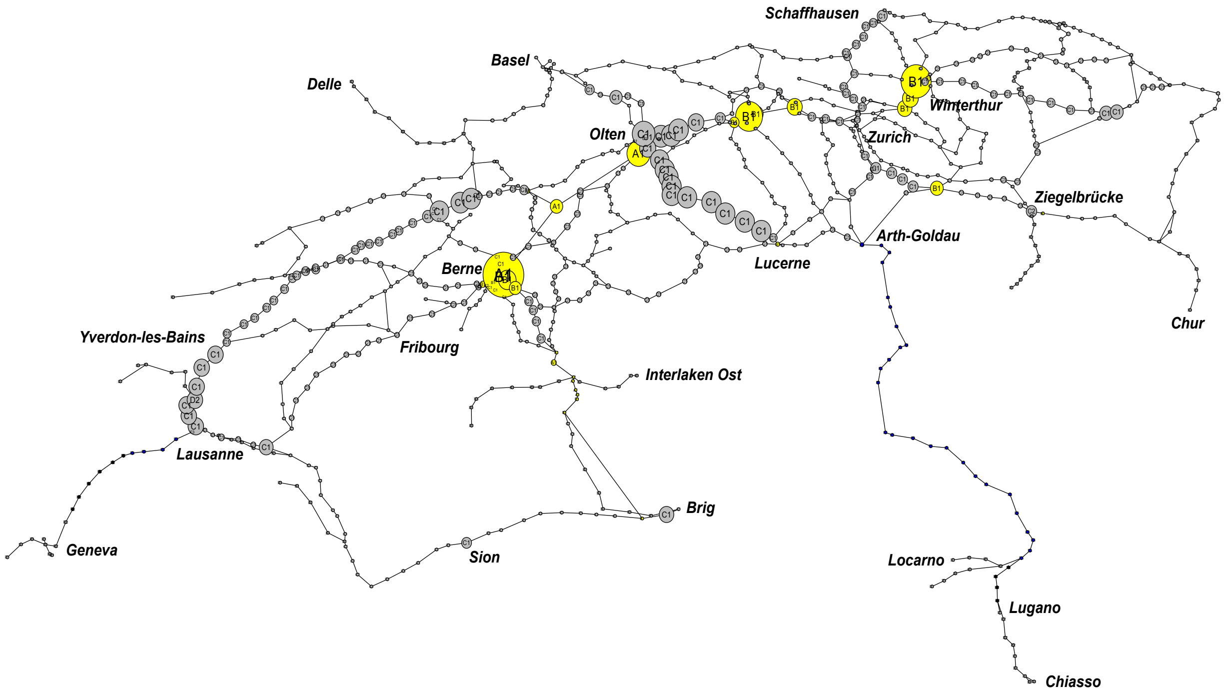
Node size depends on the reduction of the *operational system performance*

Figure 112 Visualization of the classification of a node and the consequences of its removals on the *connectivity value* for the *Swiss railway* network



Node size depends on the reductions of the *connectivity value*

Figure 113 Visualization of the classification of a node and the consequences of its removals on the *capacity value* for the *Swiss railway* network



Node size depends on the reductions of the *capacity value*

A 8 Classification of nodes for the *Zurich tramway 2006* network

The distribution of the *operational system performance,* the *connectivity value* and the *capacity value* for the different classes of *Zurich tramway 2006* nodes are shown in Figure 114. As shown in Table 52, nodes classified as *E1*, *E2*, *F1* or *F2* are not present in the *Zurich tramway 2006* network. Figure 115 shows how the dispositive measures are distributed for removing the nodes of a specific class.

