Leibniz University Hannover

Faculty of Civil Engineering and Geodetic Science

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Bachelor Thesis

Identification of Resilience-Based Life Cycle Strategies for Road Infrastructures Using Stochastic Simulation

Degree Course: Civil and Environmental Engineering (B.Sc.)

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Abstract

Road networks play an important role in the transportation of people and goods. They are critical infrastructure, especially for a nation's economy. In Germany, nearly 80 percent of goods are transported by road. Therefore, high demands are made on maintenance to ensure the efficiency and resilience of a road network, which results in high maintenance costs. This bachelor thesis proposes a decision making approach that allows authorities to select a cost-effective maintenance strategy considering a resilience threshold. The strategies are a combination of preventive and corrective maintenance, with varying intensities over time. To calculate resilience for each strategy, a Monte Carlo simulation is utilized. The pavement degradation of the roads is modeled by a linear combination of two gamma processes. This approach is applied to different road networks in Germany. The Python package OSMnx, which can extract network topologies from Open Street Map, is utilized. The results are discussed from an engineering perspective in terms of feasibility and computational complexity. Additionally, the thesis provides an outlook on future challenges and potential developments.

Keywords: Resilience; Monte Carlo Simulation; Maintenance Strategies; Road Network; Pavement Degradation

Contents

List of Figures

List of Tables

1 Introduction

Like all infrastructure networks, road networks are an important factor in maintaining a modern way of life and the economic development of a nation. They offer the necessary infrastructure for transporting passengers and freight, forming the foundation for public transport and logistics networks as well. The amount of goods transported on road networks is significant. In 2022, Germany transported 4,583,963 tons of goods [1]. Of the total, 3,642,700 tons [1] was transported by road freight, representing 79 percent. Therefore, it is necessary to maintain an efficient and resilient road network in a further increasing road goods transport [2] and allow for the preservation of prosperity and economic growth. Freight transport is the main cause of the degradation of roads and there is currently a considerable investment deficit in the maintenance of roads and bridges in Germany. The German Association of Towns and Municipalities (Deutsche Städte- und Gemeindebund) has reported a renovation delay of 166 billion euros [3]. As a result, necessary repairs to roads, bridges, sidewalks and cycle paths have to be postponed time and again, often for cost reasons. This problem affects municipal infrastructure nationwide and has worsened dramatically in recent years. This investment hold-up is the result of rising maintenance costs and the resulting growing unwillingness of authoreties to properly fund road maintenance [4]. For this reason, the privatization of road networks or sections is a political issue.

This bachelor thesis develops a method for decision makers to determine a resilient, cost-effective maintenance strategy over time for a road network. The approach extracts a regional road network based on Open Street Map data and simplifies it. Maintenance strategies are identified, which consist of combinations of preventive and corrective measures. The strategies are applied to the extracted network and the network efficiency is measured over time. A Monte Carlo simulation is used to determine the network efficiency. The degradation of the roads in the network is realized by a stochastic process.

This thesis is structured as follows: In chapter "Theoretical Foundations", the necessary theoretical foundations are presented (probability and graph theory, degradation, efficiency and resilience quantification, road networks characterization, etc.). This is followed by a short "Literature Review". The individual parts of the approach are presented in the "Proposed Methodology" chapter. The parameters used are specified. The approach is applied to various network topologies of German cities in "Case Studies". In "Discussion", the results are evaluated in terms of feasibility and computational complexity. Finally, the "Conclusion" will end with an outlook.

2 Theoretical Foundations

Theoretical foundations are essential for the understanding of the proposed approach. First, there will be an introduction to probabilistic methods. Graph theory is then used to mathematically represent real networks in its fundamental form. Finally, maintenance measures, potential damage patterns, mechanical behavior and deterioration of an asphalt pavement are presented.

2.1 Probability Theory

Probabilistic techniques can be used for modeling the uncertainty of a real world system. The concept of quantifiable uncertainty can be classified into two categories [5]:

Aleatory uncertainty: These are uncertainties that are subject to the variability of the system or the process itself. They cannot be quantified or predicted in detail (inherent randomness). Examples include inhomogeneous and anisotropic material behavior, traffic loads, lifetime of machine components, climate, etc.

Epistemic uncertainty These uncertainties relate to the lack of exact data for estimating model parameters. The algorithms of a model are also subject to epistemic uncertainties, e.g. when simplifications have to be made due to the complexity of the real model.

Probabilistic models that want to represent real world systems or processes are usually subject to a combination of both types of uncertainty.

2.1.1 Stochastic Process

A stochastic process is a family of random variables $\{X(t)\}_{t\in T}$ on a given probability space (Ω, Σ, P), where Ω represents the sample space, Σ represents the σ-algebra and P denotes a probability measure [6]. Depending on the time set T, the stochastic process can be a continuous-time stochastic process, where $T = \mathbb{R}^+$, or a discrete-time stochastic process, where $T = \mathbb{N}_0$. Considering a discrete time set T, a step process can be obtained if it holds that the random variable can only change at the discrete time points and is constant between these points.

2.1.2 Monte Carlo Simulation

Monte Carlo simulation (MC) is a probabilistic method that generates a sample by repeating a random experiment. This sample can be utilized to estimate the expected value of a function. The method becomes increasingly more precise as the size of the sample generated increases. The law of large numbers dictates that the mean value of a generated sample from an MC simulation will converge to the expected value. The primary constraint of the approach is the necessity of generating sufficiently large samples, which increases the computational complexity exponentially with the size of the problem.

2.2 Degradation Process

Real world systems and their components are subject to degradation. Degradation is influenced by physical, chemical and/or biological external influences. It describes the accumulation of damage over time and is therefore an irreversible process that leads to the failure of a system or a system component. There are various approaches that model the causes and behavior of degradation, which is presented in more detail in subsection 3.3.

2.2.1 Gamma Process

A gamma process is a type of stochastic process consisting of gamma distributions that are independently distributed. A gamma distribution is a two parametric probability distribution with a shape parameter α and a scale parameter β. Let a random variable be gamma-distributed $X \sim \text{Gamma}(\alpha, \beta)$, then the probability density function is given by

$$f_X(x; \alpha, \beta) = \frac{\beta^{-\alpha}}{\Gamma(\alpha)} x^{\alpha-1} e^{-x/\beta} \mathbf{1}_{\{x>0\}} \qquad \text{for } \alpha > 0, \beta > 0 \tag{1}$$

where $\mathbf{1}_{\{\cdot\}}$ is the indicator function and $\Gamma(\cdot)$ denotes the gamma function: $\Gamma(z) = \int_0^\infty u^{z-1} e^{-u}\, du$. The mean and variance are given by $E[X] = \beta\alpha$ and $Var[X] = \beta^2\alpha$. Figure 1 shows different gamma distributions under various parameters.

Let a random variable be gamma-distributed $X_k(t) \sim \text{Gamma}(\alpha_k, \beta_k)$ and let the gamma process $\{X_k(t)\}_{t\geq 0}$ have the following properties:

1. $X_k(0) = 0$,
2. the increments $\Delta X_k(t) = X_k(t + \Delta t) - X_k(t)$ are independent of t,
3. $\Delta X(t)$ follows a gamma distribution $\Delta X(t) \sim Gamma(\alpha_k(t + \Delta t) - \alpha_k(t), \beta_k)$, with shape parameter $\alpha_k(t + \Delta_t) - \alpha_k(t)$ and scale parameter β_k, where $\alpha_k(t)$ is a given monotone increasing function in t and $\alpha_k(0) = 0$.

Then the probability density function is given by

$$f_X(x; \alpha_k(t), \beta_k) = \frac{\beta_k^{-\alpha_k(t)}}{\Gamma(\alpha_k(t))} x^{\alpha_k(t)-1} e^{-x/\beta_k} \mathbf{1}_{\{x>0\}} \tag{2}$$

The gamma process can be interpreted in the context of a degradation process as the increase in damage. As the probability distribution changes over time, the intensity of

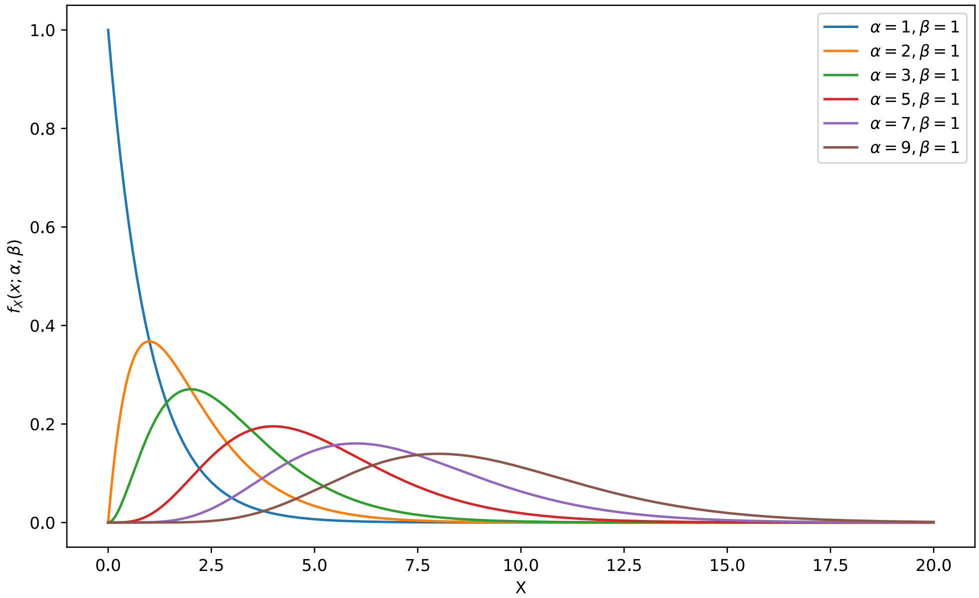

Figure 1: Density functions of the gamma distribution with different shape parameters α and constant β.

the damage expansion also changes. An example of this is the expansion of a crack or pothole on the upper asphalt layer.

2.2.2 Weighted linear combination of Gamma Processes

Multiple stochastic processes can be combined into a linear combination of stochastic processes. In [7], Wu and Castro present a methodology involving multiple weighted linear combined gamma processes to model a degradation progress.
Given are several gamma processes n with $\{X_k(t)\}_{t\geq 0}$ and weighting factors $\xi \in \mathbb{R}_{\geq 0}$, then their overall stochastic (degradation) process $\{Y(t)\}_{t\geq 0}$ is given by

$$Y(t) = \sum_{k=1}^{n} \xi_k X_k(t), \quad t \geq 0, \quad \xi_k \geq 0 \tag{3}$$

The following characteristics define $\{Y(t)\}_{t\geq 0}$:

1. $Y(0) = \sum_{k=1}^{n} \xi_k X_k(0) = 0$,

2. If the increment $\Delta X_k(t) = X_k(t + \Delta t) - X_k(t)$ is independent of t, then $\Delta Y(t) = \sum_{k=1}^{n} \xi_k \Delta X_k(t)$ is independent of t as well.

The expected value and the variance can also be described as a linear combination with $E(Y(t)) = \sum_{k=1}^{n} \xi_k \beta_k \alpha_k(t)$ and $Var(Y(t)) = \sum_{k=1}^{n} \xi_k^2 \beta_k^2 \alpha_k(t)$.
This linear combination can be described as the total degradation of a system, where each individual gamma process can be considered as a specific influencing factor on the degradation process. The advantage is that this comes closer to many real degradation

processes, since degradation is caused by several factors (e.g. temperature, friction, etc.) and these occur with different intensities. An example is shown in figure Figure 2.

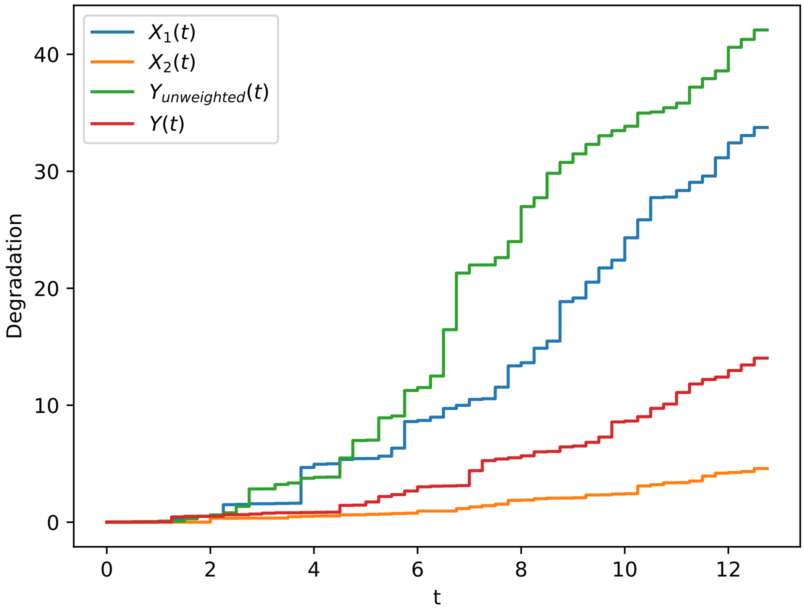

Figure 2: Realization of two degradation processes $X_1(t)$, $X_2(t)$, their unweighted linear combination $Y_{unweighted}(t)$ and the corresponding weighted linear combination $Y(t)$.

2.3 Graph Theory

There are various techniques to mathematically represent a road network. One approach is to describe the network as a weighted graph [4]. A weighted graph $G = (V_G, E_G, W_G)$ is a mathematical object consisting of the three finite sets for edges $E_G = \{e_1, e_2, ..., e_n\}$, nodes $V_G = \{v_1, v_2, ..., v_n\}$ and weights $W_G = \{w_1, w_2, ..., w_n\}$ [8]. The elements of the edge set E_G connect the elements of the node set V_G with each other. In addition, edges can have one or more attributes, which are referred to as the weight of the edge $w_i(e_i) \in W_G$. Graphs can be divided into the following types based on their edge structure:

Non-directional Graph: There is only one undirected edge between two different nodes.
Directional Graph: There is only one directed edge between two distinct nodes.
Multigraph: There are multiple undirected parallel edges between two distinct nodes.
Multi-directional Graph: There are multiple directed or undirected parallel edges between two distinct nodes.

In addition, all types of graphs can have either directed or undirected loops.

