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Resilience-Based Optimization of Rehabilitation Planning under Budget Constraints: Developing a Risk-Oriented Decision Model considering Supply Security

Master's Thesis

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Abstract

Ensuring a reliable, long-term supply of drinking water is a significant challenge for municipal water utilities, particularly given strict budget constraints and challenging topographic conditions. This thesis aims to develop a transferable, risk-oriented optimization model for rehabilitating municipal water supply networks. The model evaluates renewal needs and financial sustainability. Through lifespan simulations, the model prioritizes specific pipeline sections using a risk-based, multi-criteria framework.

This model is based on the concept of localized risk, which is defined as a function of structural failure probability and the resulting socioeconomic and physical consequences. The relevant evaluation criteria, including asset age, material generations, empirical damage rates, operating pressure, and traffic loads, are defined based on the technical guidelines of (DVGW e.V. W 403, 2025) and scientific literature. The Analytic Hierarchy Process (AHP) is systematically applied to determine the objective weighting of these conflicting criteria. Furthermore, this systematic approach establishes a mathematically reliable ratio of conditions to consequences, thereby eliminating qualitative biases. Based on the evaluated criteria, a risk index is derived to enable detailed prioritization of pipeline sections. Additionally, the model incorporates resilience indicators and consumer criticality metrics to account for the impact of potential pipeline failures on populations and infrastructure that are most vulnerable.

The developed evaluation model was applied and validated using a real pipeline network in a Stadtwerke Freudensstadt case study. This application demonstrates that combining multi-criteria, risk-based prioritization with strategic rehabilitation planning under fixed financial constraints establishes a consistent, transparent, and structured basis for municipal decision-making. Furthermore, the model transforms local boundary conditions into a methodology that can be applied to other water utilities. The model provides a robust foundation for short-, medium-, and long-term rehabilitation planning.

Keywords: risk-based optimization, water distribution networks, analytic hierarchy process, asset management, infrastructure resilience, pipeline deterioration.

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List of Abbreviations

AHP	Analytic Hierarchy Process
AZ	Asbestos Cement (Asbestzement)
CI	Consistency Index
CR	Consistency Ratio
DIN	German Institute for Standardization
DN	Nominal Diameter
DVGW	German Technical and Scientific Association for Gas and Water (Deutsche Vereinigung des Gas- und Wasserfaches e.V.)
EN	European Standard (Europäische Norm)
e.V.	Registered Association (eingetragener Verein)
GG	Grey Cast Iron (Grauguss)
GGG	Ductile Cast Iron (Duktiles Gusseisen)
GIS	Geographic Information System
GK	Gauss-Krüger (Coordinate System)
GmbH	Limited Liability Company (Gesellschaft mit beschränkter Haftung)
HZ	High Pressure Zone (Hochzone)
IEC	International Electrotechnical Commission
ISO	International Organization for Standardization
MCDA	Multi-Criteria Decision Analysis
MPIEE	Infrastructure and Environmental Engineering (Master's Program)
MZ	Middle Pressure Zone (Mittelzone)
NZ	Low Pressure Zone (Niederzone)
PE	Polyethylene
PE-HD	Polyethylene High-Density
pH	Potential of Hydrogen
PVC	Polyvinyl Chloride
QGIS	Quantum Geographic Information System
RI	Random Index
RI	Risk Index
SDR	Standard Dimension Ratio
St	Steel
UTM	Universal Transverse Mercator
WAREM	Water Resources Engineering and Management (Master's Program)
ZV	Public Water Association (Zweckverband)
ZVKK	Public Water Association Kleine Kinzig (Zweckverband Kleine Kinzig)

1. Introduction

1.1 Problem Statement and Project Context

A continuous supply of high-quality drinking water is essential for municipal public services and critical infrastructure protection around the world. Subsurface water distribution systems are the most capital-intensive assets for municipal utility companies and require active preservation strategies to prevent structural decay. Water utilities face the severe challenge of deciding which pipeline sections to rehabilitate and when to do so, all while operating under limited financial and personnel resources. Since it is impossible to implement comprehensive rehabilitation measures across an entire grid simultaneously, a fundamental engineering decision problem arises. Asset replacement before its expected end of life results in inefficient capital expenditure and unnecessary investment. On the other hand, delaying renewal exponentially increases the probability of structural failure. In interconnected municipal networks, failure of a core pipeline section can trigger immediate effects that spread throughout the network, isolating downstream sectors and causing severe supply deficits.

In modern engineering practices, the risk-based prioritization of pipeline segments is becoming increasingly important. Traditional asset management approaches that rely on age limits or simple condition assessments often fail to consider the many factors influencing the probability of failure. Furthermore, these traditional methods inadequately capture the potential extent of damage. Risk-oriented approaches overcome these limitations by evaluating both failure probability and potential damage simultaneously. This allows for a highly specific, localized evaluation of individual pipeline segments according to technical frameworks, such as the (DVGW e.V. W 403, 2025). In addition to local technical risks, the planning process must consider systemic resilience and supply security. In complex distribution grids, localized disruptions can have a major impact on overall supply security. This underlines the importance of analyzing consumer criticality, network redundancy, and operational restoration capabilities.

This research project aims to develop a generalized, transferable evaluation framework for water supply systems by using Stadtwerke Freudenberg's municipal network to analyze and solve real-world infrastructure challenges. The network consists of approximately 166 kilometers of pipelines, 16 elevated storage reservoirs, and two centralized waterworks facilities, providing a vital water supply to 23,183 residents. The operational environment is highly complex due to the challenging topography of the Black Forest region. The network is divided into 21 independent pressure zones managed by a specialized configuration of pressure-reducing valves and booster stations. Due to strict budget constraints, the annual capital expenditure available for rehabilitation is limited. Consequently, the municipal utility company hired RBS wave GmbH, an engineering company specializing in water management, hydraulic modeling, and optimization, to develop a comprehensive rehabilitation model. A strategy must be both scientific and structured to manage the infrastructure effectively. Without it, the aging materials, varying soil chemistry, and hydraulic stress will inevitably lead to exponential failure rates, increased water losses, and a critical decline in supply security. Therefore, there is an urgent need for a generalized, transferable evaluation approach that can structure decision-making processes successfully and support transparent, data-driven planning under these strict budget constraints.

1.2 Research Objectives and Scope

This master's thesis develops a transferable, risk-oriented decision model for optimizing pipe rehabilitation under strict budget constraints. This model moves beyond traditional age-based replacement strategies by integrating resilience criteria, such as redundancy. This model prioritizes pipe systems based on their criticality to the overall system, including the potential impact of failure on unserved customers and high-priority consumers, such as hospitals, (DVGW e.V. W 403, 2025). This methodology is grounded in a risk-based approach where risk is defined as the product of the probability of failure and the extent of the resulting damage.

$$\text{Risk} = \text{Probability} \cdot \text{Extent}$$

In accordance with DVGW guidelines, the extent of the damage is quantified using standardized factors (DVGW e.V. W 403, 2025). The model shall identify high-risk pipe sections requiring immediate intervention to preserve supply security by combining these indicators with historical damage statistics and hydraulic importance.

1.3 Research Questions

This thesis provides a clear framework for analyzing the challenges that municipal utilities face when trying to maintain supply security under severe financial constraints. The research questions that follow are designed to bridge the gap between the need for technical rehabilitation and economic feasibility in the context of Stadtwerke Freudenstadt. The main research questions are:

How can an efficient and transferable strategy be developed to balance cost and socioeconomic impact when allocating limited budgets?

The following sub-questions explore the technical and strategic dimensions of the proposed decision model to achieve the primary research objective:

1. How can a prioritization matrix be developed that considers ageing infrastructure and materials, as well as the socio-economic impact?

Context: This question focuses on the technical integration of systemic criticality and resilience metrics to move beyond traditional age-based replacement strategies.

2. How will short-, medium-, and long-term investment scenarios affect water supply security up to the year 2050?

Context: This research question aims to evaluate the long-term impact of various rehabilitation rates on asset value preservation and financial sustainability. Stadtwerke Freudenstadt's pipe network will serve as the case study.

2. State of the Art

2.1 Technical Regulations and Performance Indicators in Water Supply

Public drinking water supply systems must be planned, constructed, and operated according to the generally accepted rules of technology specified in the Drinking Water Ordinance (Bundesministerium für Gesundheit, 2023). These rules reflect the current consensus among technical experts, and violations may result in criminal penalties. These rules include various standards (e.g., DIN, EN, and ISO), as well as rules, regulations, information sheets, and worksheets issued by professional associations, such as the German Technical and Scientific Association for Gas and Water (DVGW).

In Germany, the rehabilitation of water networks is governed by the technical rules of the DVGW. To ensure an objective assessment of network health, several key performance indicators are utilized, primarily based on the framework provided by DVGW (DVGW e.V. W 1100-2 (M), 2023). These metrics allow for a standardized evaluation of the system:

- **Real Water Losses:** Utilizing the Infrastructure Leakage Index, according to (DVGW e.V. W 392, 2025)
- **Pipe Damage Rate:** Calculated as failures per kilometer per year (*damage/km/a*) in accordance with (DVGW e.V. W 403, 2025)
- **Supply Reliability:** Measured as the average interruption duration in minutes per customer per year according to (DVGW e.V. W 399, 2020)
- **Supply Quality:** Assessed via the load cases and criteria defined in (DVGW e.V. W 1003 (A), 2022)

A key metric in this context is the "Sustainability of Pipe Rehabilitation". According to (DVGW e.V. W 1003 (A), 2022), a rehabilitation rate below 0,3 % indicates an immediate "Need for Action", signaling that current renewal rates are insufficient to maintain the network's condition. The new draft of (DVGW e.V. W 403, 2025) further refines this by providing specific decision-making aids that shift the focus toward a risk-oriented approach, balancing the probability of failure with the potential extent of damage.