Figure 114 Calculated *operational system performances* for removals of nodes of different classes from the *Zurich tramway 2006* network (capacity restrictions are neglected)

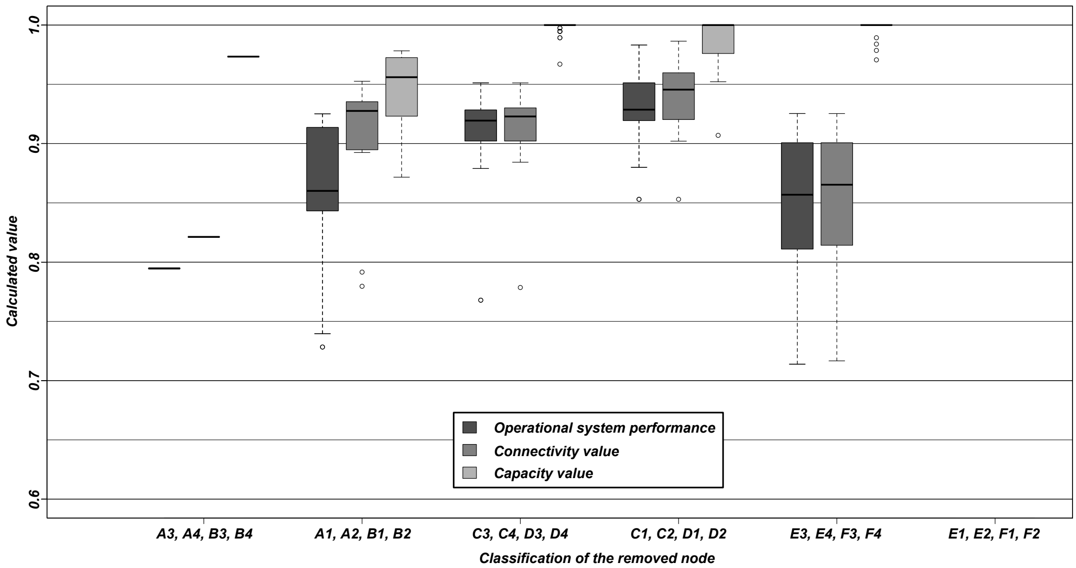
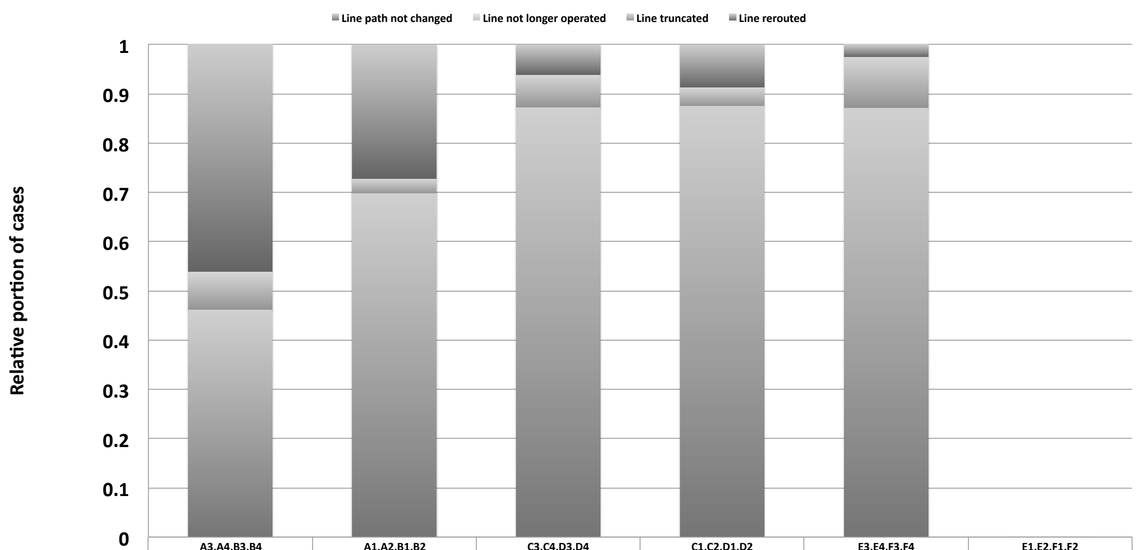