In the context of a road network, the edges of the multi-directional graph shown in Figure 3 can be interpreted as road connections, whereby the edges $\{2, 3\}$ could stand for a road with two structurally separate directional lanes, the edges $\{1, 5\}$ stand for a road whose directional lanes are not structurally separated. Finally, the edge $\{4\}$, which is a self-loop, could represent a dead end. Alternatively, individual lanes can also be represented as edges. The weight of the edges could be: length, travel time, speed limit, number of lanes, etc.
The nodes $\{A, B, C\}$ are the intersections (microscopic view) or settlements (macroscopic view).

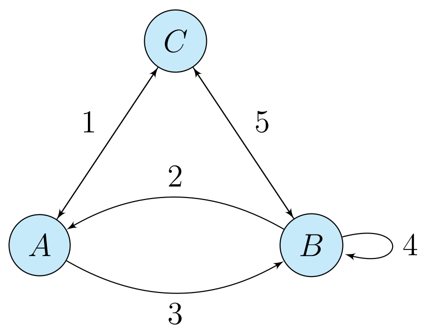

Figure 3: Simple Multi-directional graph.

2.3.1 Shortest Path Algorithm

The shortest path problem is a route finding problem. It asks for the path between two different nodes in a graph with the lowest weight. For example, if the edge weight is the length, then the shortest path is being searched for. The problem can be divided into a single-pair or a all-pairs shortest path problem. In this thesis, the Floyd-Warshall algorithm is used, which solves the all-pairs shortest path problem.
The Floyd-Warsahll algorithm can be applied to all presented graph types under the condition that $W_G \subseteq \mathbb{R}^+$. It initializes a matrix with zero distances for each vertex to itself and edge weights for direct connections. The algorithm then uses a triple-nested loop to systematically check and update the matrix if a shorter path is found through an intermediate node. After completion, the matrix contains the shortest distances between all vertex pairs. This algorithm is an example of dynamic programming and has a cubic time complexity of $\mathcal{O}(n^3)$, where n is the number of nodes in the graph. A exemplary pseudocode of the algorithm is given in Figure 4.
The Floyd-Warshall algorithm is well suited for dense networks, which is closer to road networks. A widely used alternative is the Dijkstra algorithm, which solves the single-pair shortest path problem in $\mathcal{O}(n^2)$. If Dijkstra is adapted to the all-pairs shortest path problem, it has the same time complexity as Floyd-Warschall ($\mathcal{O}(n^3)$). Nevertheless, Dijkstra is preferable for large sparse graphs[8].

Algorithm 1 Pseudocode of Floyd-Warshall Algorithm

Require: A directed weighted graph $G(V_G, E_G, W_G)$
Ensure: Shortest path between each pair of vertices in G

```
for each d ∈ V_G do
    distance[d][d] ← 0;
end for
for each edge (s, p) ∈ E_G do
    distance[s][p] ← weight(s, p);
end for
n = cardinality(V_G);
for k = 1 to n do
    for i = 1 to n do
        for j = 1 to n do
            if distance[i][j] > distance[i][k] + distance[k][j] then
                distance[i][j] ← distance[i][k] + distance[k][j];
            end if
        end for
    end for
end for
```

Figure 4: Pseudocode for the Floyd-Warshall algorithm to compute the shortest paths in a weighted graph.

2.3.2 Network Efficiency

Network efficiency (network or system performance) describes the efficiency of information exchange between all pairs of nodes in a network. As nodes are geographically farther apart, their information exchange becomes less efficient. This concept can be applied to a road network, where information exchange is now refers to the travel time of a traveler between two different nodes. A formula for calculating network efficiency was developed by Latora and Marchiori in [9].

$$E(G) = \frac{1}{N(N-1)} \sum_{i \neq j \in V} \frac{1}{d_{ij}} \tag{4}$$

Where N is the number of all nodes and $\frac{1}{d_{ij}}$ is the pairwise efficiency of the nodes $\{i, j\}$. In the case of a weighted network, the network efficiency must be standardized by dividing $E(G)$ by the ideal state network $E_{ideal}(G)$ (e.g., optimal travel times on all edges). What results in:

$$E_{glob}(G) = \frac{E(G)}{E(G_{\text{ideal}})} \tag{5}$$

2.4 Resilience Quantification

Resilience in engineering science describes the ability of a system and its components to resist, absorb and recover from performance reduction triggered after an external disruptive event within a defined time period. The concept was first defined by Holling [10] for ecological systems and has since evolved, alongside resilience metrics, over the years. Metrics for the quantification of resilience are necessary in engineering applications. Various resilience metrics therefore exist. Ayyub gives a comprehensive definition of resilience and resilience metrics for complex technical systems in his paper [11]. Also Salomon et al. [12] provide an overview of various resilience metrics. The typical phases of system performance following a disruptive event are illustrated in Figure 5. In this process, the performance curve goes through the following phases: After an initially stable state, the curve drops due to a disruptive event. The extent to which the curve falls depends on the system's vulnerability (or robustness) against disruptive events. The subsequent recoverability phase defines the duration and the rise of the curve until a stable state is reached again (worse than old, as good as old, better than old).

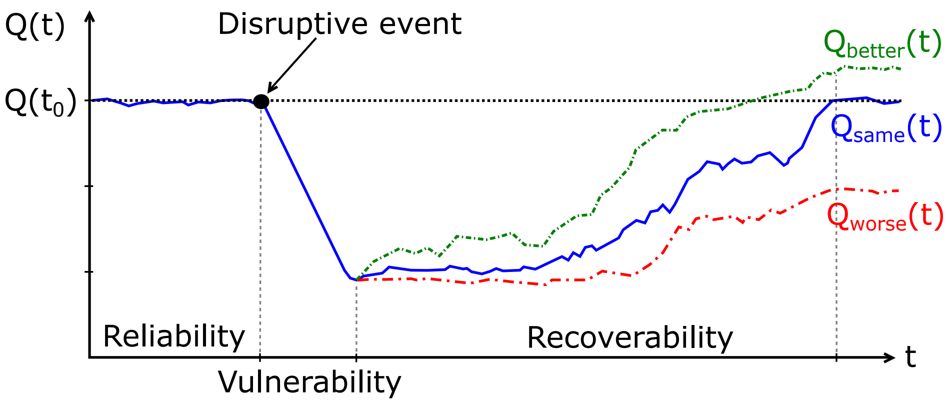

Figure 5: System performance course after a disruptive event. Figure by author.

For the algorithm proposed in this thesis, a simplified version of the probabilistic resilience metric developed by Ouyang et al. [13] is utilized. The expected resilience R for a given time interval $[0, T]$ is calculated as the quotient of the integral of the system performance $Q(t)$ and the integral of the target system performance $Q_{target}(t)$. The system's performances are obtained from stochastic processes. The equation is given by:

$$R = E[Y], \qquad \text{where } Y = \frac{\int_0^T Q(t)\,dt}{\int_0^T Q_{target}(t)\,dt} \tag{6}$$

For simplicity, the equation can be rewritten assuming a discretized time interval $T = [t_1, t_2, t_3, ...]$ and a constant non-random target performance $Q_{target,const.}$ in the following form:

$$R = E[Y_{simplified}], \qquad \text{where } Y_{simplified} = \frac{\sum_0^T Q(t)}{Q_{target,const.} \cdot T} \tag{7}$$

The resilience metric can take values between $[0,1]$. Where $R = 0$ indicates a failed system and a value closer to 1 indicates a system performance more corresponding to its target performance.

2.5 Road Infrastructure Networks

Road networks are linear infrastructure networks. They have a hierarchical mesh structure and occur on a small scale as suburban road networks, on a supra-regional, an international, and even intercontinental road network scale. Road networks are historically evolved networks and their design is subject to technological developments, traffic planning theories, political trends and, above all, the economic situation of a society that depends on an efficient road network to maintain economic operations. Highly meshed road networks have low structural vulnerability [4].
The German road network is classified as follows: Bundesfernstraßen (Autobahnen respectively highways for supra-regional connection of cities and regions), Bundesstraßen (federal roads), Kreisstraßen (sub-regional district roads) and Gemeindestraßen (local municipal roads. For this study, only the supra-regional roads are considered, which include highways (Autobahnen) and federal roads (Bundesstraße).
The individual components of a road network are the roads, for which there are different types of construction. The most common is asphalt (or asphalt-concrete). Asphalt roads consist of three layers: surface layer (provides the driving surface, grip, and resistance to deterioration from vehicle tires), binder layer (acts as an intermediary between the surface and base layers, distributing loads and contributing to structural strength), and base layer (serves as the main load-bearing layer, distributing weight and stresses to the substructure, aiding in stability and longevity of the road). Asphalt pavements are not rigid structures, they behave elastically (cold ambient temperature) or viscoelastically to plastically (warm ambient temperature) depending on the temperature and load. Roads are most stressed by heavy traffic (trucks, buses etc.). This

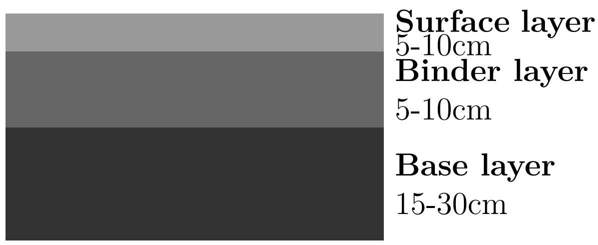

Figure 6: Structure of a upper structure of a asphalt road.

phenomenon is described by the fourth power law, which states that as the axle load of a vehicle increases, the load on the roadway caused by the vehicle increases in proportion to the fourth power of the axle load. A loaded truck with a total mass of 30 tons and 3 axles has an axle load of 10 tons per axle. According to the fourth power law, this results in a relative road damage of $10^4 = 10,000$ units per axle. For a car with a total mass of 3 tons and an axle load of 1.5 tons, the relative road damage is $(1.5)^4 = 5.0625$ units. These values are relative measures of road damage and cannot be converted directly into tons. Possible damages that can occur on the pavement are: alligator/ fatigue cracking (caused by heavy traffic loads and erosion due to deterioration, can form potholes as erosion progresses), rutting (caused by repeated heavy loads and viscoelastically behavior in warm temperatures), longitudinal/cross cracks (fatigue) and patches (due to local repairs). Three influencing factors can therefore be identified for the occurrence of distress: (heavy) traffic load, age and climate. Figure 7 shows two road conditions with different distresses.

Figure 7: Advanced deteriorated road with fatigue cracking, potholes, cross cracks and patches. Images by author.

2.5.1 Road Maintenance

Technical systems (mechanical, infrastructural, etc.) are subject to component and system-wide degradation. Maintenance can be understood as all measures (technical and management) that delay or reset this degradation. A classification of maintenance that is consistent with many standards (e.g. EN 13306 2017) is to divide maintenance into two main categories: corrective maintenance and preventive maintenance [14].

Corrective maintenance: This includes all measures that are taken when a failure is detected in a item. In the context of a road, a failure could mean that a certain speed limit is no longer safe for traffic. This means that in most cases, the item will be severely deteriorated before its condition will be strongly improved or fully restored. Actions could include resurfacing or reconstruction.

Preventive maintenance: This includes actions that delay degradation and only slightly restore the condition. This type of maintenance can be performed at fixed intervals (clock based) once the item has reached a certain age (age based) or has fallen below a certain condition (condition based). In the road sector, the following measures can be included: crack sealing, patching of cracks and small potholes, surface treatments etc.

Most authorities are unable to maintain all roads in the system optimally at all times due to limited financial and human resources. The more developed a road network is, the greater the financial burden on the authorities. This is why authorities often delay maintenance to keep current costs low. However, this leads to higher costs in the future, due to more extensive measures. It also increases the risk of infrastructure failure [4].

2.5.2 Pavement Condition Index

For the maintenance operators of a road network, precise knowledge of the road conditions is necessary; at the same time, a quantifiable value of the road condition is required in order to plan e.g. maintenance measures.
The Pavement Condition Index (PCI) describes the condition of asphalt- and concrete-surfaced road pavements. The condition is indicated with a numerical value between 0 and 100, where 100 stands for a distress-free condition (new condition) and 0 for a failed condition. The procedure consists of an optical survey (of the number of road distresses) and statistical evaluation of road segments. However, the information provided by the PCI is mainly limited to the surface layer. Based on the optical data acquisition, no conclusions can be drawn about the lower layers. Only in the case of a very poor condition with e.g. many and in particular deep potholes can some insight be gained into deeper layers.

PCI range [15]	Classification [15]	Distresses
85 – 100	Good	Fatigue Cracking: none Rutting: none Potholes: none Patches: none
70 – 85	Satisfactory	Fatigue Cracking: low Rutting: low Potholes: none Patches: low
55 – 70	Fair	Fatigue Cracking: low Rutting: medium Potholes: medium Patches: medium
40 – 55	Poor	Fatigue Cracking: medium Rutting: high Potholes: high Patches: high
25 – 40	Very poor	Fatigue Cracking: high Rutting: high Potholes: high Patches: high
10 – 25	Serious	Fatigue Cracking: very high Rutting: very high Potholes: very high Patches: very high
0 – 10	Failed	Fatigue Cracking: very high Rutting: very high Potholes: very high Patches: very high

Table 1: PCI classifications.

3 Literature Review

The literature review is divided into three parts. First, the concept of resilience and its quantification for complex engineering systems is considered. It also examines the incorporation of resilience into decision-making strategies for complex systems. This is followed by an overview of infrastructure simulation frameworks and the extent to which they incorporate the concept of resilience. The review concludes with a look at degradation modeling researches.

3.1 Resilience

The concept of resilience was first introduced in the context of ecological systems by Holling [10] and has since been continuously developed and applied to various other disciplines such as ecology, economics, psychology, mechanical and infrastructure systems. Holling defined resilience as the ability of systems to absorb change and disturbance while maintaining their fundamental relationships between components or state variables. This definition provides the foundation for numerous following definitions. Ayyub provides a very detailed derivation of a resilience definition in [11] and presents various definitions of reputable entities (e.g. Presidential Policy Directive [16], ASCE Committee on Critical Infrastructure [17] etc.). Ayyub himself proposes a definition of resilience based on [16] in [18]:"Resilience notionally means the ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions. Resilience includes the ability to withstand and recover from disturbances of the deliberate attack types, accidents, or naturally occurring threats or incidents. The resilience of a system's function can be measured based on the persistence of a corresponding functional performance under uncertainty in the face of disturbances."
Various metrics have been proposed to quantify resilience for engineering applications. The majority of resilience metrics are based on the system performance profile. Bruneau et al. [19] proposed a time-dependent resilience metric, where resilience is the area between the undisturbed system performance and the system performance after a disruptive event in the time boundaries $[t_0, t_1]$, where t_0 denotes the beginning of the disruption and t_1 the time point after recovery. In this context, the authors also described the "resilience triangle" for the first time, which describes the triangle-like area between undisturbed and reduced system performance. Bruneau and Reinhorn [20] proposed to measure resilience as expected system degradation by quantifying robustness, redundancy, resourcefulness and recovery. Ouyang et al. [13] describe a probabilistic resilience metric, which has already been explained in subsection 2.4.
The topic of decision making and resilience has been explored by Salomon et al. in [12], who integrate a resilience metric with a systemic risk measure to balance investments in resilience improvement. They searching space is two-dimensional. The authors extend

their method in [21] for complex and substructured systems with a multi-dimensional search space.