2.2 Concepts of Risk-Based Infrastructure Rehabilitation

To demonstrate and evaluate the short-, medium-, and long-term effects of rehabilitation activities, the rehabilitation of water distribution systems must be divided into three interdependent sub-processes, depending on the planning period under consideration.

- Determination of a long-term rehabilitation strategy
- Drafting a medium-term rehabilitation plan,
- Implementation of the rehabilitation measures required in the short term.

The scope and budget required for long-term maintenance of sufficient supply quality and system condition must be determined when developing the rehabilitation strategy.

As part of the planning process, the necessary rehabilitation measures are selected and sequenced for a medium-term period, including cost estimates. During implementation, the specific execution of the rehabilitation measure is determined, including the construction method, dimensions, materials, etc.

The depth of processing, level of detail, and overall effort required for the respective sub-processes increase with shorter observation periods. This increased level of detail leads to a more concrete definition of the necessary rehabilitation. The results of the sub-processes must be compared.

Infrastructure planning often requires evaluating and prioritizing multiple courses of action based on various criteria. These alternatives are usually evaluated using multiple criteria. These models provide structured support for the processes they describe, which makes them a valuable resource for anyone working in this field. In practice, however, simple evaluation approaches are often used, such as point-based models that combine various criteria into an overall score. One such approach is described in (DVGW e.V. W 403, 2025) for risk-based rehabilitation planning of supply networks. For more complex decision-making problems involving multiple evaluation criteria, multicriteria decision analysis methods are recommended to be used in scientific literature.

2.3 Fundamentals of Multi-Criteria Decision Analysis and the AHP

2.3.1 Multi-criteria Decision Analysis

Multi-criteria decision analysis (MCDA) is an approach that uses formal methods to support systematic decision-making processes involving multiple (and often conflicting) evaluation criteria. These methods allow criteria to be weighted and decision alternatives to be evaluated based on those criteria. Thus, MCDA methods enable the structured, transparent evaluation of complex decision-making problems (Belton & Stewart, 2002). MCDA is also listed as a possible risk assessment method in ISO/IEC 31010 (ISO, 2019).

The Analytical Hierarchy Process (AHP) is one of the most well-known MCDA methods. The AHP is often used for hierarchical decision-making problems involving qualitative and quantitative criteria because it transparently weights the criteria and ensures the consistency of the evaluations (Belton & Stewart, 2002).

2.3.2 Analytic Hierarchy Process (AHP)

The AHP, developed by Thomas L. Saaty, is a method of multi-criteria decision making that structures and quantifies complex problems. The goal is to convert qualitative judgments into numerical weights, providing a transparent and rational basis for decision-making (Saaty, 1980). The following section explains the procedure for constructing an AHP model in more detail.

First, the decision problem is represented as a hierarchical structure comprising three levels (Saaty, 1980)

- Decision objective (top level)
- Evaluation criteria (middle level)
- Action alternatives (bottom level)

This structure allows complex problems to be systematically broken down into smaller components that are more easily evaluated (Saaty, 1989). The AHP process is based on pairwise comparisons of criteria, in which all criteria at the same level are compared with each other. Evaluations are made using a semantic scale. A commonly used scale is the Saaty scale. (see Table 1; (Saaty, 1980))

TABLE 1: RATING SCALE FOR PAIR COMPARISON (SAATY, 1980)

Scale	Definition	Interpretation
1	Equal importance	Both compared elements have the same importance for the next higher-level element.
3	Slightly greater importance	Experience and judgment indicate a slightly greater importance of one element compared to another.
5	Significantly greater importance	Experience and judgment indicate a significantly greater importance of one element compared to another.
7	Very strong importance	The much greater importance of one element has been demonstrated in the past.
9	Absolutely dominant	This represents the maximum possible difference in importance between two elements.
2; 4; 6; 8	Intermediate values	Intermediate values used to fine-tune assessments between two adjacent main values.

The pairwise comparisons are summarized in matrix A, where the following is true:

$$a_{ii} = 1$$

$$a_{ij} = \frac{1}{a_{ji}}$$

These types of matrices are referred to as "positive inverse matrices." The priority vector, which specifies the relative weights of the criteria or alternatives, is derived from the matrix. Traditionally, this is done using the eigenvalue method, which involves calculating and normalizing the matrix's principal eigenvector.

$$A \cdot w = \lambda_{\max} \cdot w \quad (2.1)$$

Where:

A	Pairwise comparison matrix
w	Priority vector
$\lambda_{\max}$	Largest eigenvalue

A key advantage of the AHP is its ability to verify the consistency of judgments. Since human judgments can be inconsistent, mathematical verification is necessary. A pairwise comparison matrix is considered perfectly consistent if the following holds for all sets of three numbers, i , j , and k :

$$a_{ij} \cdot a_{jk} = a_{ik}$$

The consistency index (C_I) measures the degree to which results deviate from perfect consistency.

$$C_I = \frac{\lambda_{\max} - n}{n - 1} \quad (2.2)$$

Where:

C_I	Consistency index
$\lambda_{\max}$	Largest eigenvalue
n	Number of criteria

The consistency ratio (CR) is the ratio of the C_I to the R_I . The R_I is expected to be random.

$$CR = \frac{C_I}{R_I} \quad (2.3)$$

Where:

CR	Consistency ratio
C_I	Consistency Index
R_I	Random Index

Table 2 shows the randomness index values as a function of n , the number of criteria.

TABLE 2: R_I VALUES (SAATY, 1980)

Number of criteria (n)	1	2	3	4	5	6	7	8	9	10
Random Index (R_I)	-	-	0,58	0,90	1,12	1,24	1,32	1,41	1,45	1,49

Values of $CR \leq 0,10$ are considered acceptable. Higher values require adjusting the ratings (Saaty, 1980). The AHP offers several advantages for evaluating complex decision-making problems. It clearly structures complex decisions, integrates qualitative and quantitative criteria, and verifies the consistency of ratings. However, limitations occur when there are many criteria or alternatives because the effort required for pairwise comparisons increases correspondingly. Additionally, the results may be affected by the judgment of the decision-makers (Ishizaka & Nemery, 2013).

2.4 Mathematical Deterioration Modeling and Stochastic Survival Analysis

Simulation models provide the most meaningful projections because they account for the uncertainty involved in the deterioration of assets. Rather than assuming a fixed service life, they use mathematical distribution functions, such as the Weibull or Herz distribution, to describe the probability of an asset transitioning to a failed state (DVGW e.V. W 403, 2025). This approach involves creating a survival model, in which the ageing process is quantified as the probability of failure at a given age. To ensure methodological clarity, it is important to distinguish between the stochastic probability of failure and the empirical pipe damage rates. The damage rate reflects documented, localized failure events within the network.

The function of the lifetime distribution $f(x)$ describes the density of failure events at a specific time. The cumulative failure probability $F(x)$ represents the measure of the cumulative probability that a pipe will fail before or at age x . The Survival function $S(x)$ represents the proportion of the stock remaining in a functional state over time and is determined by:

$$S(x) = 1 - F(x) \quad (2.4)$$

The current failure or renewal rate $\lambda(x)$ is defined as the ratio of the lifetime distribution to the survival function, expressing the probability of failure relative to the remaining intact assets:

$$\lambda(x) = \frac{f(x)}{(1 - F(x))} = \frac{f(x)}{S(x)} \quad (2.5)$$

Finally, the remaining life expectancy $R(x)$ forecasts the expected additional service duration of existing assets based on these structural deterioration probabilities.

3. Materials and Methods

3.1 Framework of the Case Study Network from Stadtwerke Freudenstadt

The public utility company Stadtwerke Freudenstadt commissioned RBS wave GmbH to develop a comprehensive rehabilitation plan for the city's water distribution network. The project's primary objective is to establish a long-term, strategic, condition-based maintenance plan to preserve pipes and ensure a stable water supply.

Stadtwerke Freudenstadt obtains drinking water from its own sources and from the two companies: Schwarzbrunnen ZV and Kleine Kinzig ZV (ZVKK). The system features a water pipe network spanning approximately 166 kilometers and two waterworks to supply the districts. The decentralized infrastructure also comprises 16 elevated tanks, 15 of which are owned by Stadtwerke Freudenstadt and one by ZVKK. Due to the unique topography of the Black Forest, the supply area is divided into numerous zones separated by space and altitude, to ensure supply security and asset preservation. Shut-off valves, such as gate valves, maintain pressure levels across varying altitudes.

To achieve precise pressure regulation, most supply areas are categorized as high (HZ), middle (MZ), or low (NZ) zones. As detailed in the service area overview, the city of Freudenstadt is divided into two northern high zones (A15 and A17), one southern high zone, one middle zone, and two low zones (NZ I and NZ II). These zones collectively serve 15,758 people. Districts on the outskirts, including Wittlensweiler, Dietersweiler, and Kniebis, function as independent supply areas. These districts have populations ranging from 63 in Zwieselberg to over 2,000. The different supply zones can be seen in Table 3.

TABLE 3: SERVICE AREAS AND DISTRICTS

Service area	District	Inhabitants
HZ South	Kernstadt	15758
HZ Nord A17		
HZ Nord A15		
NZ I		
NZ II		
MZ		
Wittlensweiler	Wittlensweiler	2130
Dietersweiler	Dietersweiler	2055
Kniebis	Kniebis	848
Musbach	Musbach	745
Frutenhof & Grüntal	Grüntal	619
	Frutenhof	369
Igelsberg	Igelsberg	244
Christophstal	Christophstal	199
Lauterbad	Lauterbad	153
Zwieselberg	Zwieselberg	63

In general, supply systems can be classified into three structural configurations: branched networks, simple ring networks, and ring networks with meshing. As illustrated in Figure 1, these configurations differ in their operational characteristics regarding hydraulic routing and supply redundancy. Branched systems are prone to downstream isolation in the event of failure. In contrast, meshed ring networks allow pipe sections to be supplied from multiple sides, offering

better security. However, these highly interconnected systems require extensive infrastructure and careful hydraulic monitoring to prevent stagnation zones.