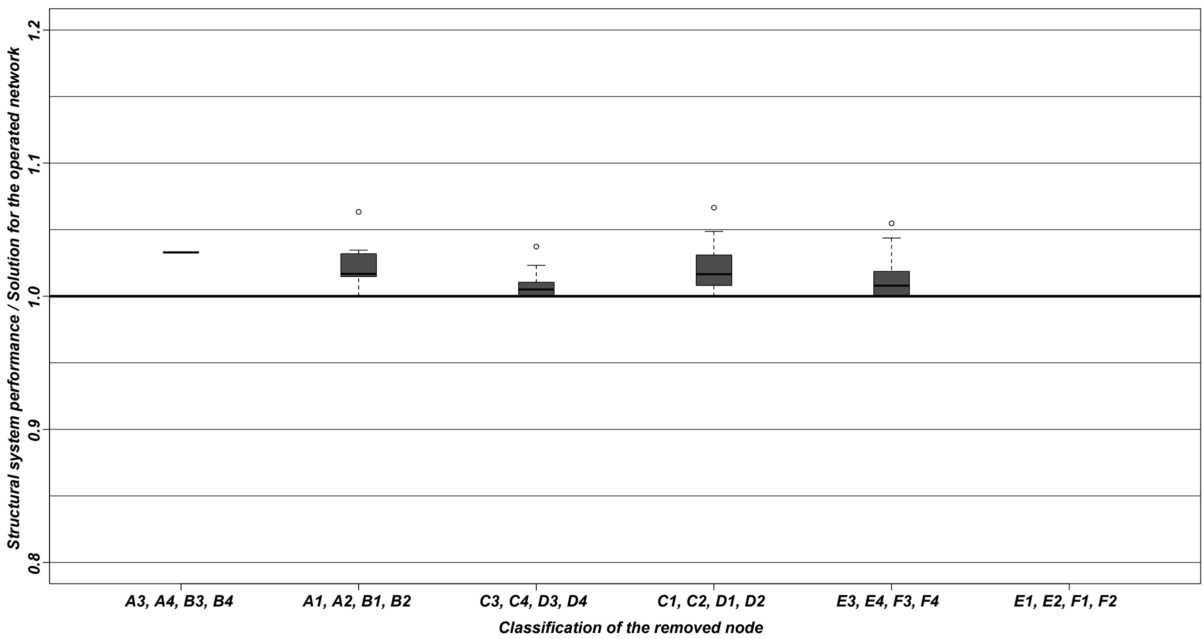
Figure 115 Distribution of dispositive measures for removing nodes of different classes from the *Zurich tramway 2006* network (capacity restrictions are neglected)



	A3,A4,B3,B4	A1,A2,B1,B2	C3,C4,D3,D4	C1,C2,D1,D2	E3,E4,F3,F4	E1,E2,F1,F2
Line rerouted	0.462	0.272	0.061	0.087	0.026	0
Line truncated	0.077	0.03	0.066	0.037	0.103	0
Line not longer operated	0	0	0	0	0	0
Line path not changed	0.462	0.698	0.873	0.876	0.872	0

Figure 117 shows how the values of the *structural system performances* differ between the degraded topology and the degraded operated network for different node classes. As already found for the *Zurich tramway 2025* network (shown in Figure 68), the largest differences are observed for nodes classified as *A1*, *A2*, *B1* or *B2* and *C1, C2, D1* or *D2*.

Figure 116 Comparing the *structural system performance* and those for operated networks for different classes of *Zurich tramway 2006* nodes