3.2 Infrastructure Simulation Frameworks

Fundamental literature in understanding the structure of a transportation network is the monograph by Rodrigue [4]. In his book, the author provides a comprehensive overview of the structure and characteristics of various transportation networks (rail networks, maritime networks, road networks, etc.). In addition, the author explains the interactions between these networks on society, the economy and administration. Various types of network modeling are also presented.
A comprehensive review of research on transportation infrastructure simulation frameworks for the period 2010 - 2020 is provided by Dong et al. in [22]. For the authors, simulation methods can be divided into four fundamental types (Monte Carlo simulation, network-based simulation, numerical simulation, and agent-based simulation). The approaches are reviewed from three perspectives (purpose, data demand, modeling approach). Of the 32 analyzed papers, 9 concern road networks with different focuses of investigation (recoverability, reliability, robustness and resourcefulness), which consider only partial aspects of the topic of resilience. In [23], Aydin et al. developed a stochastic framework that investigated different road recovery strategies for restoring connectivity after earthquakes and earthquakes-triggered landslides. Their study was limited to rural transportation networks only. [24] et al. developed and applied a framework to assess and compare the resilience of the Valencia and Sardinia road networks, eliminating sections, integrating climate change factors and identifying critical areas, ultimately supporting transportation planning and policy making. Ganin et al. [25] investigated the resilience and efficiency in transportation networks. They measured efficiency as the annual average delay per peak period. They concluded that not only efficiency, but also resilience should be considered when investing in road projects.

3.3 Degradation Modeling

In their review on degradation modeling, Gorjian et al. [26] classified the available degradation modeling approaches into four categories, namely experience-based, model-based, knowledge-based, and data-driven approaches. Shahraki et al. give in [27] an extensive overview of existing degradation models in engineering applications and classified the methods into two categories. Data-driven models using statistical methods (e.g. general path model and stochastic process models) without taking into account (physical) degradation mechanisms, whereas physics-based methods (e.g. Physics-of-failure model) are deterministic and considers physical failure mechanisms. The authors draw the following conclusions:

1. Most of the current literature only deals with a single degradation process and thus heavily simplifies the degradation model, especially if the degradation is caused by different influences.

2. It is necessary to develop models that take into account the time-varying operating conditions (e.g. time-varying loads) of the system.

3. Hybrid degradation models should be explored more in the future. For example, by combining two different types such as data-driven models and physics-based models.

4. More research is needed to further integrate degradation modeling into decision-making strategies.

In [28] Abaza developed an optimum network-level pavement rehabilitation model to create long-term, cost-effective rehabilitation schedules using a discrete-time Markov model. This model predicts the performance of original and rehabilitated pavements by incorporating pavement improvement rates into the transition probability matrix. The results provided the minimal annual budget required to progressively remove the “very poor” pavements that greatly affect the life-cycle cost. Salem [29] applied a variance gamma process to predict the remaining useful life of a water tank pump. She highlights the importance of collecting real data from the degradation in addition to the basic stochastic process in order to adjust the parameters of the stochastic process properly. Wu and Castro [7] applied a weighted linear combination of degradation processes (gamma processes) to optimize the time between preventive maintenance actions and the number of preventive maintenance for a system subject to three different defects.

4 Proposed Methodology

For the thesis, a probabilistic approach was developed that determines time-dependent maintenance strategies for a road network. The optimal strategy is selected on the criteria of satisfying a certain resilience threshold and the expected costs in the considered time interval. In more detail, the algorithm can be divided into the following aspects:

1. Retrieval of a road network graph and data from Open Street Map (OSM)
2. Simulate pavement degradation of a road (edge) using a stochastic process to consider environmental and traffic load dependent deterioration.
3. Simulate the relationship between pavement condition and travel time.
4. Consider maintenance measures with different levels of quality to improve the pavement condition after deterioration.
5. Implement Monte Carlo sampling to calculate expected network efficiency for a system with different maintenance strategies over time.
6. Using the brute force technique to identify all maintenance strategies and select the optimal maintenance strategy based on reliability and expected cost.

4.1 Road Network Retrieval

To obtain real road networks and their geospatial data, the Python package OSMnx [30] is used for the algorithm. OSMnx is able to extract all route data stored in Open Street Map. This includes all classes of roads, bike lanes, pedestrian paths, tram and rail lines, etc. Two built-in functions of OSMnx can be used for the algorithm. The function `graph_from_place` extracts the network data within its official boundaries (e.g. district, city, state borders etc.), `graph_from_point` extracts the data within a radius around a geo-differentiated point.
Due to the very large, but also partly inconsistent amount of data available in Open Street Map, filters and simplifications have to be applied in order to extract a manageable network for further calculations. The above functions allow a custom filter to extract only specific road classes (highway ∼ motorway, trunk, primary, secondary, tertiary etc.). Only Autobahnen (highway ∼ motorway, trunk) and Bundesstraßen (primary) are considered for the algorithm. If any unclassified roads remain in the network, they will be deleted.
The `simplification.consolidate_intersections` function helps to further simplify the network by consolidating clusters of nodes. Typically, intersections in OSM are modeled in detail with multiple nodes. This function can be used to specify a tolerance value that will cause nodes within that radius (in [m]) to be consolidated into a

single node. When combining nodes, edges are also combined (e.g. turn lanes). This means that the attributes "maxspeed", "lanes", and "length" are also combined. However, for simplicity, the algorithm requires only one attribute per edge. If there are multiple values for "maxspeed", the average value is used as the "maxspeed" attribute. In the case of "lanes", only the smaller value is used, since there are often several turning lanes near intersections, but these are relatively short and not representative compared to the total length of the edge. The graph often contains vertices that connect only two edges. These are often nodes that connect to subordinate roads (not retrieved). It would not be advisable to remove these nodes, since the two adjacent edges must now also be connected to form an edge, and the attributes may differ too much. As can be seen in Figure 8, the tolerance value must be selected in a balanced manner, as otherwise too many nodes will be grouped together and distort the topology too much. Small tests have shown that a value between 150m and 200m is appropriate. The following necessary attributes are also added to the edge: "PCI", "age" (the age

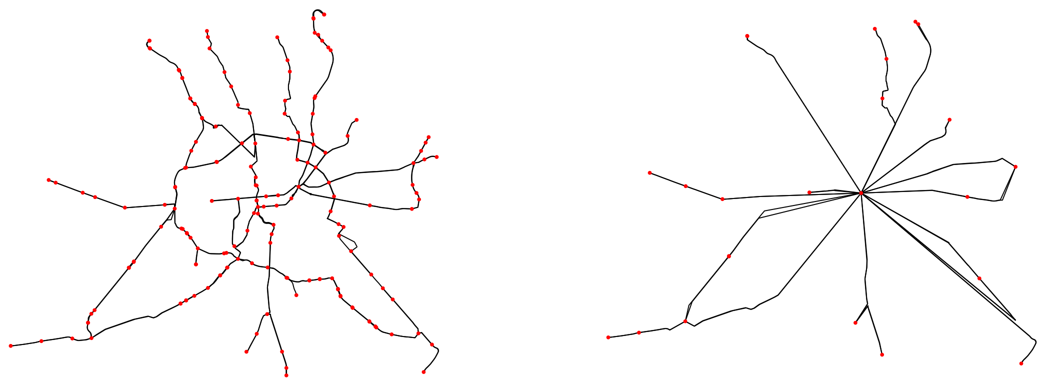

Figure 8: Berlin with cluster simplification tolerances of 200 m and 800 m.

of the edge is required for the stochastic process), "maintenance" (indicates whether maintenance measures take place on the edge) and "duration" (indicates how many time steps the maintenance is carried out). After retrieval, the edges have the following edge attributes: "length", "lanes", "maxspeed", "PCI", "time", "maintenance", "age" and "duration".

The graph can be saved in Graph Exchange XML format (.gexf) for later use for network analysis with the Python package NetworkX [31].

4.2 Pavement Degradation Stochastic Process

The pavement degradation is observed as a curve-linear shaped curve [32]. Initially, there is a slight spread of damage, which accelerates and intensifies as pavement integrity decreases. A weighted linear combination of two gamma processes is used to model pavement deterioration. One gamma process describes the influence of (heavy) traffic on the overall degradation and the other process describes environmental influences (e.g. temperature variations, heavy rain, frost, etc.). The both gamma processes are described by equation 2 with the shape parameters $\alpha_{traffic} = 1$ and $\alpha_{env.} = 0.5$, as well as the scale parameters $\beta_{traffic} = 0.6$ and $\beta_{env.} = 0.3$. In the context of degradation, α_k and β_k can represent the speed and intensity of damage expansion by stretching or compressing the gamma distribution. Several studies have shown that heavy traffic contributes significantly more to the total pavement deterioration than environmental influences [33] [34] [35]. Therefore, a weight of $\xi_{traffic} = 0.65$ and $\xi_{env.} = 0.35$ is assumed.

The overall degradation process $\{Y(t)\}_{t\geq 0}$, where t is the age of the pavement, is described by

$$Y(t) = \xi_{traffic} X_{traffic}(t) + \xi_{env.} X_{env.}(t), \quad with \quad t \geq 0. \tag{8}$$

Table 2 is a summary of the parameters and Figure 9 is a visualization of the degradation process under these parameters.

	α_k	β_k	ξ_k
$X_{traffic}$	1.00	0.60	0.65
$X_{env.}$	0.50	0.30	0.35

Table 2: Parameters summary.

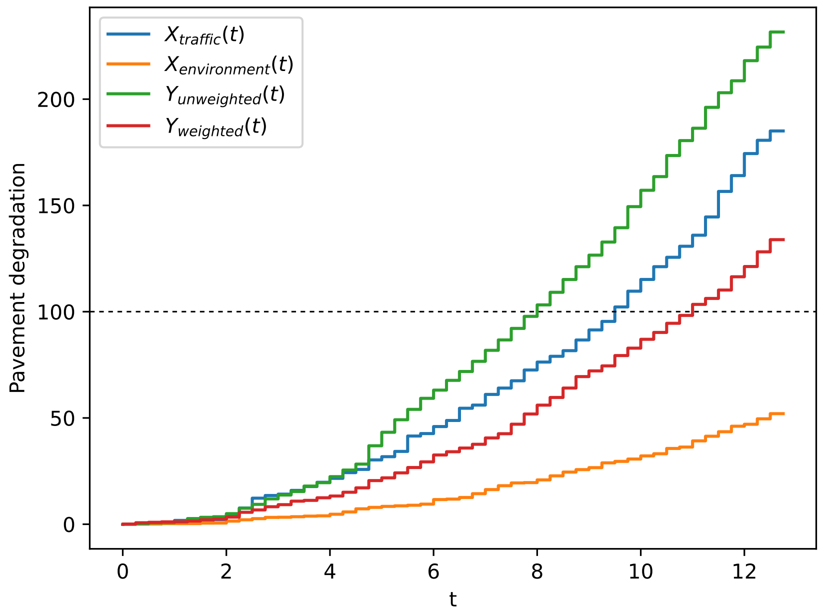

Figure 9: Realization of the degradation process with its partial degradations.

4.3 Edge Performance

A deterioration of the road surface leads to a reduction in the speed of the vehicles. The relationship between speed and PCI was investigated in [36] and [37]. In [37], a linear decrease in speed can be observed for decreasing PCI for all vehicle classes. Whereas in [36] a curve-linear decrease was detected. For simplicity, the model assumes a linear relationship between speed and PCI. The equation 9 describes the velocity $v(e_i)$ of an edge e_i, where $v_{max}(e_i)$ is a constant value for the maximum allowed velocity (official speed limit) and $PCI(e_i)$ is the condition of the edge.

$$v(e_i)\left[\frac{km}{h}\right] = v_{max}(e_i) - (0.5 \cdot (100 - PCI(e_i))) \tag{9}$$

The performance of the edge is indicated by the travel time. For simplicity the model dose not consider traffic flow dynamics [38] (e.g. congestion, traffic density and speed flow, driving behavior etc.). A free flow is assumed on each edge and the vehicles can travel at a constant speed on the edge. The corresponding travel time $t_{travel}(e_i)$ is calculated using the following formula, where $l(e_i)$ is the length of the edge e_i:

$$t_{travel}(e_i)[min] = \left(\frac{l(e_i)}{v(e_i)}\right)\left[\frac{km}{km/h}\right] \cdot 60. \tag{10}$$

4.4 Road Maintenance Measures

The road maintenance for an edge goes through several steps:

Step 1: Inspection

If no maintenance is currently being performed on the edge, its status is checked using an inspection function. Based on the PCI determined, an appropriate measure (preventive or corrective) is defined to be initiated in the next time step. The function takes into account the limited financial and human resources of the network operators, i.e. not all edges can be maintained. Therefore, it is possible that no action is determined for the edge and it will be checked again in the next time step. In any case, the edge will continue to degrade until the next time step.

Step 2 and 3: Start of the measures and ongoing measures

The maintenance task that was defined in the previous time step is initiated. Depending on the type, intensity and duration of the maintenance, the "travel time" is increased by a predefined constant factor (travel time impact). This is to take into account any disruptions to traffic flow caused by the roadworks (lane closures, temporary and sectional speed reductions, congestion, etc.). In cases where the road surface is completely renewed, the edge is completely closed and its travel time is set to infinity.

Step 4: Completed measures

After the measures have been completed the PCI will be upgraded depending on the type and the quality of the measure. An imperfect repair is assumed (except for new construction), so that the improvement value for the PCI varies. The factor for the increasing of the travel time will be removed and the age of the edge will be reset. Reminder: The age is the time variable for the stochastic deterioration process. The road is inspected again by the inspection function in the next time step.

The costs for a single measure are calculated using the formula:

$$c_{measure}\,[EUR] = length\,[m] \cdot lanes\,[-] \cdot price\,[EUR/m]. \tag{11}$$

Table 3 and Table 4 show possible specific measures for the individual quality levels and their parameters.