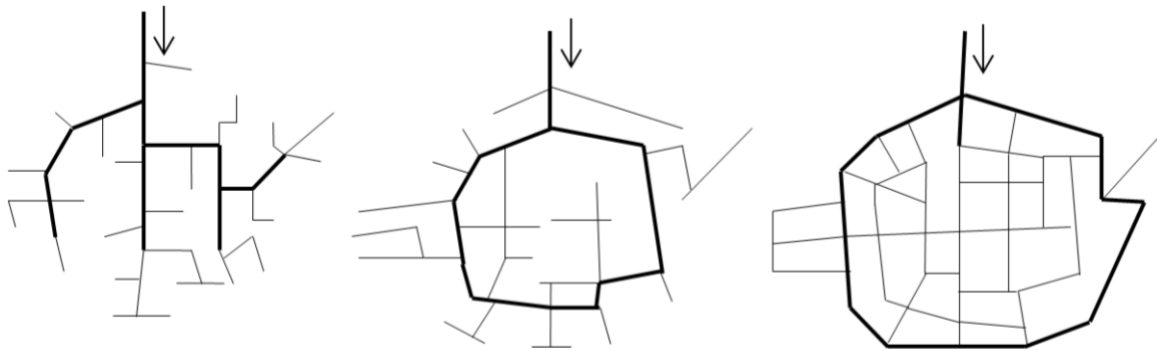


**FIGURE 1: STRUCTURAL CONFIGURATIONS OF SUPPLY SYSTEMS:
BRANCHED NETWORKS (L), SIMPLE RING NETWORKS (M), AND RING NETWORKS WITH MESHING (R)**

The water supply network in Freudenstadt is a meshed ring network. This configuration optimizes local pressure distribution, improves water availability for firefighting purposes, and enhances supply reliability throughout the municipal area. Technical pressure conditions within this localized, meshed network are managed through a combination of natural gradients and active intervention. In areas where the natural elevation of the storage tanks is insufficient, such as in Zwieselberg, active pressure-boosting systems are employed. Conversely, pressure-reducing valves are installed in lower-lying zones, such as Dietersweiler, Wittlensweiler, and Lauterbad, to prevent overpressure. This complex configuration requires precise operational oversight and balanced hydraulic conditions, demanding advanced asset maintenance. Precise rehabilitation planning is necessary to prevent structural failure. Thus, this thesis aims to develop a generalized, transferable decision model that optimizes asset management within these integrated networks.

The foundation of a risk-oriented rehabilitation model rests entirely on the integrity, completeness, and plausibility of the underlying dataset. In the context of municipal public services, where water distribution systems represent a primary capital asset, any decision-making model is only as robust as the data it processes. The initial phase of this research involved an extensive audit of the existing hydraulic and structural data provided by Stadtwerke Freudenstadt. It became immediately apparent that the 2018 baseline dataset was insufficient for strategic planning, as it lacked nearly eight years of network expansions, structural changes, and damage documentation. Consequently, one of the primary objectives was to transform this outdated information into an accurate digital representation of the technical reality of 2026.

The synchronization process began with a systematic comparison of the 2018 Geographic Information System (GIS) export and the current physical inventory maps. An early challenge identified in the audit was the presence of placeholder data. Many pipeline segments were documented as having been constructed in "1899", a generic entry used for missing historical records. The comparison between the initial and updated network states revealed that these gaps were concentrated in critical transport and distribution lines. If left uncorrected, the placeholders would have skewed the statistical failure probability because the model would have incorrectly categorized modern pipes as being over a century old.

These discrepancies underwent a manual plausibility check. This process involved cross-referencing the segments with historical plans and consulting Stadtwerke Freudenstadt's engineering staff. The methodology estimates construction years using material-age proxies where direct records were unavailable. For example, PVC segments were assigned to cohorts predating 2000, while PE-HD segments were mapped to more recent expansion phases based on surrounding

urban development. This manual alignment process ensured an accurate representation of the network's vital backbone before proceeding with hydraulic simulations. To close the identified data gaps and ensure the model's technical validity, a time-intensive process of manual data verification was initiated. The pipeline network plan of Stadtwerke Freudenberg was compared with the digital as-built model, beginning with a coordinate transformation.

3.2 Institutional Context and Departmental Role

RBS wave GmbH is a technical engineering company owned by Netze BW GmbH. The company primarily serves municipal and utility clients, mainly in Baden-Württemberg. The company's main goal is to ensure supply security and the long-term maintenance of utility assets while balancing increasing cost pressures. To achieve this, RBS wave GmbH uses advanced pipe network calculations and analyses to provide the technical basis for evaluating and optimizing water and gas network operations.

The contemporary firm was formed through the strategic consolidation of three specialized engineering firms: Genius GmbH (civil, environmental, and energy engineering); Rohrnetzberatung Stuttgart GmbH (gas and water supply); and wave GmbH (water, wastewater, and land development). Today, RBS wave GmbH leverages this combined expertise with a workforce of over 160 employees distributed across six regional locations.

Its service portfolio is categorized into three main pillars: water, energy, and infrastructure. In the water sector, RBS wave GmbH specializes in water supply, treatment, storage, transport, distribution, and wastewater management, particularly water loss management. The energy segment includes solutions for biogas, geothermal energy, hydropower, and energy recovery. The infrastructure pillar offers network rehabilitation, cathodic corrosion protection, and geotechnical engineering services. Specifically, the author worked in the Consulting Team department, which is responsible for the strategic management and optimization of utility networks.

3.3 Integrated Software Architecture and Data Interfaces

3.3.1 STANET

The program under consideration is utilized for the purpose of conducting both stationary and dynamic calculations of supply and networks in water and gas networks. The data necessary for the creation of the calculation network model is imported from GIS systems. The integration of components, such as pumps, pressure-boosting systems, valves, and related elements, enables the formation of reliable networks. These elements should either reflect the customer's existing network or be adjusted for optimization. The simulation of various network operation possibilities enables the rapid formulation of reliable conclusions regarding the impact of network changes.

3.3.2 Asset403

This rehabilitation tool is used for the strategic and condition-oriented maintenance management of water and gas supply networks. This solution can be used as a standalone program or in combination with STANET to develop customized rehabilitation strategies. These strategies are based on available damage data and DVGW guidelines. The software facilitates the estimation of technical service lives and the calculation of necessary rehabilitation rates through statistical models, such as the Weibull distribution. By simulating different strategy scenarios, such as maintaining budgets or damage rates, users can evaluate the long-term impact of maintenance decisions on network conditions and costs. Furthermore, it facilitates planning by prioritizing specific pipe segments through risk analysis. This process involves evaluating the probability of failure and the potential extent of damage.

3.4 Data Engineering, Quality Verification and Asset403 Integration

3.4.1 Spatial Coordinate Transformation and Manual Data Validation

A detailed condition assessment could not be carried out until the STANET network model had been fundamentally revised. The original model was based on the Gauss-Krüger coordinate system, which is becoming increasingly outdated for modern GIS applications and data exchange. Since the existing network had not been updated fully since 2018, including approximately 200 newly built homes and their consumption data was necessary to reflect the network's status in 2026.

To optimize the STANET network model and ensure compatibility with modern GIS standards, the system was converted from the Gauss-Krüger coordinate system to the Universal Transverse Mercator (UTM) coordinate system. Artificial intelligence was used to process the coordinates of all network components, including pipes, junction points and elevated tanks. These AI-supported tools performed the necessary mathematical conversions, significantly reducing processing time. The conversion uses a seven-parameter Helmert transformation (Mataija, Pogarčič, & Pogarčič, 2014). This is expressed by the following formula:

$$X_{UTM} = T + (1 + m) \cdot R \cdot X_{GK} \quad (3.1)$$

Where:

- X_{UTM} : Coordinate vector in the target UTM system
- T : Translation vector accounting for spatial shift and ensuring spatial accuracy
- m : Scale factor representing the scaling adjustment and ensuring spatial accuracy
- R : Rotation matrix accounting for angular rotation and ensuring spatial accuracy
- X_{GK} : Coordinate vector in the original Gauss-Krüger source system

The horizontal coordinate z does not change, and the elevation values remain unaffected. In the STANET model, z -values are stored as absolute metric measurements in meters below the surface. Following the automated process, a systematic comparison of values was performed, and critical network elements were manually verified to correct any conversion errors.

In parallel with the transformation, the new residential areas and their specific consumption profiles were imported to create a realistic model of the hydraulic load on the system. This fundamental system conversion and update ensures that all subsequent risk-oriented rehabilitation steps are based on precise, future-proof data.

The initial situation of the water supply network under investigation in Freudenstadt was characterized by the significant variability and gaps in the datasets, which made immediate strategic planning difficult. As Figure 2 shows, an initial assessment revealed that the existing model, based on a 2018 GIS export, did not accurately reflect the current technical reality.