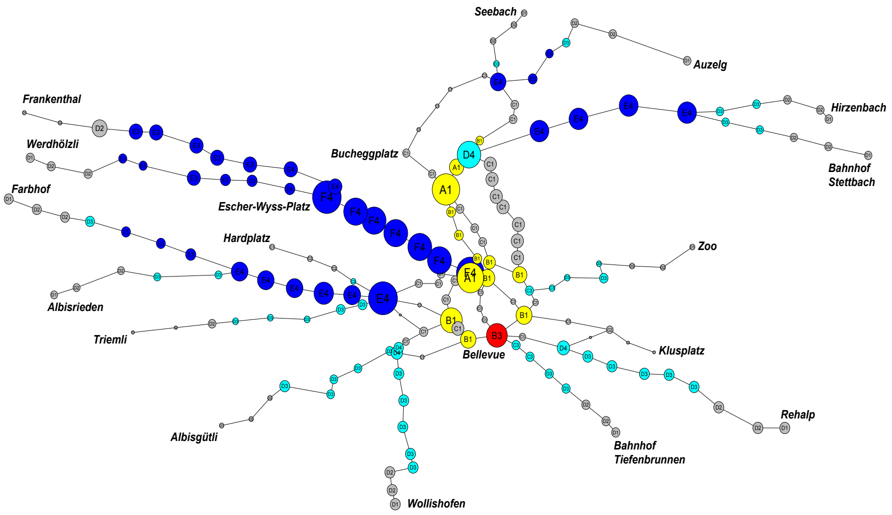


The impacts of removing a single node from the *Zurich tramway 2006* network on the *operational system performance* in degraded operation are illustrated in Figure 117. The size of each node relates to the *operational system performance* if the node is removed from the *Zurich tramway 2006* network. Larger circles indicate more severe reductions.

Figure 118 shows the corresponding correlation between the classification of a node and the reduction of the *connectivity value.* The most severe impacts are observed for removing nodes classified as *D4, E4* and *F4*. These are the nodes whose removal significantly reduces the size of the giant cluster (see Table 51).

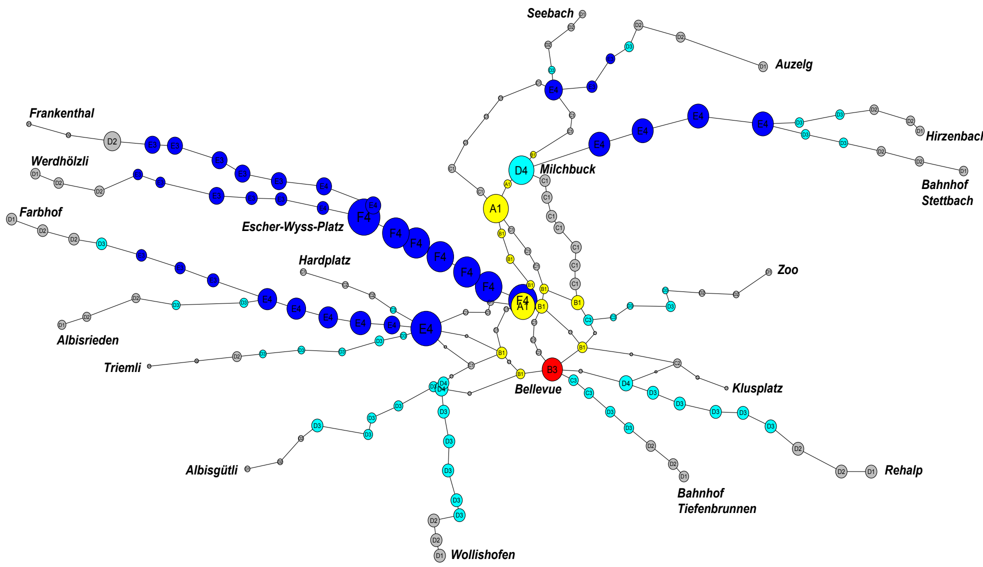
The impacts of a removing a specific node on the *capacity value* are illustrated in Figure 119. Especially removing nodes classified as *A1* and *B1* is likely to reduce the calculated *capacity values*.