	Sparse	**Moderate**	**Extensive**
Preventive maintenance	street cleaning, roadside works	patching, crack sealing, repair of small potholes	resurfacing/ repaving
Corrective maintenance	temporary, provisional repair	road rehabilitation/ renovation	reconstruction

Table 3: Comparison of preventive and corrective maintenance measures

	Sparse	**Moderate**	**Extensive**
Preventive maintenance	$5\,EUR/m$ $\Delta_{PCI} \sim \mathcal{N}(4, 2^2)$ $\Delta_{age} = 1$ $t_{duration} = 0$ $t_{impact} = 1.5$	$12.5\,EUR/m$ $\Delta_{PCI} \sim \mathcal{N}(25, 5^2)$ $\Delta_{age} = 6$ $t_{duration} = 1$ $t_{impact} = 1.5$	$25\,EUR/m$ $\Delta_{PCI} \sim \mathcal{N}(40, 5^2)$ $\Delta_{age} = 10$ $t_{duration} = 2$ $t_{impact} = 2$
Corrective maintenance	$25\,EUR/m$ $\Delta_{PCI} \sim \mathcal{N}(20, 5^2)$ $\Delta_{age} = 3$ $t_{duration} = 1$ $t_{impact} = 2$	$50\,EUR/m$ $\Delta_{PCI} \sim \mathcal{N}(60, 5^2)$ $\Delta_{age} = 15$ $t_{duration} = 2$ $t_{impact} = 2$	$100\,EUR/m$ $PCI = 100$ $\Delta_{age} = age$ $t_{duration} = 4$ $t_{impact} = \infty$

Table 4: Preventive and corrective maintenance parameters

4.5 Road Network Efficiency

For each strategy, the network efficiency is determined as the arithmetic mean of n Monte Carlo generated samples. The network efficiency is calculated according to equations 4 and for standardization 5 using travel time as the edge weight. For equation 4, the Floyd-Warshall algorithm is used to determine all pairwise shortest paths. The required target efficiency is calculated once on the ideal network immediately after the network retrieval. In the ideal network, all edges have a PCI of 100, resulting in an optimal travel time for each edge. The ideal network efficiency is a global constant and is the same for each strategy.

4.6 Resilience Optimization and Decision Making

For a road network G two different time intervals are given, one is a discrete time interval $T = \{t_1, t_2, ..., t_n\}$ and the other is a closed set of discrete decision time points $T_{decision} = \{T_1, T_2, ..., T_N\} \subseteq T$. In addition, two different maintenance types m_1, m_2, each with three quality levels $q_K = \{\text{sparse}, \text{moderate}, \text{extensive}\}$ respectively $q_K = \{1, 2, 3\}$ were given. The decision points in $T_{decision}$ are distributed equidistantly. At the decision time points, a configuration of the maintenance types is defined and described by the tuple $(q_1(T_i),\, q_2(T_i))$. This maintenance configuration now applies permanently to the system for all intermediate time steps until the next decision point is reached $T_i \leq t_i \leq T_{i+1}$.

A strategy s_i can now be described as a set of tuples over T using the following notation: $s_i = \{(q_1(T_0),\, q_2(T_0));\, (q_1(T_1),\, q_2(T_1)); ...;\, (q_1(T_N),\, q_2(T_N))\}$.

All possible combinations of tuples are computed using the brute force method, resulting in all possible strategies $S = \{s_1, s_2, ...\}$ for the time interval T. Figure 10 shows the search space. The number of all strategies in the search space can be determined with:

$$(n_q^2)^T \tag{12}$$

Where n_q is the number of quality levels and T is the number of decision points. Using

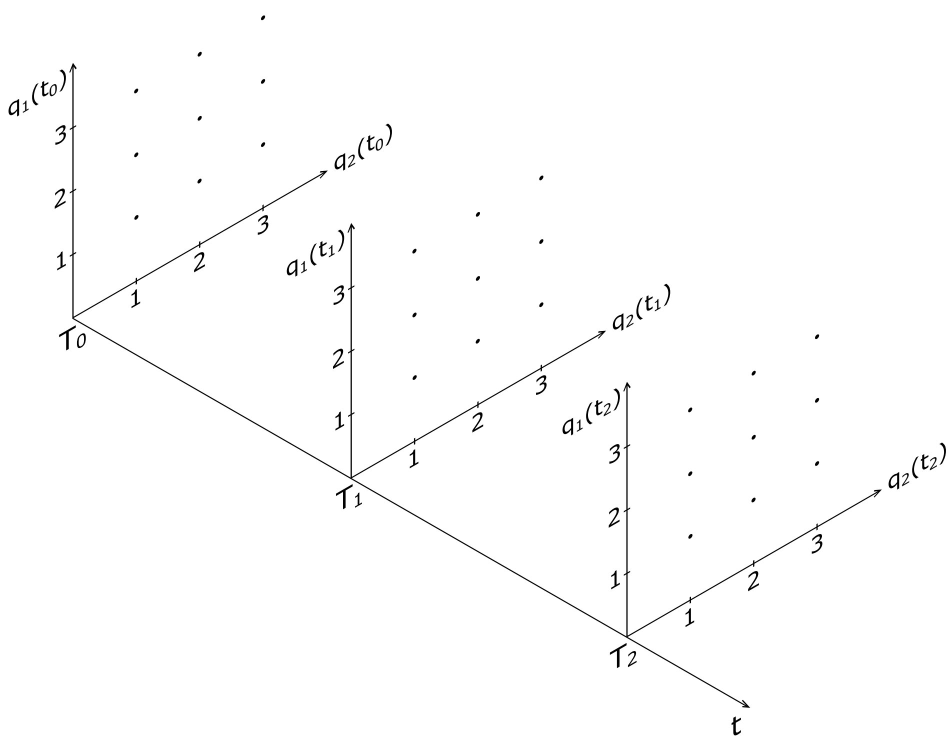

Figure 10: Search space for a system with three decision points T_i and two maintenance types, each with three quality levels q_k.

Equation 11, the expected total cost of a strategy can be given by

$$c_{total}(s_i)\,[EUR] = \sum_{i=1}^{n} c_{measure} \tag{13}$$

where n is the total number of all operations.
The decision as to which strategy s_i is optimal for a given time period T is made on the basis of two necessary criteria.

1. Taking into account Equation 7 strategy s_i satisfies the resilience criterion $R = E[Y(s_i)] \geq \kappa_{res.}$ for the time period T.

2. The expected total costs $c_{total}(s_i)$ of strategy s_i are the lowest of a set of strategies $S_{res.} = \{s_1, s_2, ...\}$, which also fulfill the resilience criterion $\kappa_{res.}$.

A flowchart is given in Figure 11 to illustrate the main process of the approach.

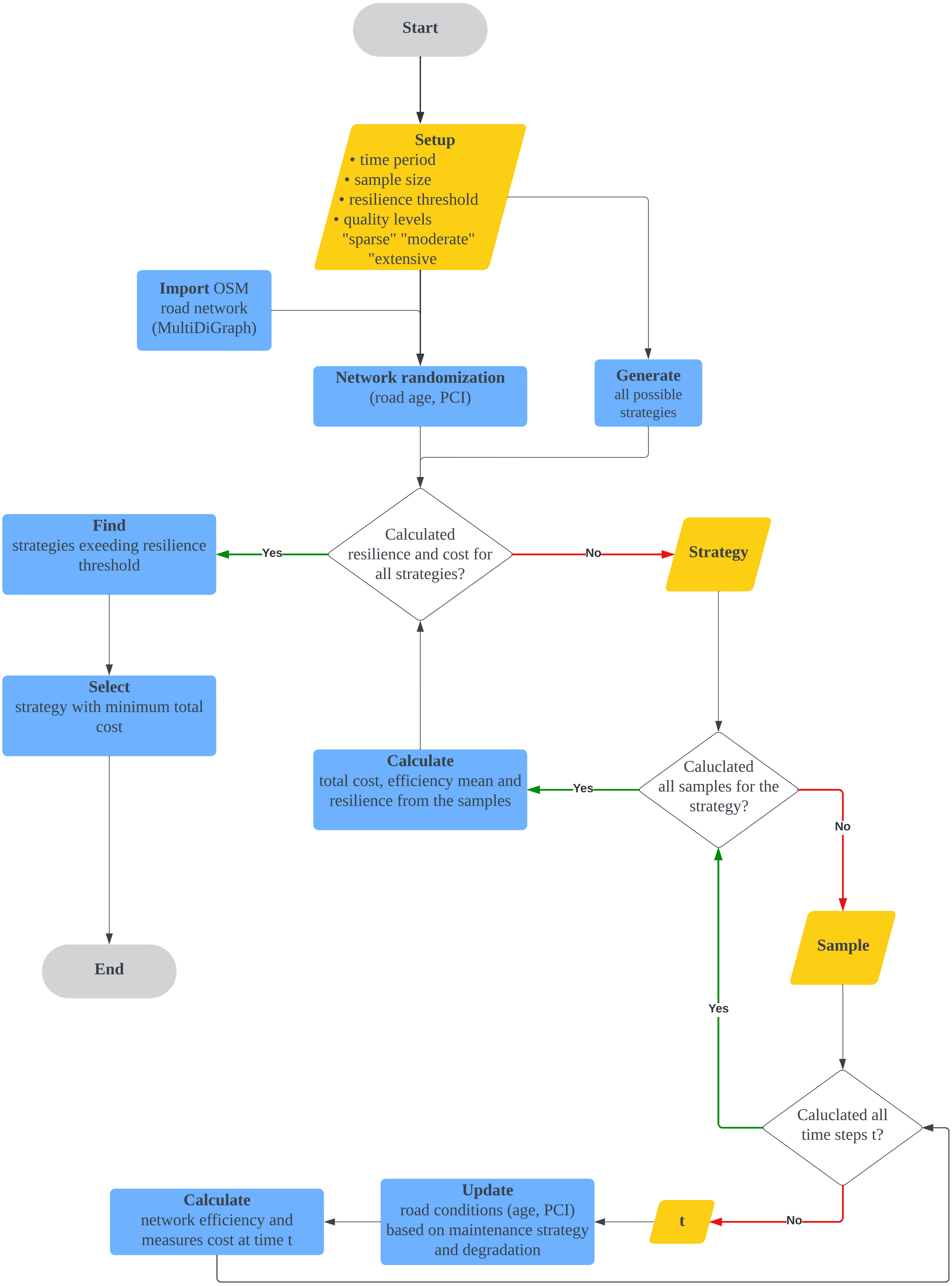

Figure 11: Flowchart of the main simulation process.

5 Case Studies

The algorithm is tested as realistically as possible on real road networks in Germany and the network topologies are extracted from Open Street Map via OSMnx. More precisely, only networks with highway (Autobahn) and federal road (Bundesstraße) road types are considered for the following reasons:

1. Highways and federal roads can be considered a autonomous network because highways and federal roads connect the same (interregional) locations. In addition, federal roads are used as preferred alternate routes in the event of highway closures or disruptions. To a certain degree, the traffic remains in the network and does not migrate to secondary networks (local roads etc.). Additionally, many federal roads, especially in regions with high traffic volumes, are developed in a motorway-like manner (e.g. structurally separated lanes, multi-lanes etc.).

2. Most heavy traffic takes place on highways and federal roads. In particular, not only national freight traffic, but also international freight transit traffic takes place on highways.

The study cases differ in network topology (star-shaped, meshed, radial ring, etc.) and sample size. The age of the roads and the associated road condition (PCI) are randomly generated at the beginning due to lack of data. The computer used for all simulations has the following specifications: CPU AMD Ryzen 5 1600 six-core processor, 3.2 GHz, 16 GB RAM, OS Windows 10.

5.1 Sample Size Estimation

For each strategy, the network efficiency is sampled using a Monte Carlo simulation. Estimating the sample size has a major impact on the accuracy of the results. According to the law of large numbers, the mean of a sample converges to the expected value of the random variable as the sample size increases. The following figures Figure 13 and Figure 14 are an attempt to get an approximate overview of sample size. The underlying network is a multi-directional graph with 6 nodes and 19 edges Figure 12. The maintenance strategy is in the lowest-level configuration $s_1 = \{(sparse, sparse); (sparse, sparse); (sparse, sparse)\}$. The Networks efficiency for the maintenance strategy with the lowest configuration can be seen to stabilize between 0.5 and 0.6. In addition, a sharp drop in the curve can always be observed at the beginning of the calculation. This observation was also made for all subsequent cases. The standard deviation σ for this sample network concentrates between 6 % and 8 % after 100 time steps. From a sample size of 800, the curve stabilizes significantly. The lowest standard deviation has a sample size of 1600. For this small network, the calculation could be performed in a few seconds. However, it turned out that a sample size of 800, for example, was no longer manageable for the networks of the following cases (run time of several days). Very small sample sizes therefore had to be used for the following case studies.

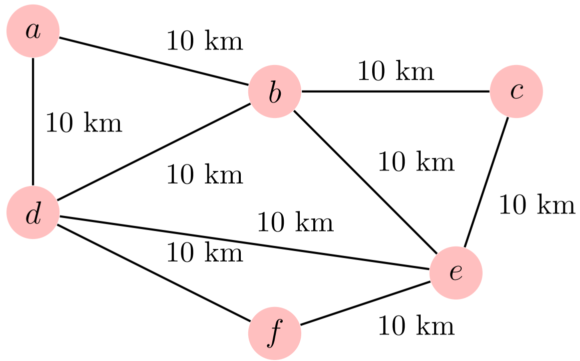

Figure 12: Simple test network.