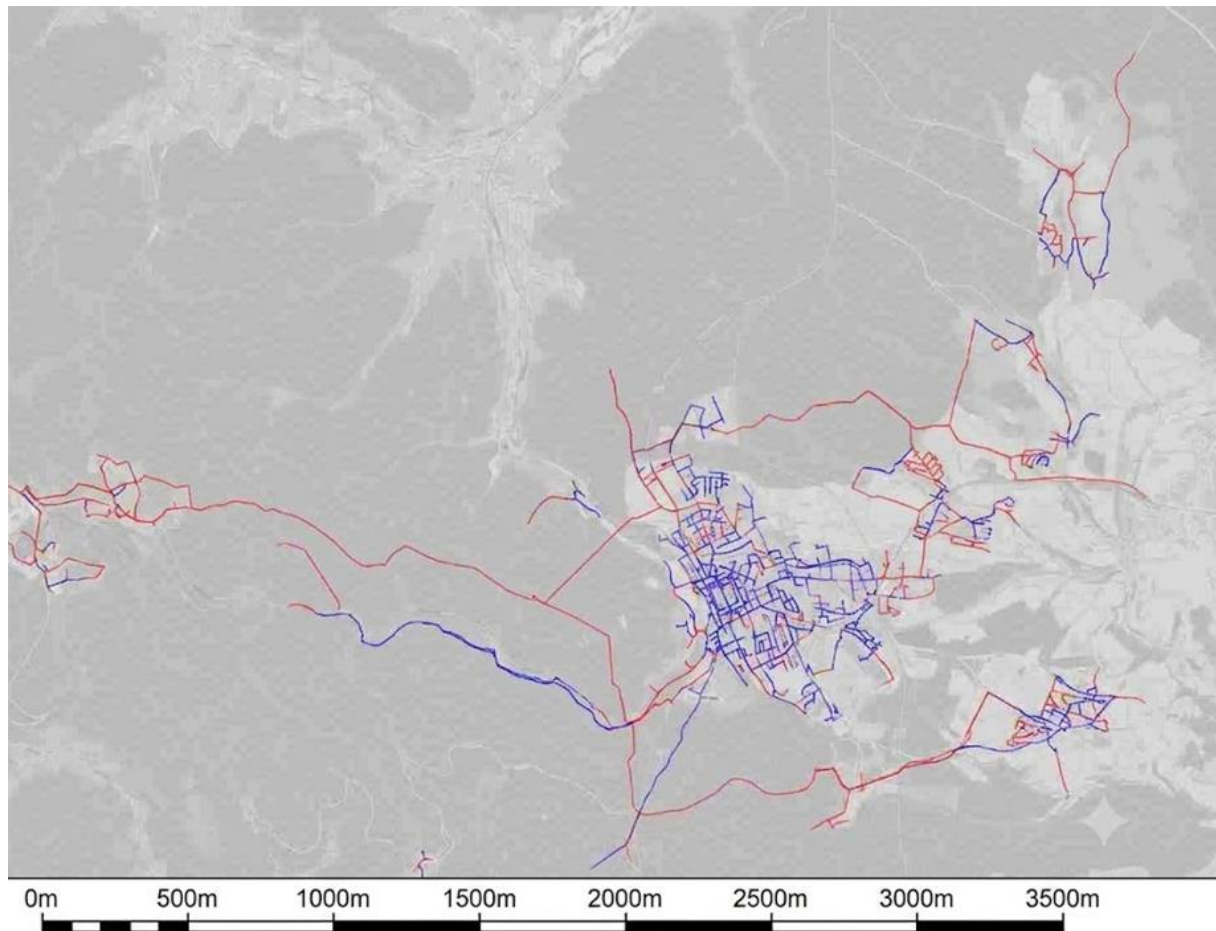


FIGURE 2: INITIAL CONDITIONS OF THE WATER SUPPLY NETWORK OF STADTWERKE FREUDENSTADT

The initial dataset has the following shortcomings: A large portion of the pipeline network (marked in red in Figure 2) has an unreliable or missing construction year and has been assigned the placeholder value of "1899". In addition to the missing chronological data, the technical attributes of numerous segments were either not clearly documented or inconsistent, particularly regarding material specifications and exact diameters. Furthermore, network expansions and structural changes from the past eight years had not yet been fully incorporated into the base dataset. There was also a lack of updated consumption profiles and nodes, which affected the calculation of the systemic criticality of the pipelines. The pipeline sections marked in blue in Figure 2 only represent the segments for which verified information was available. However, this did not provide a comprehensive picture of the network's condition. This inadequate data foundation formed the basis for the necessary transformation towards a digital twin to enable precise, risk-oriented rehabilitation planning.

Figure 3 shows a plan from Freudenstadt that differs a lot from the digital twin, shown in Figure 2. The data maintenance process involved making a detailed comparison between the existing GIS and the digital plans.

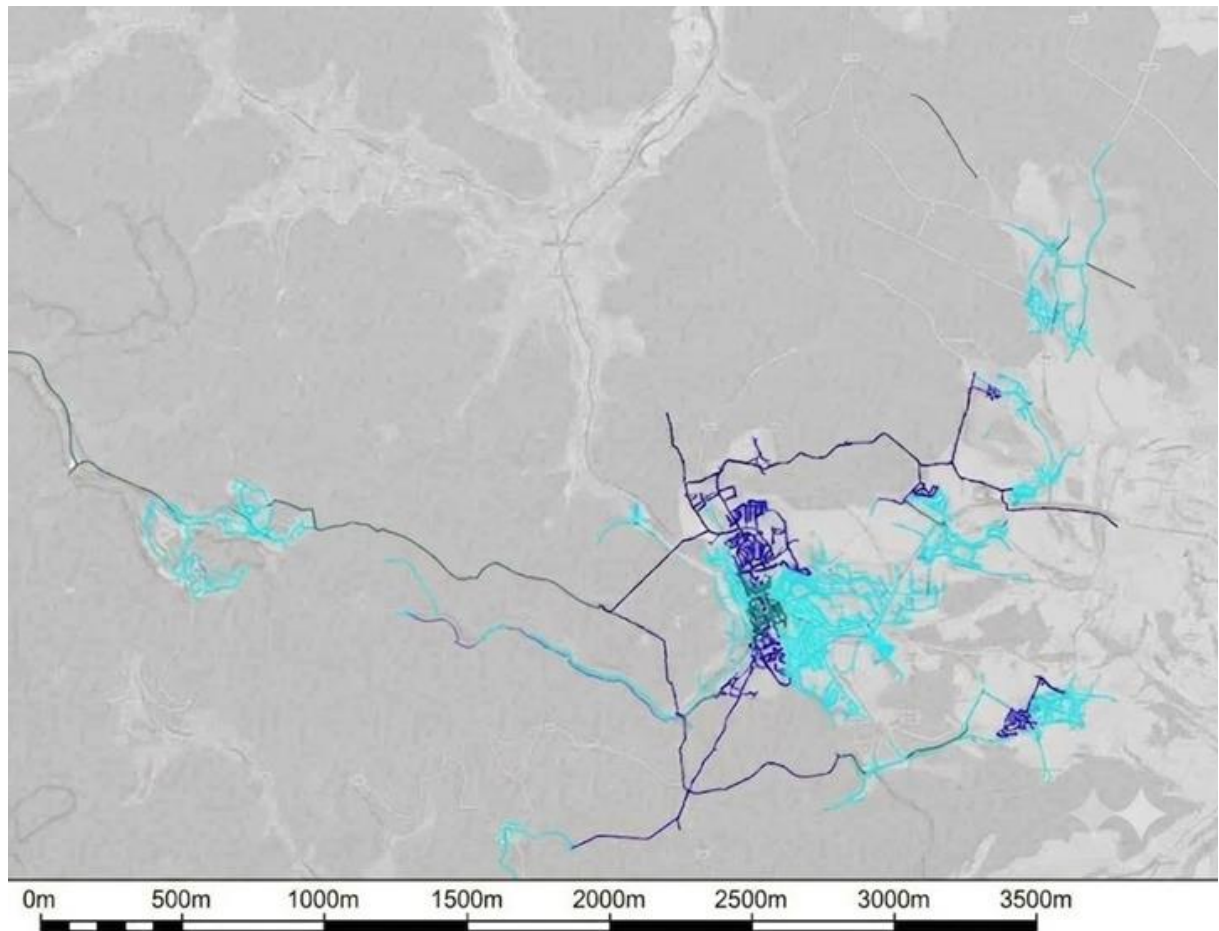


FIGURE 3: GIS PIPE NETWORK WITH NETWORK DATA SUCH AS CONSTRUCTION YEARS, MATERIALS, AND DIMENSIONS

The following steps were taken as part of this systematic review: Each pipeline segment to which the placeholder year “1899” had been assigned was checked individually in the Geoportal and against the inventory records to determine its actual construction year. A plausibility check was performed on the material specifications and the nominal diameter, alongside the time correction. Any obvious misassignments were corrected directly in the model. Where no explicit documents were available, construction years were estimated using material-age estimates, taking surrounding urban development into account. This detailed process ensured that hydraulic parameters, such as pipe friction coefficients, were based on the correct material properties.

Figure 4 visualizes the result of this comprehensive revision. Compared to the initial state in Figure 2, the proportion of verified pipes (marked in blue) has increased significantly, and the remaining red sections indicate much less statistical uncertainty in the overall model.