Figure 117 Visualization of the classification of a node and the consequences of its removals on the *operational system performance* for the *Zurich tramway 2006* network



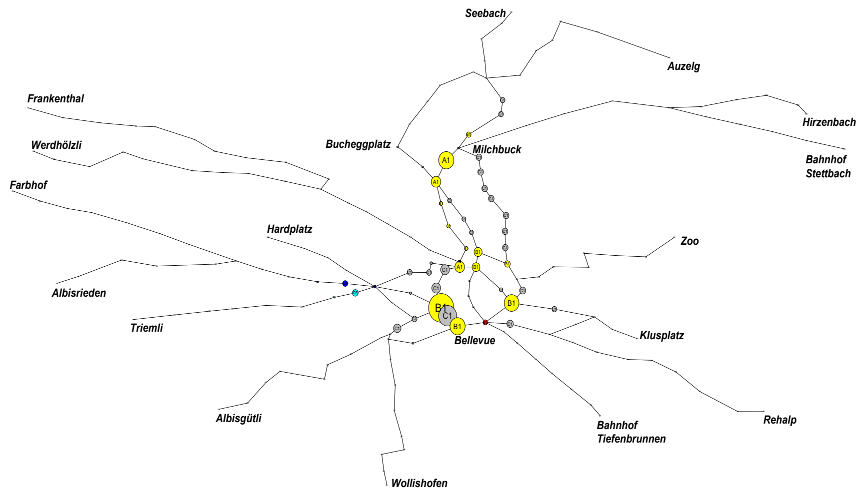
Node size depends on the reductions of the *operational system performance*

Figure 118 Visualization of the classification of a node and the consequences of its removals on the *connectivity value* for the *Zurich tramway 2006* network



Node size depends on the reductions of the *connectivity value*

Figure 119 Visualization of the classification of a node and the consequences of its removals on the *capacity value* for the *Zurich tramway 2006* network



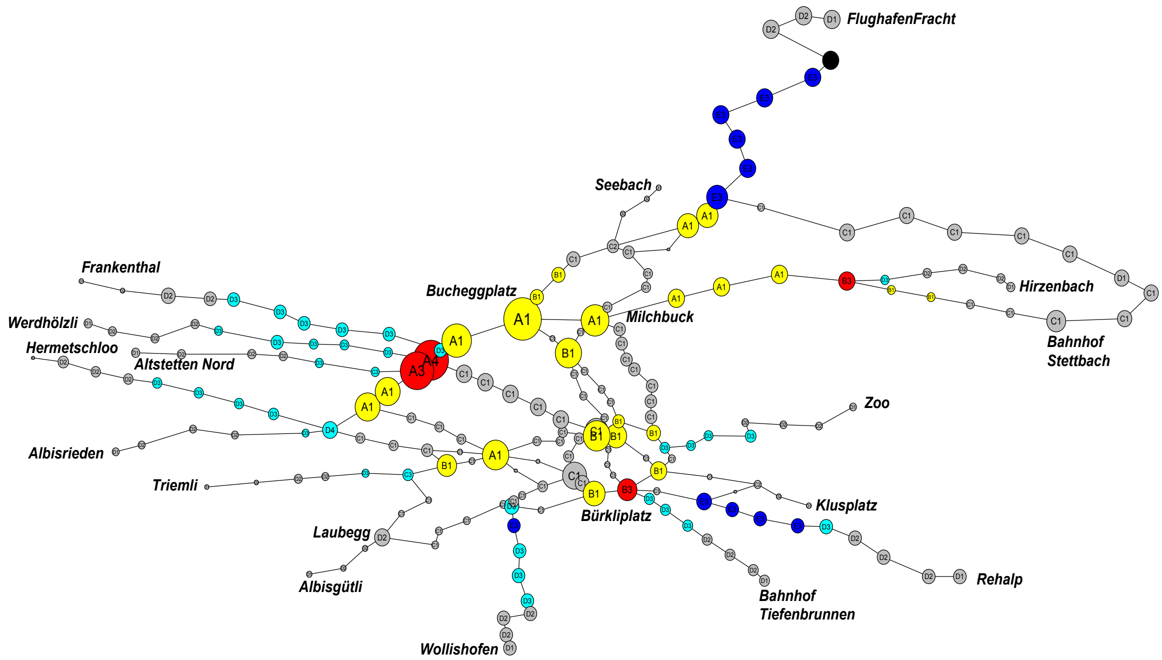
Node size depends on the reductions of the *capacity value*

A 9 Classification of nodes for *Zurich tramway 2025*

The correlation between the classification of a single node and the impacts of its removal on the *operational system performance* for the *Zurich tramway 2025* network are illustrated in Figure 111.