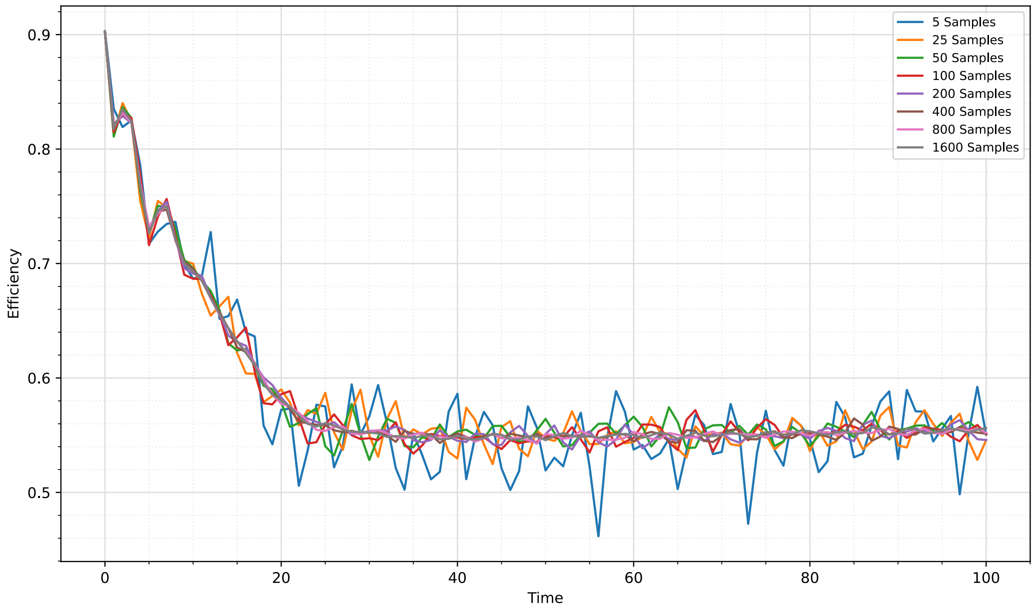

Figure 13: Network efficiency for various sample sizes.

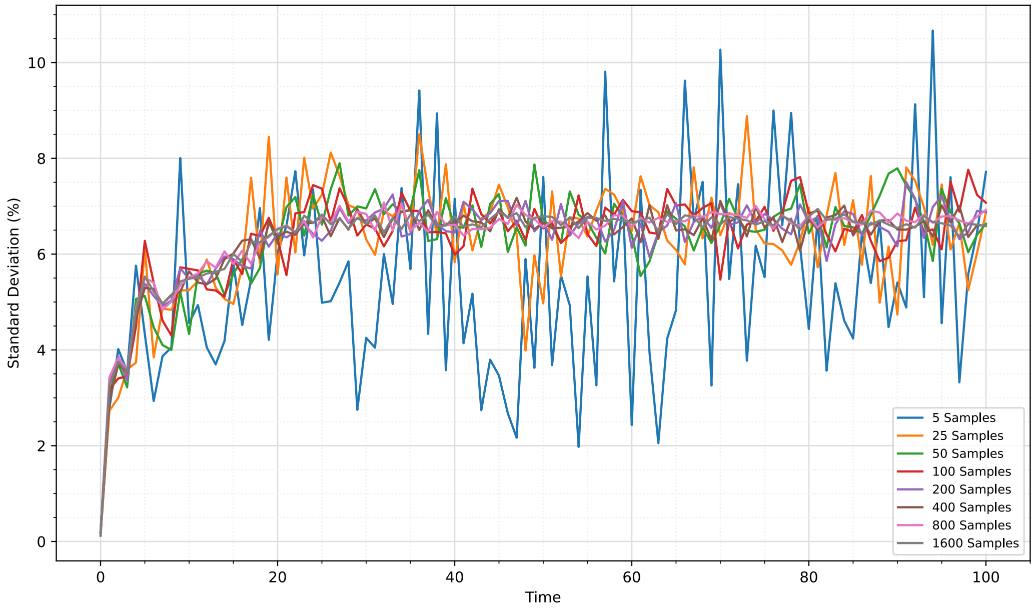

Figure 14: Relative standard deviation σ [%] for various sample sizes.

5.2 Case Study: Berlin

Berlin is the capital of Germany and also the largest city. The extracted road network is represented in Figure 15. The network is primarily star-shaped and most of the edges correspond to federal roads. The highways (A 100, A 111, A 113, A 115) only exist in the west and south. A resilience threshold of 0.75 was set for the simulation with 25 samples. The threshold could not be reached when the simulation was repeated several times. The strategy $s_{600} = (extensive, moderate); (moderate, sparse); (extensive, sparse)$ was found for a resilience threshold of 0.7. The expected costs amount to 12,267,618,658.80 EUR for 30 years.

In Figure 16 and Figure 17 the trend of the network efficiency and the expected costs are visualized. Due to the large number of measures and the corresponding traffic disruptions, the efficiency drops drastically to below 40% at the beginning of the analysis. This indicates a high number of roads in require of maintenance ("investment deficit in the past"). In general, it can be observed that an increase in measures results in disruption to traffic and a decrease in efficiency.

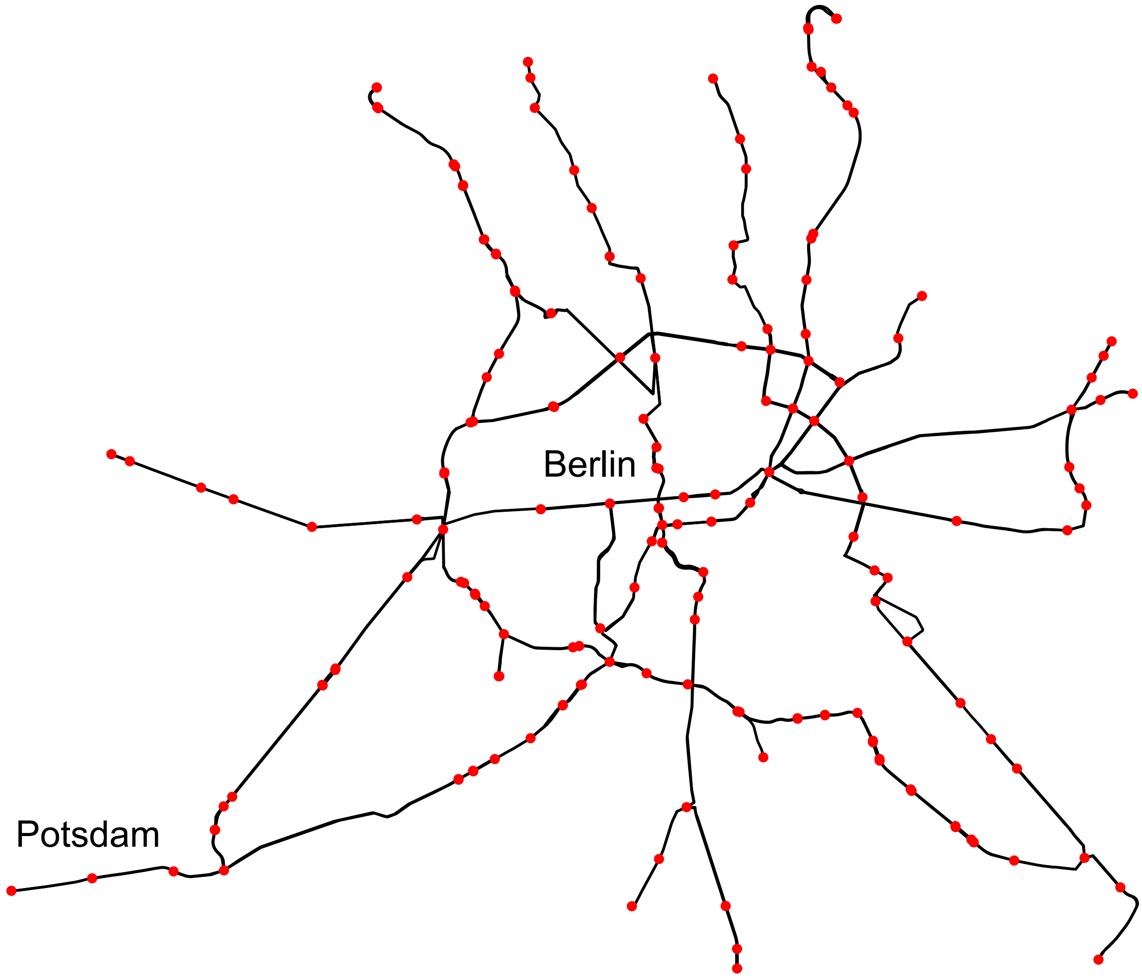

Figure 15: Investigated simplified road network of Berlin.

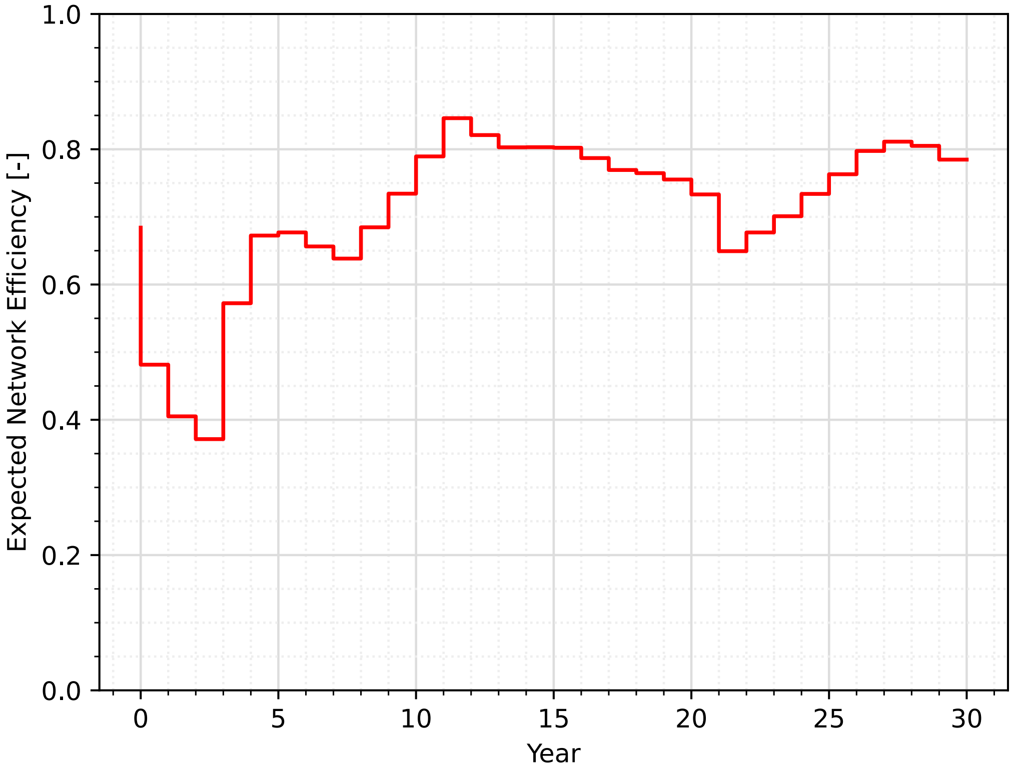

Figure 16: Expected network efficiency of Berlin.

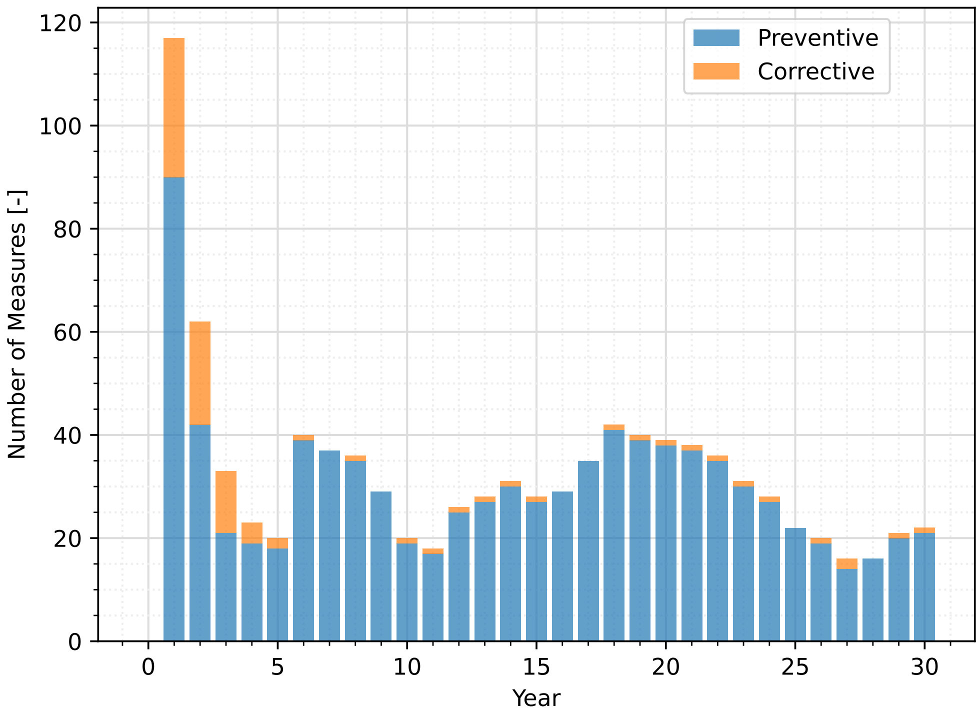

Figure 17: Number of measures of Berlin's identified strategy.

5.3 Case Study: Hamburg

Hamburg is the second largest city in Germany. The network is shown in Figure 18 and shows a more meshed structure. The A7 highway, which is an important connection between Scandinavia and southern Europe, is located in the west. A resilience threshold of 0.75 was set for the simulation with 25 samples. The algorithm has determined the strategy $s_{633} = (extensive, moderate); (extensive, moderate); (moderate, sparse)$. The resilience achieved is 0.752 and the expected costs are 12,514,275,408.21 EUR for 30 years. The results in Figure 19 and Figure 20 are very similar to those of Berlin, which indicates a similar ratio of highways and federal roads. Initially, large investments are made with many construction phases, which reduces the network performance to below 40%. As soon as the network is in a better condition again, a lower intensity of measures is selected.