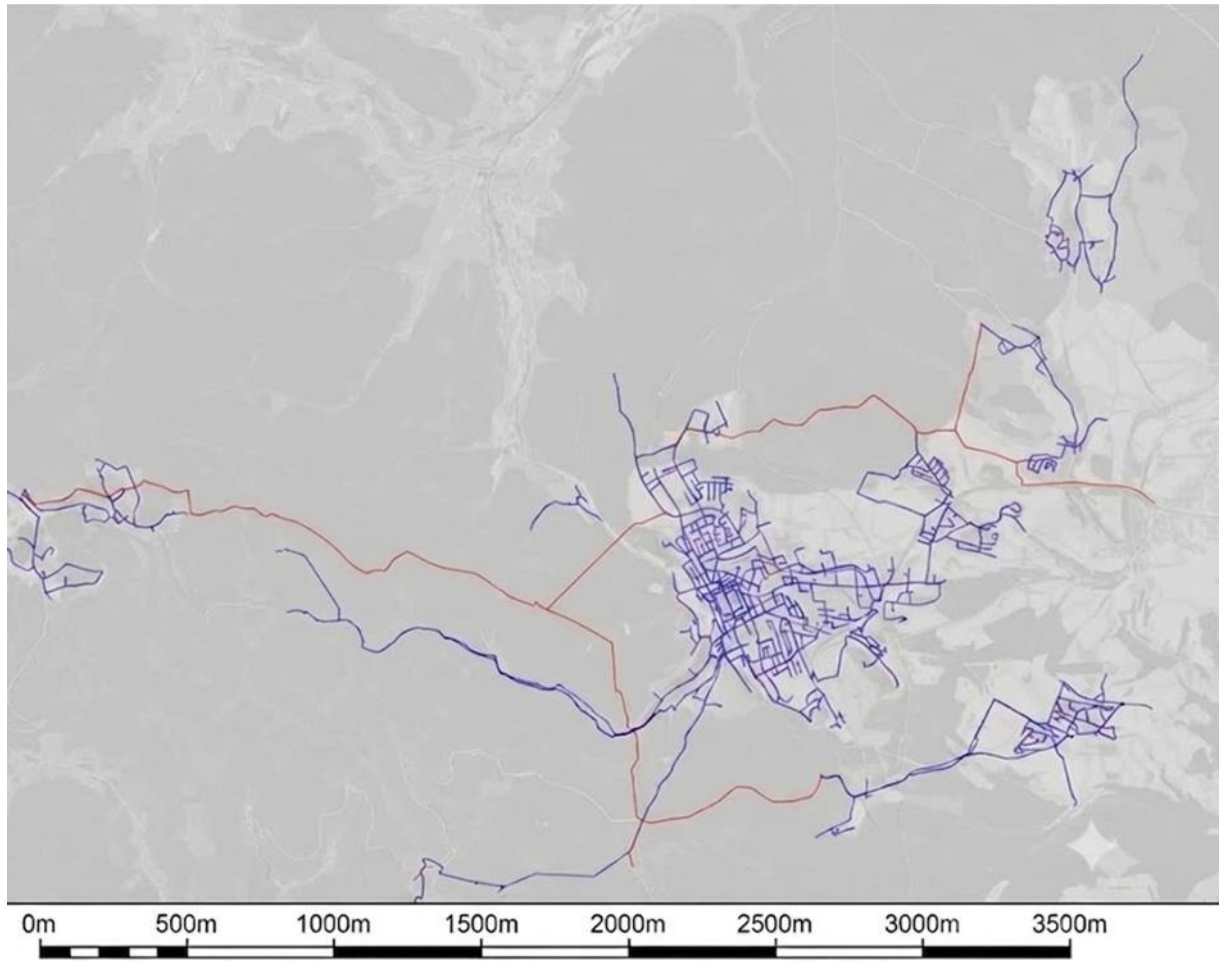


FIGURE 4: UPDATED NETWORK STATUS OF STADTWERKE FREUDENSTADT'S NETWORK AFTER THE MANUAL ADJUSTMENT OF THE CONSTRUCTION YEARS

This adjusted dataset provides a foundation for accurately incorporating damage statistics and hydraulic criticality into the risk-based decision-making model. To finalize the scope of the study, the network owners had to be precisely defined, and the types of pipelines to be assessed had to be expanded. As shown in Figure 5, a color-coding system has been implemented to visually distinguish responsibilities and relevance for rehabilitation planning purposes.

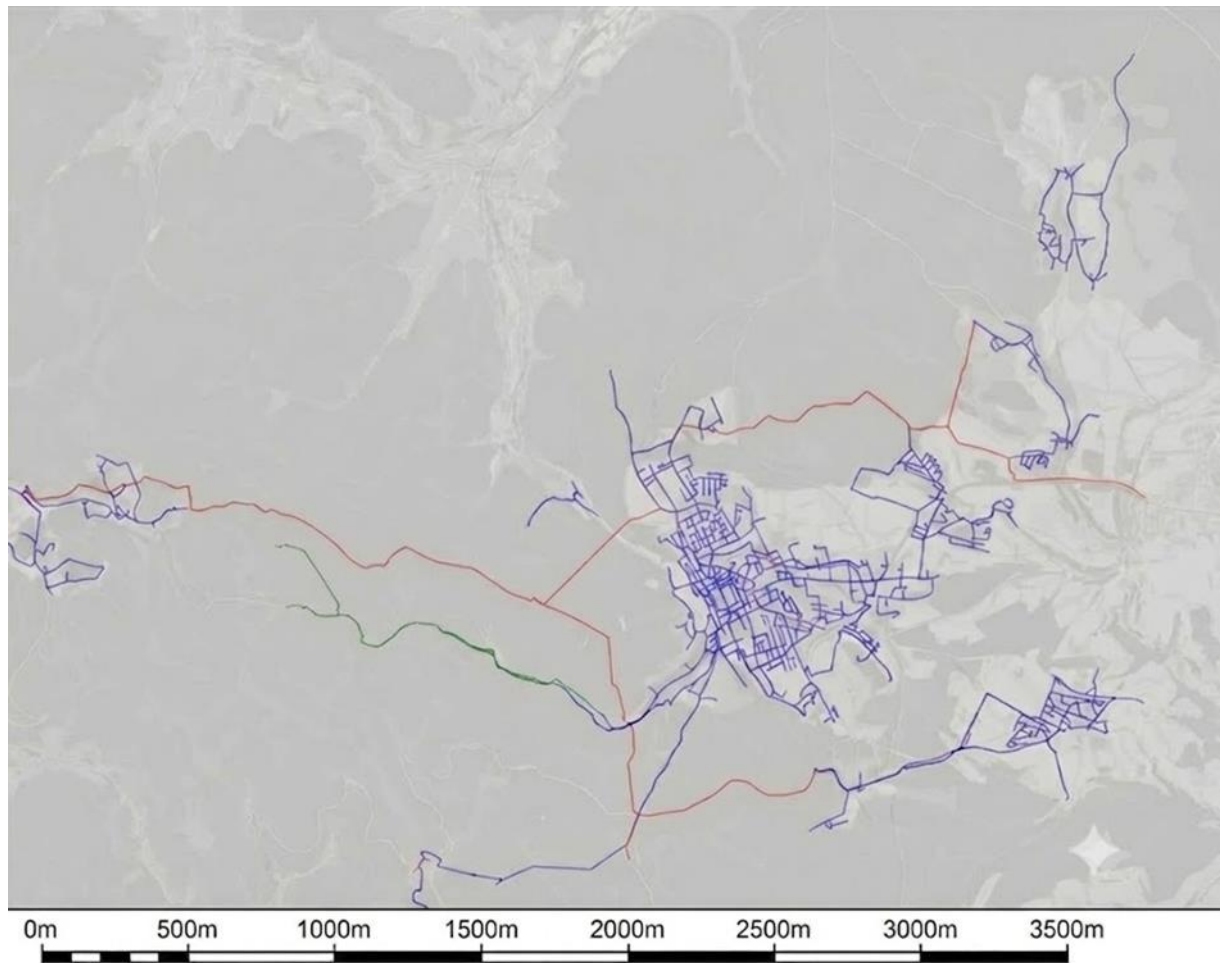


FIGURE 5: SYSTEMATIC DISTINCTION OF THE OWNERSHIP STRUCTURE

The following strategic decisions regarding further processing were made in close cooperation with Stadtwerke Freudenstadt. Figure 5 shows the differentiation based on three main categories: external long-distance water pipelines (red/no audit), municipal drinking water lines (blue/full valuation), and municipal raw water lines (green/full valuation). Figure 5 also shows that the remaining red sections are long-distance water pipelines belonging to ZVKK and not Stadtwerke Freudenstadt. Since these pipelines are not included in the project scope, they will be excluded from the analysis or entirely hidden to maintain clarity. Contrary to the original plan, raw water lines such as spring and well pipes, which are marked green in Figure 5, were included in the assessment. Although these lines do not carry treated drinking water, they form part of the local network and represent valuable assets for Stadtwerke Freudenstadt. The data was first successfully processed in STANET from geometric and technical perspectives. Following this, the model was transferred to Asset403, which is a software specializing in strategic rehabilitation planning based on mathematical life-cycle cost models. However, shortcomings in the quality of the documentation were revealed during the initial data import, which prevented direct simulation.

3.4.2 Operational Attribute Refinement and Consumption Profile Integration

A resilient water supply strategy must consider the socioeconomic evolution of the supply area. Since 2018, Freudenstadt's residential population has grown, especially in the city center. During the data preparation phase, all new residential zones, including several new streets with individual house connections, were manually integrated. Consumption profiles for these new nodes were entered into the system using longitudinal data from various years since 2018. This ensures that the criticality of each pipe segment is calculated based on current demand rather than outdated

load cases from 2018. Conversely, the consumption values of properties that were demolished were set to zero to maintain the integrity of the network and prevent the overestimation of demand. This granular, demand update is essential for accurately determining the extent of damage and the number of unserved customers in the final risk matrix.

In addition to the chronological data, significant improvements were needed to the technical attributes of the pipelines to ensure hydraulic accuracy. The existing dataset had many inconsistencies regarding pipe diameters and material specifications. The data cleaning process revealed non-standard internal diameters, such as 106 mm and 158 mm. An investigation of historical technical catalogs determined that these values corresponded to specifications for legacy ductile cast iron (GGG) pipes with nominal diameters (DN) of DN 100 and DN 150. Remapping these values to modern standards restored the hydraulic model's friction loss calculations and pressure gradient simulations. The system categorizes different material groups by age to improve the efficiency of the diagnostic process. For example, it distinguishes between older materials and modern, high-performance materials, such as polyethylene (PE). Switching from an inadequate dataset to a verified, multi-layered attribute system provides the transparency necessary for implementing rehabilitation planning.