As for the *Zurich tramway 2006* network, larger circles indicate more severe reductions than nodes of smaller size. The most severe impacts are measured if nodes classified as *A1, A3* or *A4* are removed. These are the nodes whose removal causes severe increases of the average shortest path length within the giant cluster while its size remains almost unchanged for nodes classified as *A1* or decreases for nodes belonging to classes *A3* or *A4.*

Figure 120 Visualization of the classification of a node and the consequences of its removals on the *operational system performance* for the *Zurich tramway 2025* network

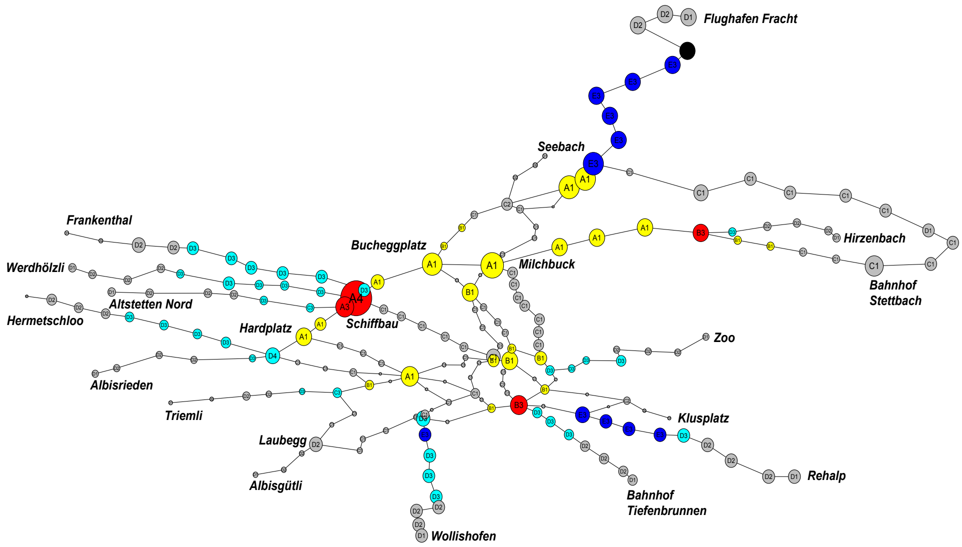


Node size depends on the reductions of the *operational system performance*

The reductions of the *connectivity values* are visualised in Figure 112. The most severe impacts are observed if nodes classified as *B3*, *A3* or *A4* are removed. But also the removal of some vertices classified as *C1* or *E3* can significantly reduce the *connectivity value*.