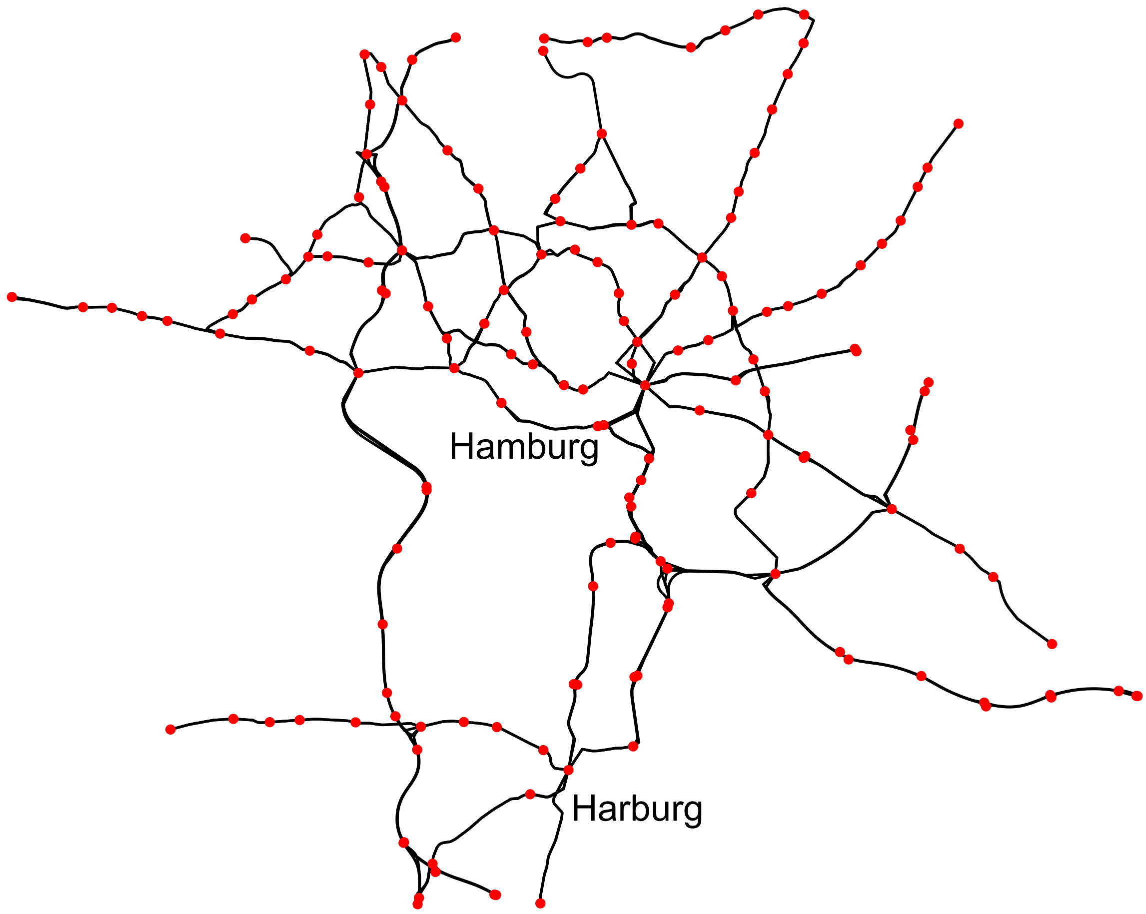

Figure 18: Investigated simplified road network of Hamburg.

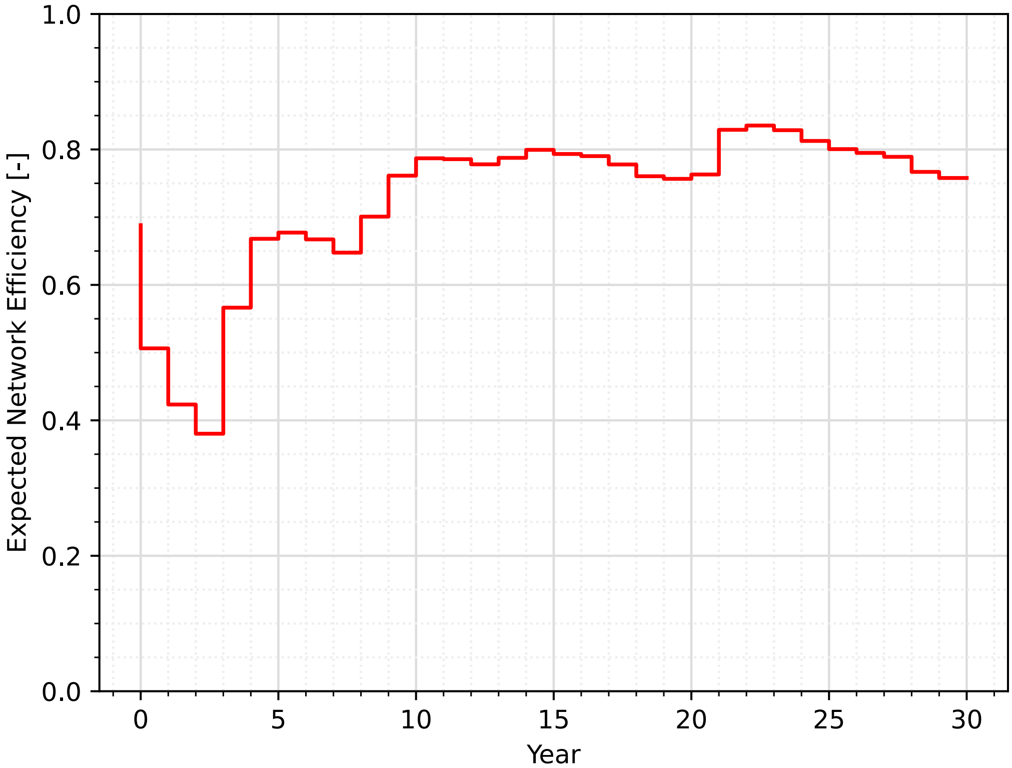

Figure 19: Expected network efficiency of Hamburg.

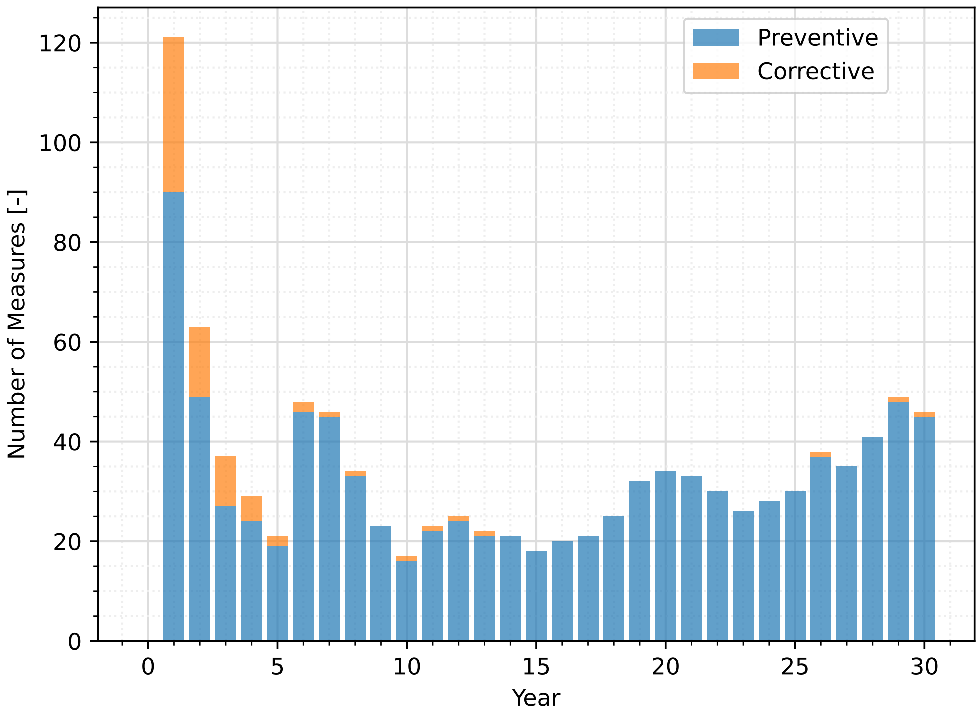

Figure 20: Number of measures of Hamburg's identified strategy.

5.4 Case Study: Frankfurt a. Main

The extracted road network of Frankfurt am Main Figure 21 is slightly smaller than Berlin and Hamburg. Frankfurt is the intersection of north-south and west-east highways. A resilience threshold of 0.75 was set for the simulation with 25 samples. The identified strategy is: $s_{625} = (extensive, moderate); (extensive, sparse); (moderate, moderate)$, with expected costs of 6,056,960,578.49 EUR for a time period of 30 years. An resilience of 0.756 has been reached. The results are illustrated in Figure 22 and Figure 23. It shows similar results to the other cases. The early drop in network performance is slightly above 0.4 and in the following years the performance stabilizes slightly above the initial performance.

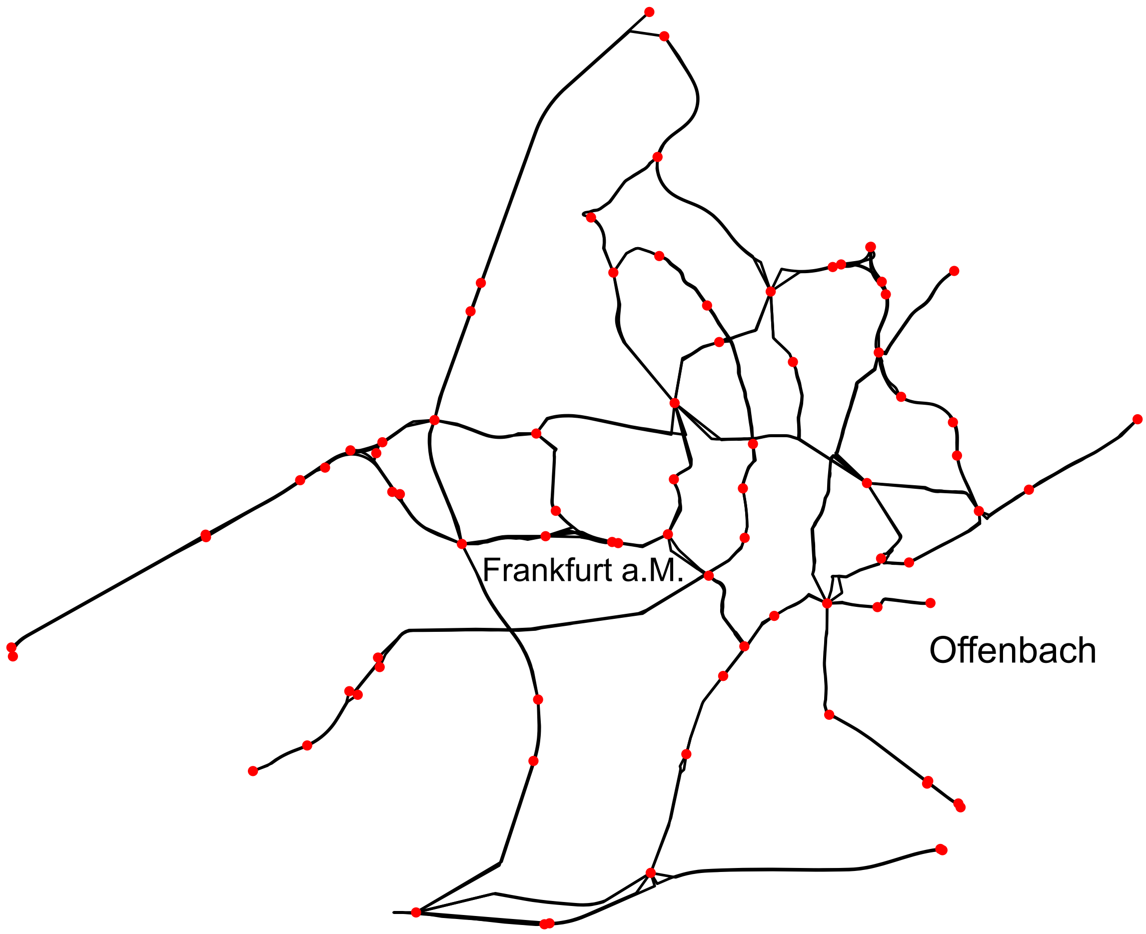

Figure 21: Investigated simplified road network of Frankfurt a. Main.

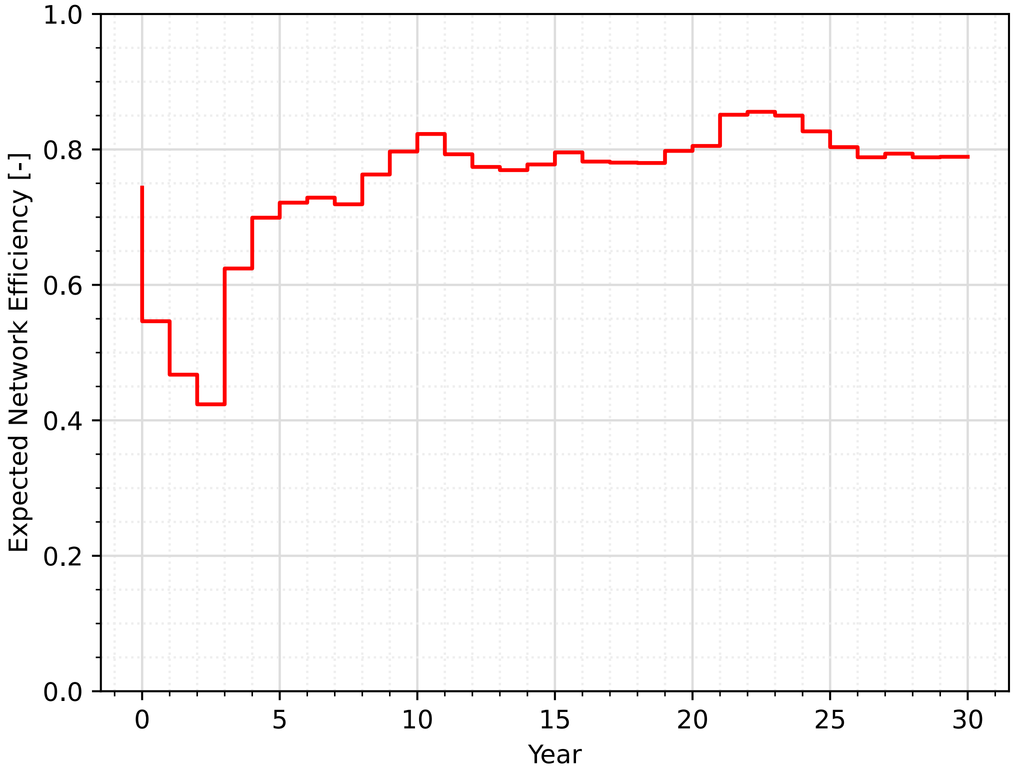

Figure 22: Expected network efficiency of Frankfurt.