3.4.3 Portfolio Analysis, Statistical Adjustments, and Software Import

The following sections describe the systematic processing and validation of the network data required for the strategic rehabilitation model. This phase involves converting various raw datasets into a uniform digital inventory within the Asset403 tool. The two core objectives of this data refinement process are statistical analysis and cleaning the pipeline to eliminate inconsistencies, erroneous construction dates, and external network components. Second, the process involves strategically categorizing material generations to reflect historical technical standards and specific failure characteristics. The goal is to categorize material generations strategically to reflect historical technical standards and specific failure characteristics. Additionally, it involves the spatial assignment and qualitative filtering of historical damage records to ensure that only systemic failures influence the long-term forecasting model. This comprehensive validation process ensures that the subsequent risk analysis is based on a realistic representation of the current network state rather than errors in the raw data.

The first import process in Asset403 was used to identify inconsistencies within the asset classes and update the inventory date. Figure 6 shows the status report following the import of the raw dataset.

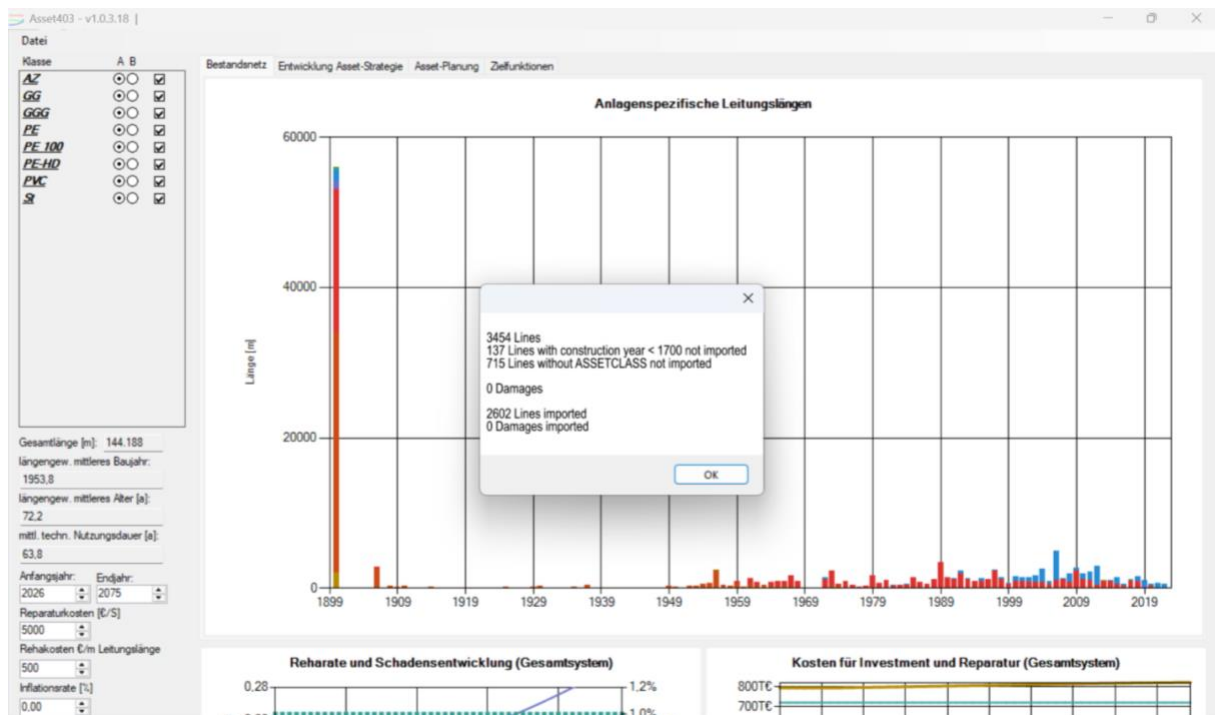


FIGURE 6: IMPORT THE STATUS AND STATISTICAL INTERFACE OF THE ASSET403 TOOL PRIOR TO DATA PREPARATION

Analysis of the import process revealed the following critical issues:

Of the 3.454 pipeline segments, only 2.602 could be successfully imported.

- 715 did not have a valid asset class assigned, meaning the material and diameter were missing.
- Construction years prior to 1700 were identified for 137 pipelines, suggesting erroneous database entries or placeholder values, or pipes from ZVKK, that haven't been sorted yet.
- The length-weighted average age of the network was initially calculated as *72,2 years*, whereas the average technical service life is only *63,8 years*.
- According to (DVGW e.V. W 1003 (A), 2022), this discrepancy indicates an urgent need for action, as the theoretical replacement date for much of the network has already been exceeded.

Figure 7 illustrates the resulting age distribution of the network, which is characterized by extreme skewness.

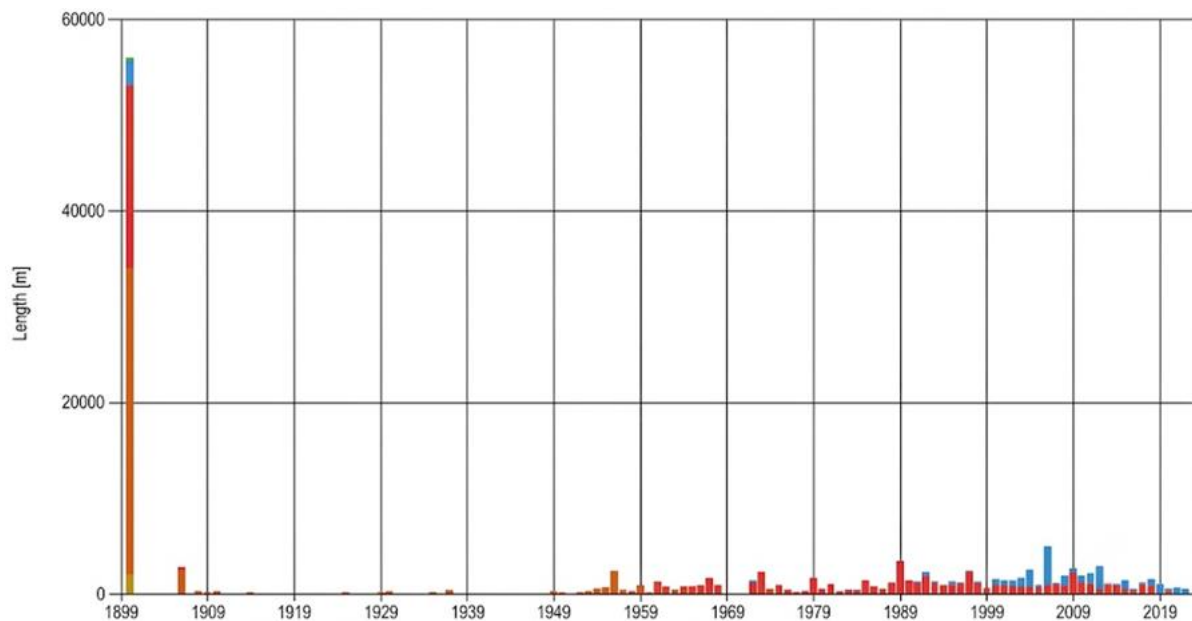


FIGURE 7: AGE STRUCTURE AND MATERIAL DISTRIBUTION OF THE PIPELINE NETWORK (INITIAL STATE)

Figure 7 shows the results of a statistical analysis of material groups and years of construction. The significant increase in 1899 does not represent actual construction activity; rather, it covers all pipelines with an unknown construction date. This peak is primarily caused by ZVKK pipelines that could not be clearly distinguished from Stadtwerke Freudenstadt's municipal utilities network when the data was imported. As no specific construction year was recorded in the dataset for these external pipelines, their presence significantly affected the initial age structure of the entire system. During the subsequent data sorting process, these ZVKK pipelines were identified and consistently excluded from the assessment to provide a realistic picture of the network to be rehabilitated.

The legend in Figure 7 distinguishes between main materials such as asbestos cement (AZ), grey cast iron (GG), ductile cast iron (GGG) and steel (St), as well as various polyethylene (PE, PE 100 and PE-HD) and polyvinyl chloride (PVC) variants. Although modern plastics such as PE-HD and PE 100 have dominated construction since around 1990, metallic materials dominate infrastructure from the mid-20th century onwards. This distribution of materials and ages provides a first basis for assigning specific failure rates and forecasting future damage.

A validated dataset was produced by systematically adjusting the construction years and consistently excluding transmission lines belonging to the ZVKK. Additionally, statistical evaluations of the network and historical damage analyses only considered currently operating pipelines. The asset database entirely excluded decommissioned or abandoned pipelines. This dataset enables a statistical assessment of the Stadtwerke Freudenstadt's municipal pipe network for the first time. Figure 8 shows the user interface of the Asset403 software, which summarizes the key performance indicators after the adjustments. The analysis of the statistical parameters on the left provides insights into the current portfolio.

The total length of the network remaining in the model and relevant for the assessment is 166.392 *meters*. Following the corrections, the length-weighted average year of construction changed to 1979,3, indicating an average age of 46,7 *years*. The average technical service life is reported as 71,3 *years*. As the actual average age exceeds the calculated service life, the model indicates a significant need for rehabilitation planning in accordance with the criteria set out in (DVGW e.V. W 1003 (A), 2022).