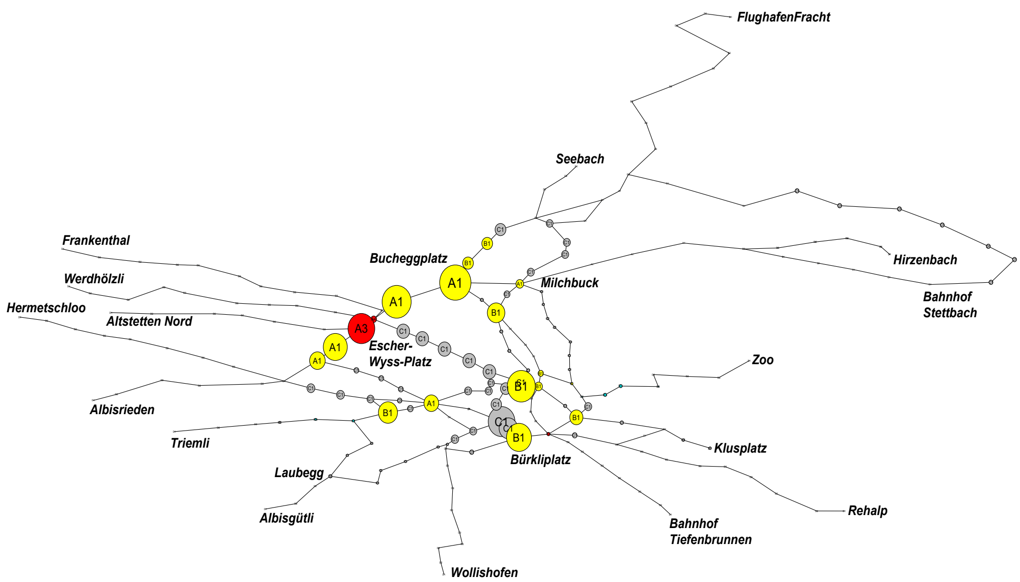
Reduced *capacity values* are calculated if nodes classified as *A1*, *B1* or *A3* are removed (see Figure 122). But also the removal of nodes classified as *C1* and located along the corridor *Bahnhofquai/HB – Escher-Wyss-Platz* decrease the *capacity value*.

Figure 121 Visualization of the classification of a node and the consequences of its removals on the *connectivity value* for the *Zurich tramway 2025* network



Node size depends on the reductions of the *connectivity value*

Figure 122 Visualization of the classification of a node and the consequences of its removals on the *capacity value* for the *Zurich tramway 2025* network