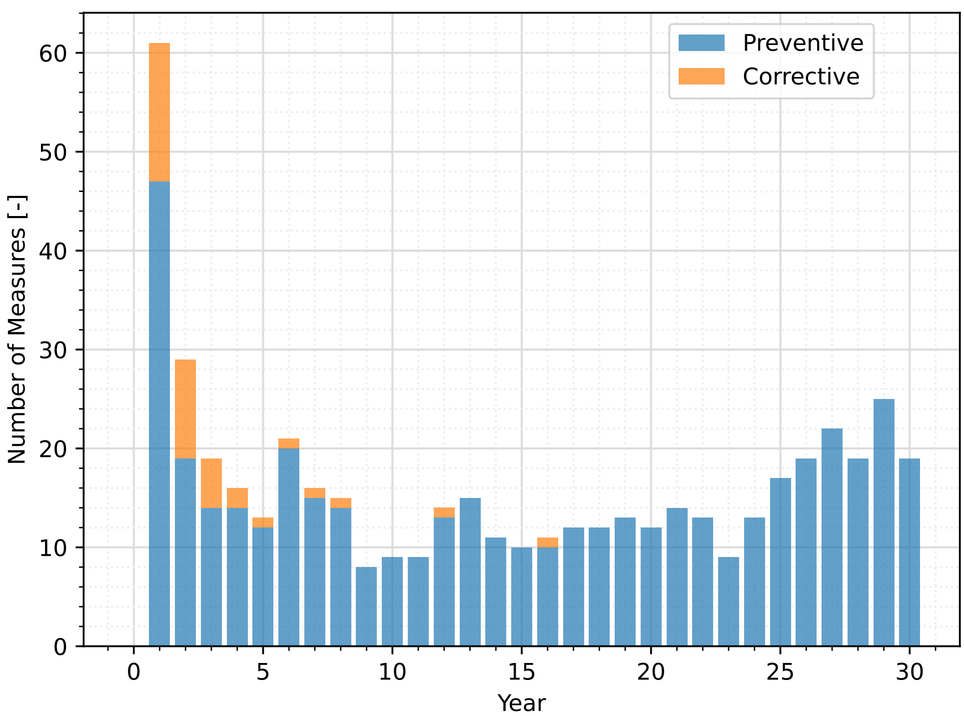

Figure 23: Number of measures of Frankfurt's identified strategy.

5.5 Case Study: Köln

Cologne (Köln) is the fourth largest city in Germany. Cologne is located in the Rhine-Ruhr metropolitan region. The metropolitan region is a combined economic area with a high density of highways and federal roads. The extracted road network in Figure 24 can be seen as a subnetwork of the metropolitan region. A resilience threshold of 0.75 was set for the simulation with 25 samples. The identified strategy is: $s_i = (extensive, moderate); (moderate, moderate); (moderate, sparse)$ with a resilience of 0.753. The expected cost over a 30-year period is 11,371,118,146.51 EUR. The results in Figure 25 and Figure 26 show a high number of initial maintenance measures to bring the road network from a poor state of maintenance to a better condition. Due to the high number of measures in the beginning, the network efficiency drops to almost 0.4. After the initial investments are completed, the performance stabilizes at 0.8.

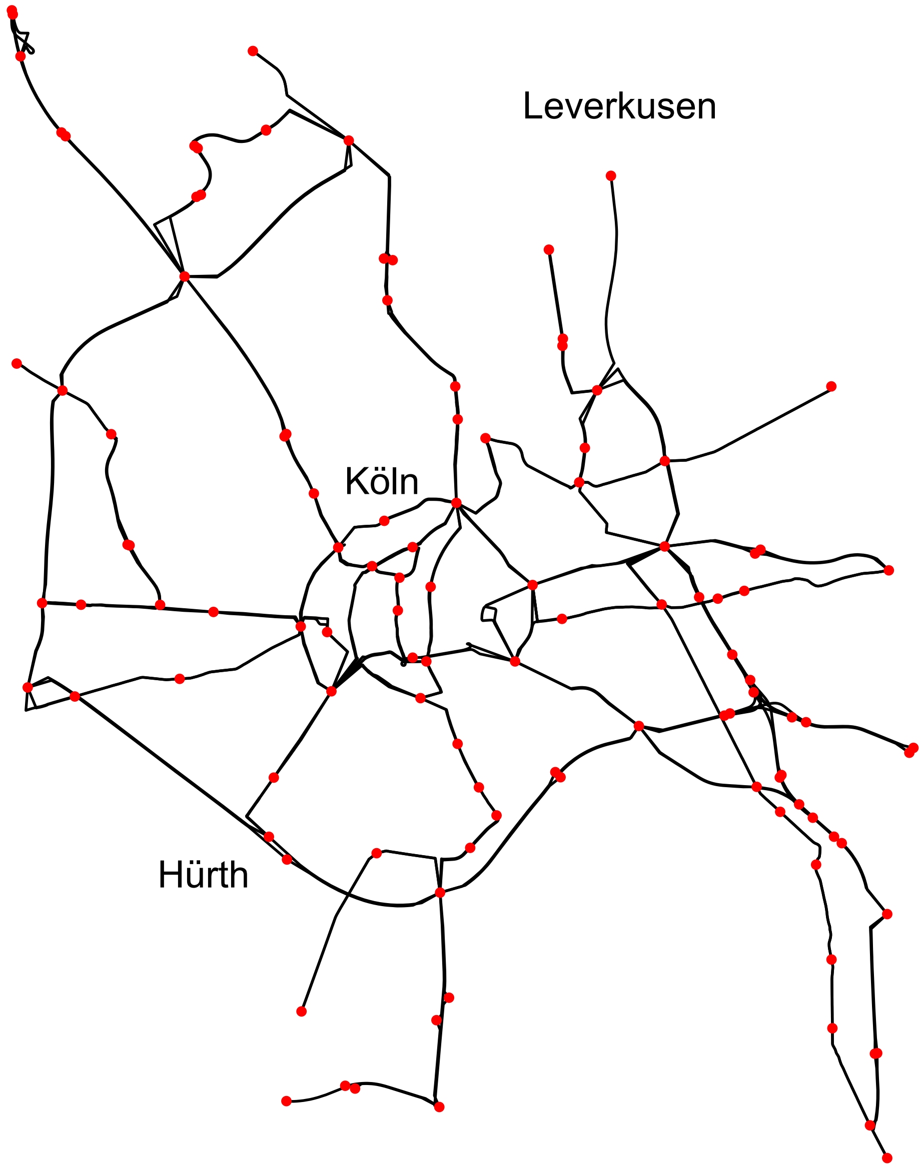

Figure 24: Investigated simplified road network of Cologne.

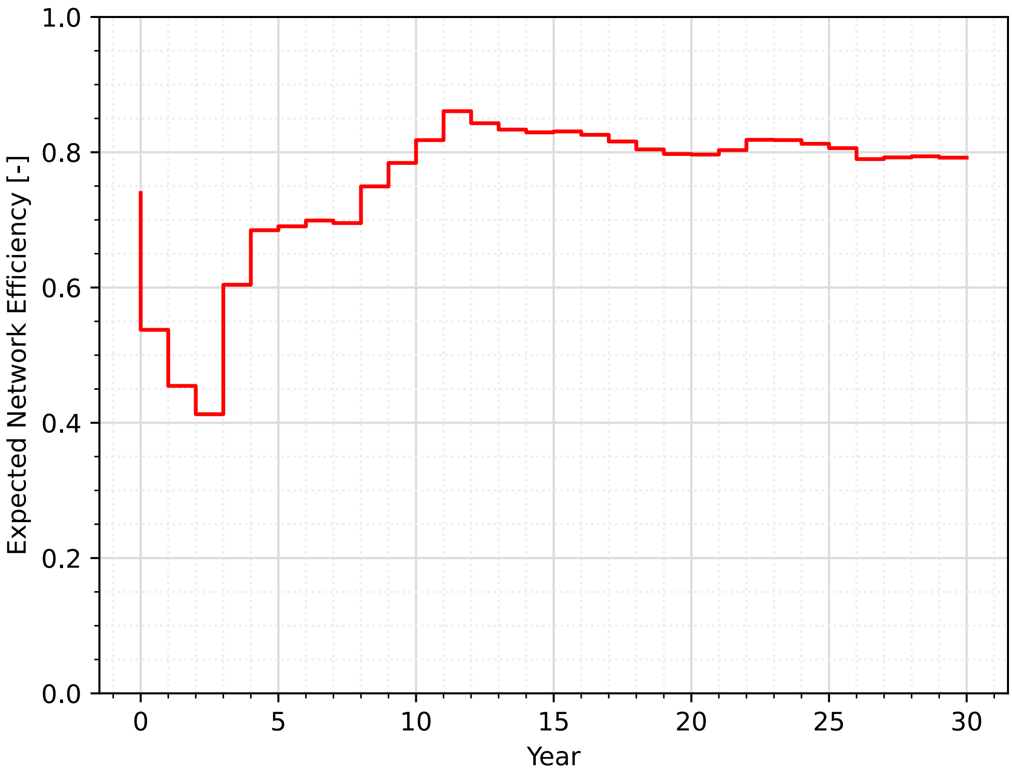

Figure 25: Expected network efficiency of Cologne.

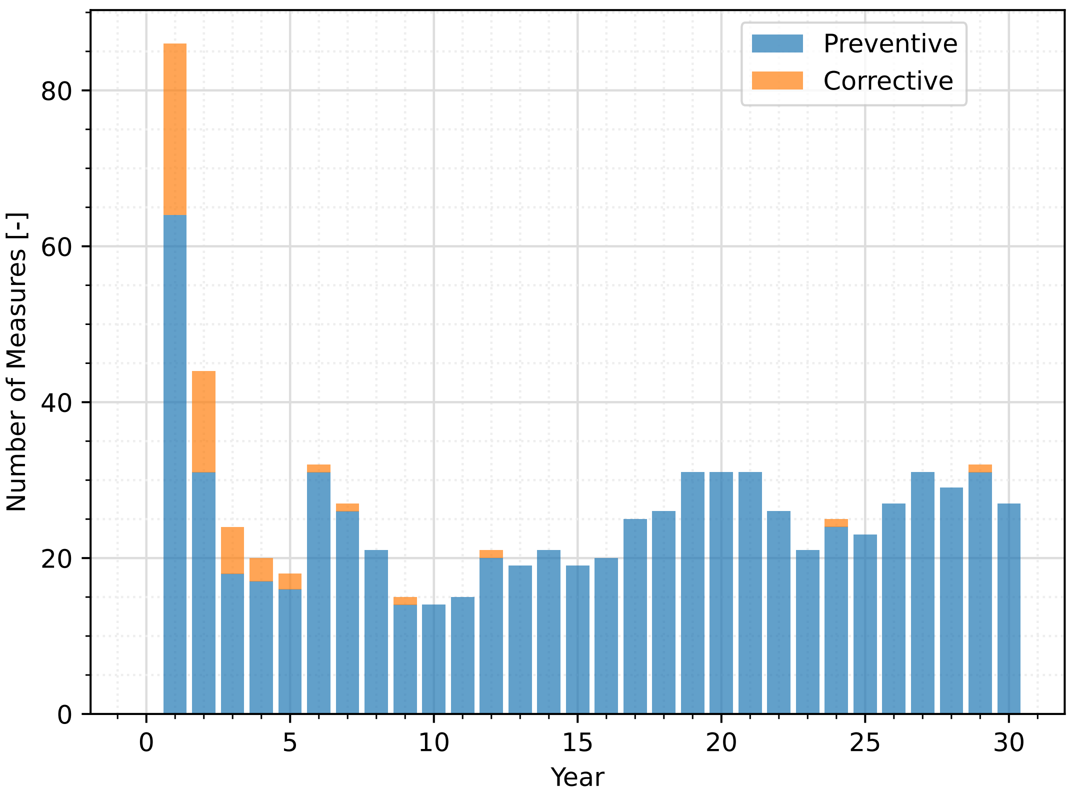

Figure 26: Number of measures of Cologne's identified strategy.

5.6 Case Study: Worms

Worms is a medium-sized city in the southwest of Germany, located on the river Rhine. The extracted road network Figure 27 has a low density of highways and federal roads. The cities of Mannheim and Ludwigshafen are located to the south. Two highways (A 60, A 61, A 5) run to the right and left of the Rhine. The highway A6 is located in the south. The Rhine divides the region spatially. The network was extracted in a radius of 20 km around Worms and there are only three crossing points over the Rhine. The "Niebelungenbrücke" in Worms is one of them. A resilience threshold of 0.75 was considered for the simulation with 25 samples. The identified strategy is: $s_{607} = (extensive, moderate); (moderate, moderate); (moderate, moderate)$ with a resilience value of 0.77. The expected cost over a 30-year period is 30,215,613,260.13 EUR. By this, the costs are by far the highest of all the cases that have been investigated. This is due to the fact that it is also the largest extracted road network in terms of area. As in the other cases studied, the efficiency of the network behaves in a similar way (Figure 28,Figure 29). Initially, large investments (many corrective measures) are made in a road network in poor condition, which is accompanied by many road works. This leads to a significant reduction in network performance. Once most of the maintenance work has been completed, efficiency increases again and stabilizes at 0.8 in the following years.

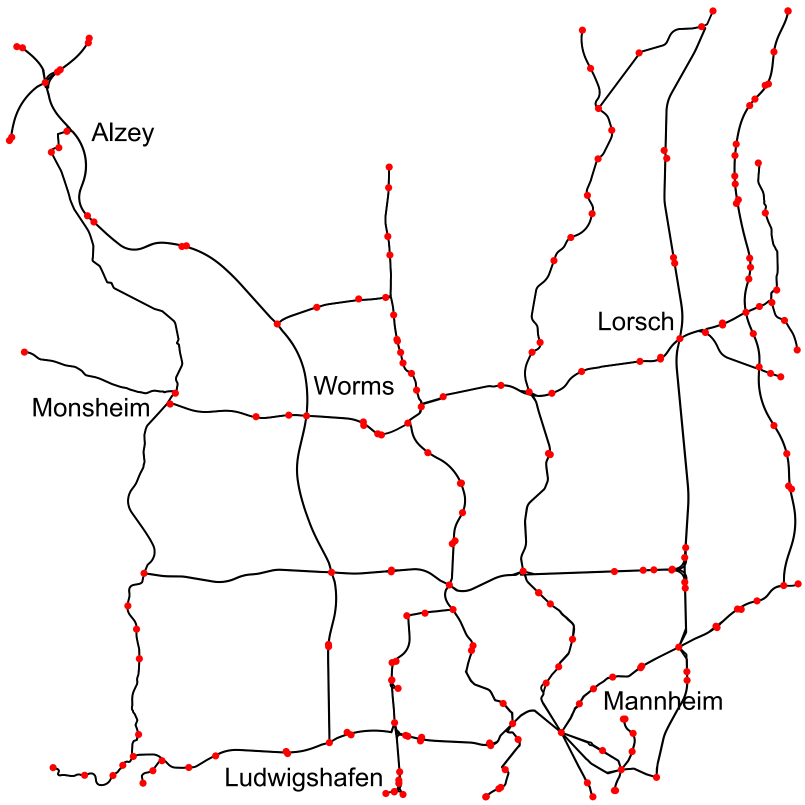

Figure 27: Investigated simplified road network of Worms.