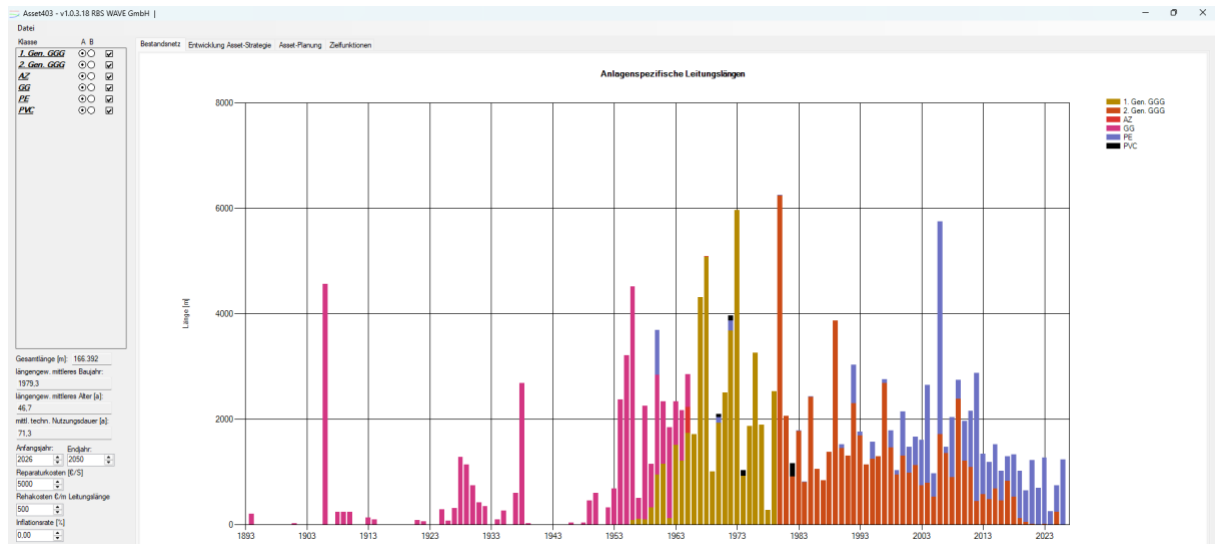


FIGURE 8: STATISTICAL METRICS FOR THE ADJUSTED NETWORK IN ASSET403

Figure 9 shows how construction activities and material composition have changed over time. The previously dominant peak in 1899 has now been eliminated through the removal of ZVKK pipelines and manual adjustments.

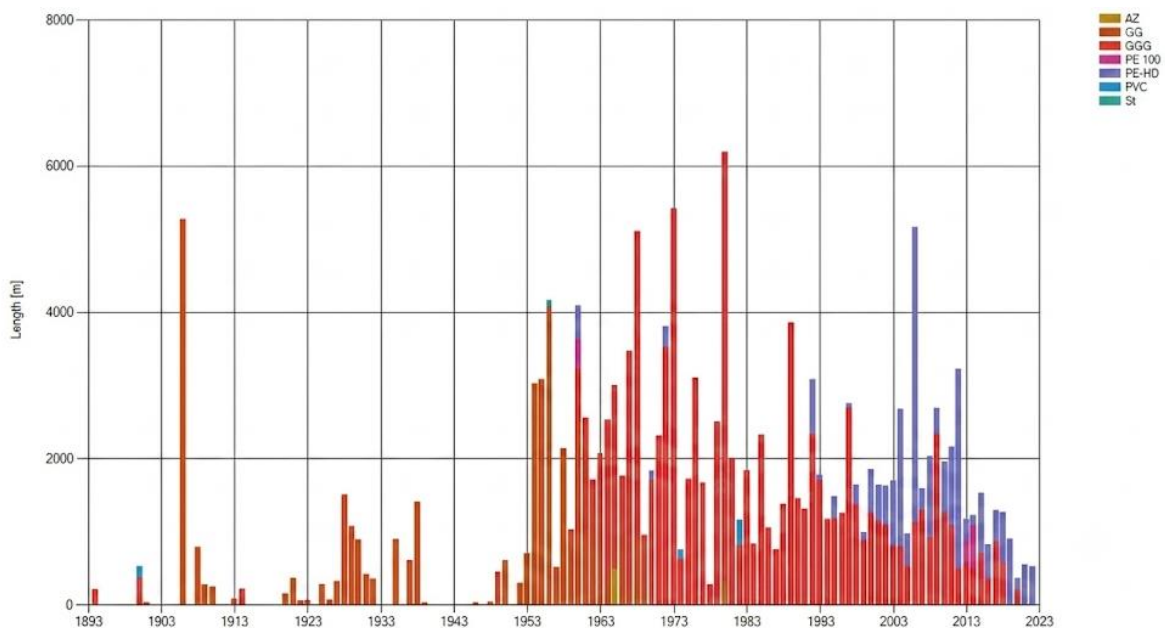


FIGURE 9: SYSTEM-SPECIFIC PIPE LENGTHS BY YEAR OF CONSTRUCTION AND MATERIAL GROUP

A graphical analysis of the material groups enables the history of the network to be interpreted in detail. Distinct construction phases can be identified in the early 1900s and between 1925 and 1935. These phases are characterized primarily by grey cast iron (GG, orange). A significant expansion and renewal phase involving ductile cast iron (GGG, red) occurred between 1955 and 1980, forming the backbone of today's supply network. More recent network sections, dating from 2000 onwards, increasingly feature modern plastic materials, such as PE 100 (light blue) and PE-HD (purple).

While the chronological classification is largely complete, the final categorization of material classes and their weighting in the assessment will be carried out in a subsequent step, in close

coordination with Stadtwerke Freudenstadt, to accurately reflect local differences in damage characteristics.

The strategic adjustment of the material classification for the water supply network aims to optimize the timeframe. This is accomplished by categorizing materials based on their unique damage characteristics. This increases the robustness of economic scenarios. The process begins with the theoretical foundation presented in Figure 10, which uses data from (Springer Nature, 2014) to illustrate the evolution of pipe generations over time. Although the referenced source provides a detailed overview of the various types of pipes, Stadtwerke Freudenstadt's model does not incorporate these distinct categories. Given the specific characteristics of the local service area, including these rarely used pipe materials would not add value to the prioritization matrix.

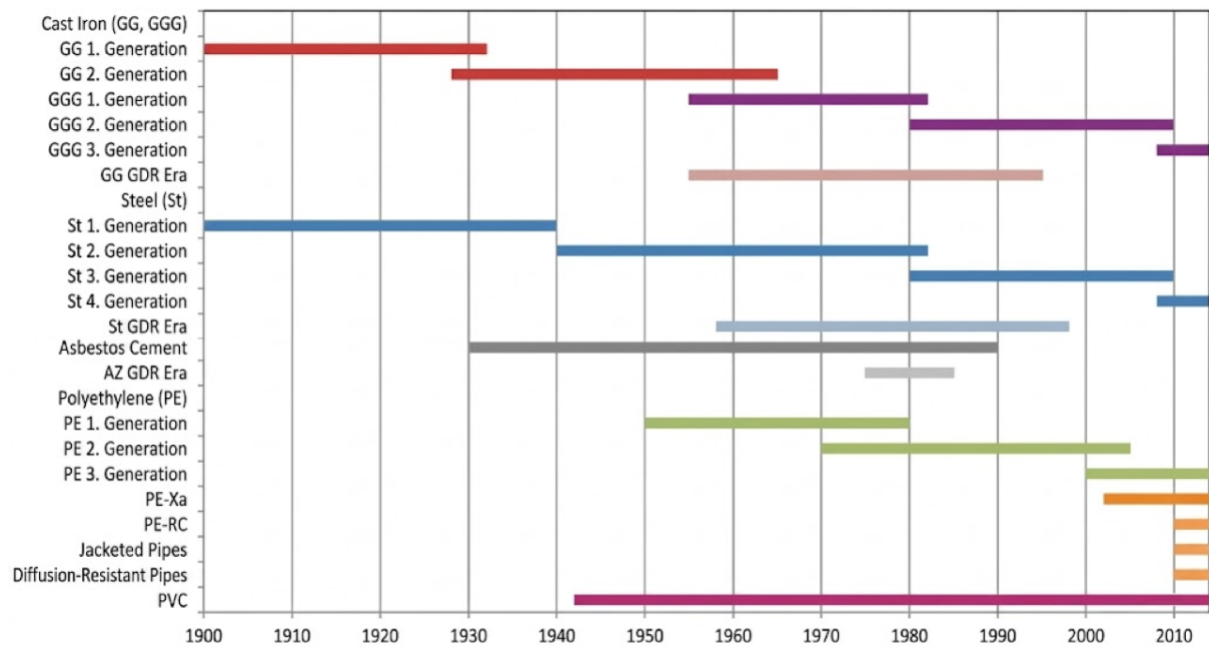


FIGURE 10: HISTORICAL APPLICATIONS OF PIPE MATERIALS IN THE WATER SUPPLY (SPRINGER NATURE, 2014)

A central element of this restructuring involves dividing ductile cast iron into two generations, with 1980 serving as the definitive transition point. Local inventory data and technical exchanges with neighboring water utilities confirm this threshold and demonstrate that the second generation became the standard around this time due to its technical improvements. Figure 11 illustrates the age-specific distribution of pipe lengths and reveals that this period marks a significant shift in material usage. The first generation of GGG has a notably higher failure probability in damage analyses, sometimes exceeding the rates of late-generation grey cast iron. In contrast, the second generation is considered a separate category due to its optimized manufacturing processes and superior coatings. These factors result in a significantly longer technical service life within the model.