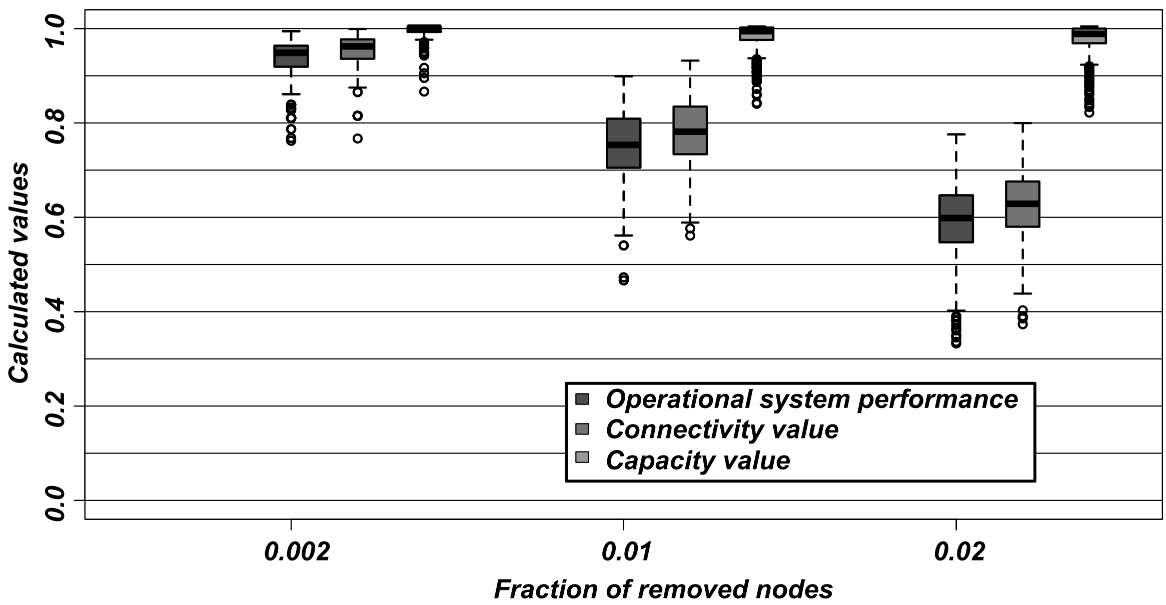


Node size depends on the reductions of the *capacity value*

A 10 Further analysis results for *Swiss railway*

Figure 123 shows calculation results if multiple nodes are simulatenously removed from the *Swiss railway* network. The figure contains boxes for the values of the *operational system performance,* the *connectivity value* and the *capacity value* for removing a single node, 1 or 2 per cent of the nodes. For each column, the results were gained for 500 simulations. The first columns were gained for removing single nodes and match previous findings illustrated in Figure 60. For each fraction of initially removed nodes, Table 62 denotes the distribution of dispositive measures as calculated by the implemented robustness analysis tool and the line disposition framework for the non-restricted case, i.e. capacity restrictions are not considered in the line disposition framework shown in . The corresponding capacity-restricted results are presented in Table 63.

Figure 123 Values for the *operational system performance*, *connectivity value* and *capacity value* for the *Swiss railway* network in case of multiple simultaneous node removals



For single node removals, Table 91 shows the fraction of taken branching paths as introduced in the line disposition framework illustrated in Figure 36. The numbers in the first row correspond to those in the circles within Figure 36.

The results show that due to operational capacity thresholds, in 3.7 % of cases lines cannot be rerouted in the *Zurich tramway 2006* network. For the *Zurich tramway 2025* network this value is about 3 %. For both networks, considering theoretical capacity thresholds do not hinder line rerouting. The values refer to the calculated fractions of dispositive measures taken as denoted in Table 61.

Table 91 Distribution of branching paths in the line disposition framework according to Figure 36 for single node removals from the analysed network in [%]

Network	*Swiss railway*			*Zurich tramway 2006*			*Zurich tramway 2025*		
	No Cap	Cap Theo.	Cap Oper.	No Cap	Cap Theo.	Cap Oper.	No Cap	Cap Theo.	Cap Oper.
Step (1)	6.30	6.30	6.29	14.09	14.09	14.09	13.59	13.59	13.59
Step (2)	93.70	93.70	93.71	85.91	85.91	85.91	86.41	86.41	86.41
Step (3)	5.97	5.97	5.96	14.09	14.09	14.09	13.59	13.59	13.59
Step (4)	0.33	0.33	0.33	---	---	---	---	---	---
Step (5)	2.03	2.03	2.03	10.33	10.33	10.33	6.79	6.79	6.79
Step (6)	4.57	4.57	4.57	6.05	6.05	6.05	8.01	8.01	8.01
Step (7)	---	---	---	---	---	---	---	---	---
Step (8)	---	---	---	---	---	---	---	---	---
Step (9)	0.19	0.19	0.19	1.69	1.69	1.69	1.11	1.11	1.11
Step (10)	1.84	1.84	1.84	8.64	8.64	8.64	5.68	5.68	5.68
Step (11)	1.55	1.55	1.58	5.14	5.14	5.53	3.17	3.17	3.41
Step (12)	0.29	0.29	0.26	3.50	3.50	3.11	2.51	2.51	2.26
Step (13)	3.12	2.89	2.62	5.49	5.32	1.94	6.45	6.31	2.23
Step (14)	1.45	1.67	1.91	0.56	0.73	0.39	1.57	1.71	2.82
Step (15)	0.55	0.78	0.99	0.30	0.52	0.30	0.94	1.11	2.02
Step (16)	0.90	0.89	0.92	0.26	0.22	0.09	0.63	0.59	0.80
Step (17)	0.53	0.76	0.98	0.26	0.48	0.30	0.94	1.11	2.02
Step (18)	0.02	0.02	0.02	0.04	0.04	---	---	---	---
Step (19)	---	---	0.04	---	---	3.72	---	---	2.96
Step (20)	4.57	4.57	4.52	6.05	6.05	2.33	8.01	8.01	5.05
Step (21)	---	---	---	---	---	0.04	---	---	---
Step (22)	---	---	0.04	---	---	3.67	---	---	2.96
Step (23)	0.04	0.04	0.04	---	0.04	---	0.03	0.03	0.03
Step (24)	0.50	0.73	0.93	0.26	0.43	0.30	0.91	1.08	1.99