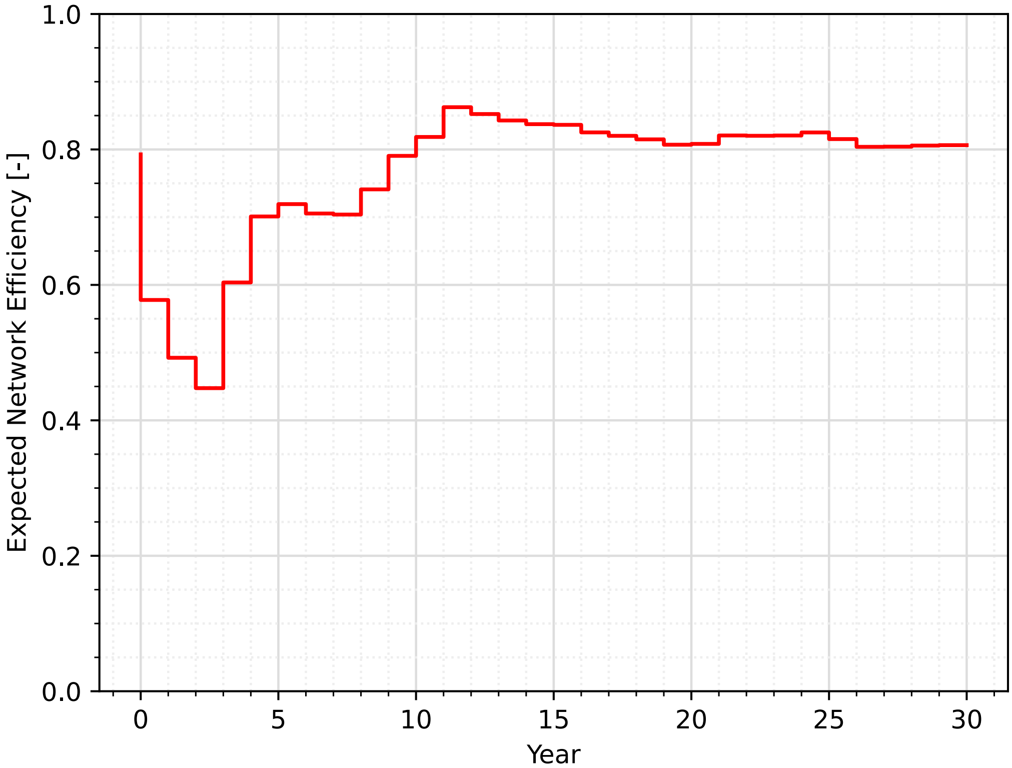

Figure 28: Expected network efficiency of Worms.

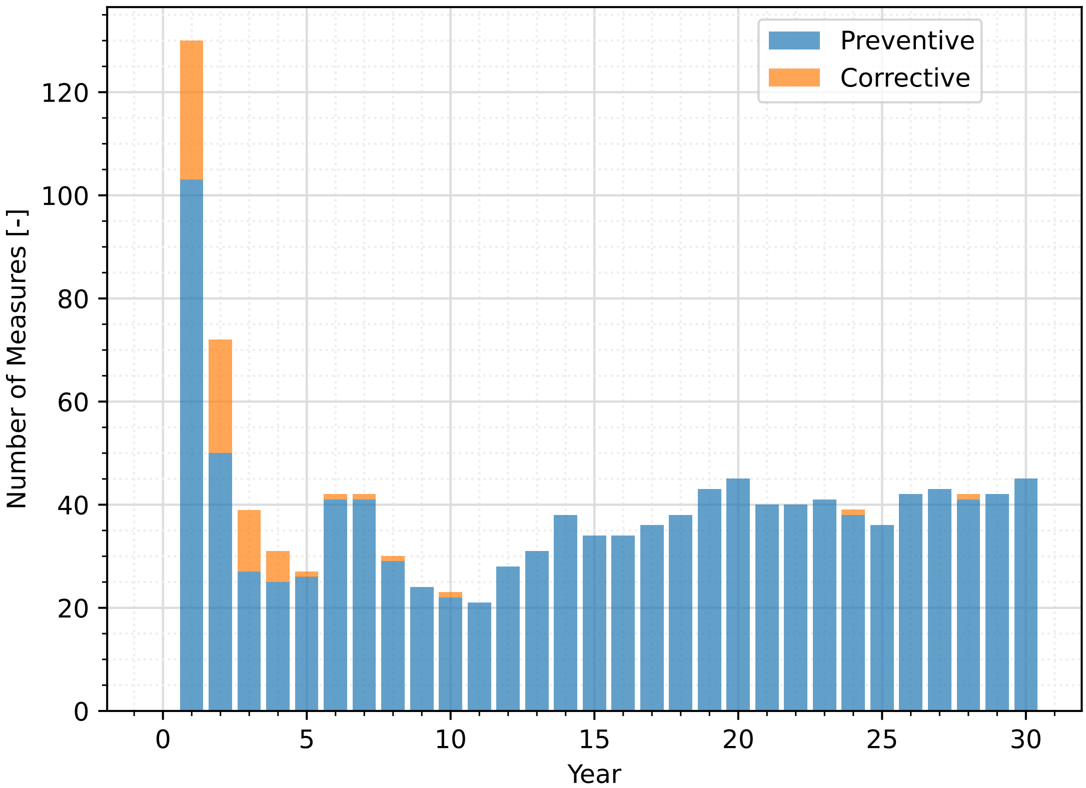

Figure 29: Number of measures of Worm's identified strategy.

6 Discussion

The algorithm has been successfully applied to simplified road networks and a maintenance strategy has been determined for different network topologies, taking into account both cost and resilience. In all examples, maintenance strategies are proposed that initially invest a lot in the road infrastructure. This is followed by a period in which less investment is made. This tendency is easy to understand, as many randomly generated pavement states are in a poor condition at the beginning, it is necessary to invest a lot. If you did not invest much at the beginning (highest quality level for both maintenance types), the resilience would fall even further and only later investments would be higher due to even more deteriorated road conditions. In addition, network efficiency can no longer be established quickly enough in the period observed and the resilience criterion can no longer be achieved. This phenomenon can also be seen in reality. As presented in the introduction, many road network operators have an investment deficit with consequently many roads in need of maintenance. The algorithm now suggests working off this investment deficit with large investments. At the end of the period under consideration, very little is invested in order to keep costs low. This results in a falling network efficiency and, if this last strategy is continued over the period under observation, will again lead to an investment hold-up. The main consideration of decision making on costs (in addition to resilience) is common practice for most maintenance authorities. However, other decision criteria should also be taken into account. For example, as part of a multi-criteria decision making process, the number and frequency of measures implemented can be taken into account and selected and prioritized according to aspects such as sustainability and available resources. The high investments identified at the beginning in particular are accompanied by a large demand for resources and personnel. Not all authorities are in a position to implement all measures promptly. The rapid drop in network efficiency at the beginning is much more serious. Most investments are made during this period, which leads to a high number of construction activities and traffic disruptions. Such a rapid drop in performance is not affordable for the transport sector or the economy. To minimize this, measures should be spread more widely over the time period. This can stabilize the performance in the initial phase. One way of implementing this in the program would be to define a minimum level of efficiency that a strategy must not fall below in the period under consideration.

For the Berlin investigation, no maintenance strategy could be found that achieved a resilience of 0.75. This could be due to the network topology. As shown in [39], star-shaped networks are more vulnerable than meshed networks. At the same time, densely meshed networks are more resilient due to their redundant structure [4]. In this specific case, a possible cause of this result is the incorrect delimitation of the study area. Only the network within the administrative area (federal state) of Berlin was extracted. The A 10 highway ("Berliner Ring"), which runs in a ring around Berlin, was not considered. If it were implemented in the network, the result would be a structurally more resilient system.

In general, it can be said that the calculated resilience only relates to the network of highways and federal roads. There is no value for the resilience of the entire road network. However, this simplification (due to the complexity of the complete networks) can be considered useful, as disruptions in this network have an impact on the entire network. This includes traffic redistribution to the subordinate networks (municipal roads etc.). It is therefore in the interest of the network operators to keep this network efficient and resilient.

The costs calculated for all cases cannot be assumed to be representative. They overestimate real expenses significantly. This should be made clear using the example of Berlin. Berlin had scheduled expenditure of EUR 201,192,300 for roads in the 2022/23 financial year [40]. This value covers all roads and not just highways and federal roads. The amount of the costs may be due to an incorrect assumption of the measure costs per meter. The methods used in the algorithm to calculate the costs may also be inappropriate. It is assumed that a measure is carried out for the entire length of a road (edge). In reality, many measures are only carried out in sections (e.g. patching of potholes).

Although the algorithm is able to be applied to real road networks from Open Street Map (OSM), there are still some limitations. The data from OSM is sometimes inconsistent or does not match the official authorities data. The chosen method for pavement degradation using a stochastic process simplifies the modeling of pavement deterioration considerably, as the probability structure is given by the gamma distribution at any point in time (unlike a Markov process, for example, where the transition probabilities in the transition matrix must be exactly specified). However, the stochastic process is dependent on the selected parameters. If these parameters are estimated incorrectly, this can lead to an overestimation or underestimation of the degradation. As presented in [32] and [41] for a Markov chain approach, a combined method with actual measurements of the road condition can be applied. This can be done simultaneously with a more accurate knowledge and involvement of the PCI in the measurement process.

A major simplification that has been made is the neglect of traffic redistribution due to construction and road closures. A quick and easy solution to integrate these traffic redistribution into the existing model would be to identify the alternative routes from a capacity constrained or closed edge. This can be done with graph-based traffic redistribution models like [42] and [43]. Subsequently, the traffic influence on the identified edges can be temporarily weighted more heavily in the weighted linear combination gamma process. The travel time on these edges can also be increased with a delay factor.

In transportation, it is common to simulate the model under different traffic scenarios (increase, decrease and stagnation of future traffic) for decision making. This could also have a significant impact on the optimal strategy. The implemented model assumes stagnation and therefore the results can only be evaluated in this respect. In Germany, an increase in heavy traffic of 34 % is expected between 2019 and 2051 [2].
The main limitation of the proposed decision-making method is its computational complexity. As shown in subsection 5.1, the applicability of the method to real networks is a trade-off between the size of the network and the sample size. The implemented brute force method significantly limits the possibilities of the algorithm by only allowing a small search space that is still feasible. For the study cases, a search space of 729 strategies was available and this could only be implemented for small networks, taking into account a large sample size. If one were to consider more decision time steps and divide the two maintenance types into more than just three levels, the search space grows with a combination of quadratic growth (due to increasing quality levels) and exponential growth (due to increasing decision points). If a growing network size is added, an NP-hard problem could be present. Table 5 shows the different search space sizes using Equation 12. The more precisely this search space is modeled, the more

Quality levels	Decision points	Number of strategies
3	3	729
10	3	10^6
3	10	3^{20}
10	10	10^{20}

Table 5: Various searching spaces for two maintenance types.

representative the results are for practical applications. An algorithm that searches this three-dimensional search space for the best strategy without having to calculate all strategies would be a significant further development.
In addition to optimizing the algorithms used, there are also programming options to at least reduce the calculation time. One possibility would be multiprocess programming, whereby several processes are calculated simultaneously by the CPU. For example, several strategies could be calculated simultaneously. This depends on the number of CPU cores available.
If solutions can be found for these problems that significantly reduce the high computational complexity, the potential of this method can be better exploited. In this way, larger, more realistic networks can be extracted. Furthermore, the use of a finer grid of decision points (e.g. monthly change of maintenance configuration) is possible. The possibility of a more wide-ranging classification of quality levels is also given. Finally, different traffic scenarios can be considered.
Finally, it should be noted that the method only considers road networks that do not change their structure over time (static networks). However, in order to better repre-

sent reality, measures for the new construction or deconstruction of roads should be considered (dynamic networks). The same applies to changing attributes of a road (e.g. speed limit). Furthermore, transport networks should also be seen as part of an interdependent transportation network (road, rail, ship and air). Goods transportation does not only take place in a single transport network, but across several networks simultaneously. Goods change from one transport type to another via interfaces. For example, supra-regional freight traffic is handled via the rail network and the local distribution ("last mile") of goods via trucks. Germany's transport policy also targets this goal by transporting more goods on the rail network than on the road network. For this reason, it would be important to extend the algorithm to interdependent networks (entire transportation network) in order to better adapt the financial budget of a country to a sustainable orientation of the entire mobility.

7 Conclusion

In this bachelor thesis, a method was derived to determine an optimal maintenance strategy taking into account network resilience and maintenance costs. The method is intended to help public authorities struggling with high maintenance costs and investment delays in their decision making. The algorithm was successfully applied to simplified German road networks extracted from Open Street Map. The results showed that the algorithm favors large investments at the beginning of the period to bring the road network in need of maintenance to a good condition. This is accompanied by a significant drop in network performance due to the large number of maintenance operations. Later, performance increases and stabilizes. Such a significant drop in performance is not optimal for traffic and the economy, so the method should be changed to distribute maintenance more evenly. In addition, many authorities do not have the financial and human resources to carry out many measures from the beginning. In addition, there should be a better understanding of the costs in order to obtain realistic information on the expected cost. To meet the new challenges, it is not enough to consider cost alone - multi-criteria decision making could also take sustainability and other factors into account in the selection process.

The biggest limitation of the method is its computational complexity. It has been shown that the complexity increases exponentially with increasing network size, more maintenance-related quality levels and a more precisely subdivided time interval. A possibility should be found to replace the brute force method by restricting the search space in advance (similar to the search for a Pareto front).

The linear combination of two gamma processes used to model pavement deterioration can be used to describe a deterioration process consisting of several factors. If the authorities have experience values, the parameters of the process can be estimated more accurately.

If solutions to the limitations can be found, the method has strong potential for future expansion and applicability to other infrastructure beyond road networks (e.g., water supply networks, power grids and more).

Finally, road networks should be considered as part of an interdependent overall transportation network. A better understanding of the interfaces and the consideration of dynamic topologies increase the validity of the method and can be a suitable tool for financial policy decisions for a future-oriented and sustainable transportation network.

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Declaration of Authorship

Hereby, I declare that I have composed this Bachelor Thesis independently and without any other resources than the ones specified. All thoughts taken directly or indirectly from external sources are properly denoted as such. The work has not yet been submitted to any examination authority in the same or a similar form.

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