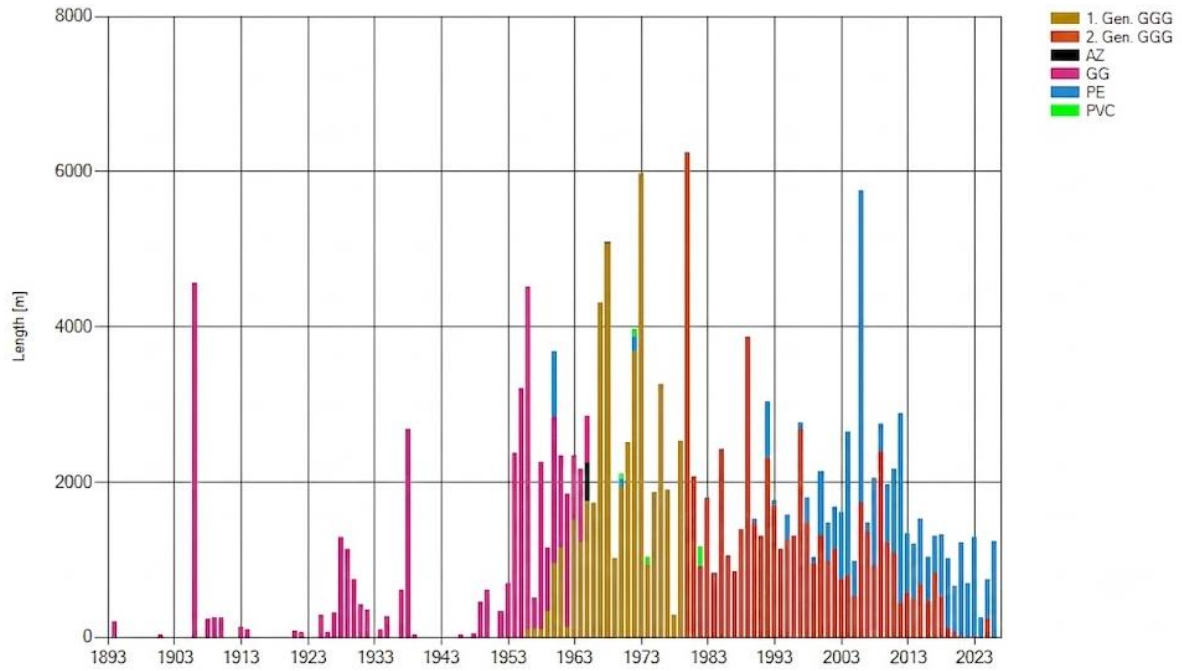


FIGURE 11: FINAL MATERIAL AND GENERATION MODEL, INCLUDING DAMAGE DISTRIBUTION (AS OF 2026)

Likewise, thermoplastics fall into two main categories: polyvinyl chloride (PVC) and polyethylene (PE). This effectively eliminates the distinction between PE-HD and PE 100. The identical risk analysis parameters for these subtypes within the investigated network justifies this simplification. By focusing on these relevant categories, the model avoids unnecessary complexity while maintaining high accuracy. Figure 11 illustrates the historical context of network expansion, highlighting construction standstills during World Wars I and II, followed by massive infrastructure growth in the postwar era. This data-driven approach ensures that investment strategies for the coming decades are based on a realistic, straightforward representation of existing pipeline assets.

3.5 Conceptual Formulation and Weighting of the Multi-Criteria Risk Model

3.5.1 Application of the AHP in Water Supply

The assessment system for pipeline sections uses two main dimensions: Condition Assessment, which determines the probability of damage, and Damage Extent, which estimates the potential impact of a failure. The criteria for each dimension are scaled on an index ranging from 0 (no influence) to 1 (maximum influence). This section provides an overview of the core evaluation framework. The following will present a thorough analysis of each criterion within these two dimensions. It will detail the specific evaluation methodologies and indexing scales used for each criterion.

Condition Assessment

This dimension considers technical and external stress factors that significantly affect the aging and damage of pipelines. Technical criteria include the age of the pipeline and the material of the pipe. The historical damage rate is a direct operational indicator of material wear and tear. External influences from traffic and rail loads are also considered. These parameters are graded according to the intensity and frequency of dynamic load inputs.

Damage Extent

This dimension evaluates the importance of a pipe burst based on its potential social, economic,

and operational consequences. Proximity to critical infrastructure and distinguishing between replaceable assets and irreplaceable facilities are key factors. General criticality is quantified by the number of residents who could be affected. A pipe's hydraulic relevance within the network is represented by its importance, i.e., whether it is a main or secondary flow pipeline. Experts conducting a criticality assessment also consider specific constraints, such as accessibility issues. The assessment also considers physical consequences, such as the erosion radius near buildings and operating pressure.

3.5.2 Evaluation of Criteria and Derivation of Weighting

The evaluation framework is structured into two stages to determine the overall risk priority of pipeline sections. The process begins with a condition assessment to quantify the probability of failure. This is followed by an evaluation of the potential extent of damage, to establish the consequences of a failure event. The AHP framework derives the relative weights of the criteria for both dimensions. The overall risk index for each pipeline section is calculated by combining the condition assessment and the damage extent. To reflect the operational priorities of the network, different weights are given to the dimensions. All different categories can be seen in Figure 12.

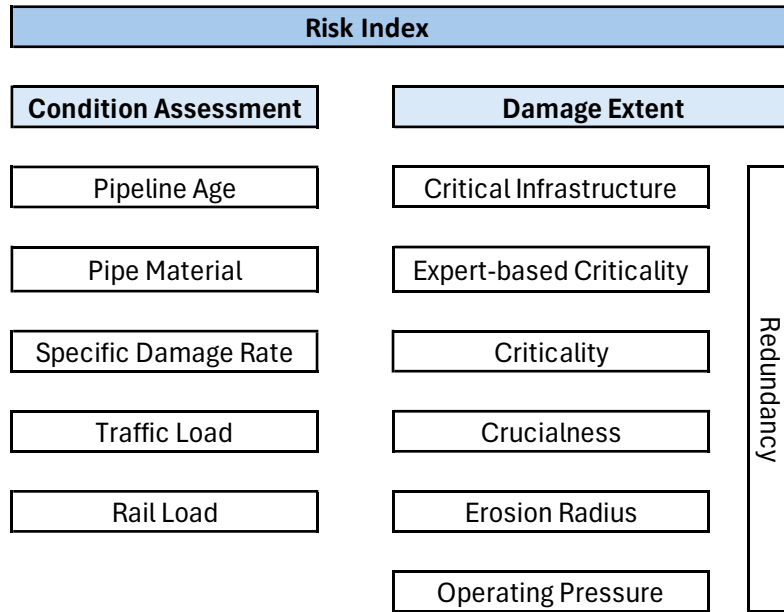


FIGURE 12: CRITERIA FRAMEWORK FOR CALCULATING THE RISK INDEX

While the Condition Assessment consists of five sub-criteria directly affecting pipe degradation, the Damage Extent evaluates the local consequences through six specific environmental and structural parameters. This local impact is structurally adjusted by a vertical redundancy factor that accounts for the importance and type of the pipeline. Based on this *structural* framework, the mathematical formulation of the risk index is defined as follows:

$$RI = \left(0,6 \cdot \sum_{i=1}^n I_{CA,i} \cdot W_i + 0,4 \cdot \left(\sum_{i=1}^n (I_{DE,i} \cdot W_i) \cdot R_i \right) \right) \quad (3.2)$$

Where:

RI	Overall Risk Index for one pipe segment
$I_{CA,i}$	Index of Local Condition Assessment Criteria
$I_{DE,i}$	Index of Local Damage Extent Criteria

W_i	Weight of the Criteria
R_i	Redundancy factor based on the pipeline type

This weighting ensures that rehabilitation planning is primarily driven by the technical condition of the asset at 60%. Preliminary sensitivity analyses comparing alternative macro distributions (e.g., 50/50 and 70/30) revealed that the 50/50 split overemphasized operational consequences at the expense of urgent physical decay. Conversely, the 70/30 distribution underestimated critical supply risks to key infrastructure. The 60/40 ratio yielded the most balanced and practical prioritization. This was confirmed through close consultation with the engineering staff at Stadtwerke Freudenberg and RBS Wave GmbH. The criticality and surrounding environment contribute the remaining 40% to the final score, which is further modified by the systemic importance (redundancy) of the pipe section.

3.5.3 Condition Assessment

This chapter focuses on the technical aspects of pipeline infrastructure to assess the likelihood of structural failure. It systematically evaluates asset-specific properties and direct external mechanical stresses. The AHP objectively and mathematically determines the criteria's weights. The five core criteria are evaluated by balancing the attributes of the assets with the environmental risk factors using a pairwise comparison matrix.

TABLE 4: PAIRWISE COMPARISON MATRIX FOR CONDITION ASSESSMENT CRITERIA

	Pipeline Age	Pipe Material	Specific Damage Rate	Traffic Load	Rail Load
Pipeline Age	1	3	2	3	5
Pipe Material	1/3	1	2	2	4
Specific Damage Rate	1/2	1/2	1	2	4
Traffic Load	1/3	1/2	1/2	1	3
Rail Load	1/5	1/4	1/4	1/3	1

Table 4 shows the operational prioritization and relative importance of each criterion, which are determined by pairwise comparisons. The qualitative evaluations are converted into a standardized priority vector by calculating the principal eigenvector. The resulting weight distribution for the condition assessment criteria is shown in Table 5.

TABLE 5: RESULTING WEIGHTS AND PRIORITIES FOR CONDITION ASSESSMENT

Condition Assessment Criterion	Weight
Pipeline Age	30,2 %
Pipe Material	23,8 %
Specific Damage Rate	21,9 %
Traffic Load	15,4 %
Rail Load	8,7 %

- ❖ Pipeline Age (30,2 %):
This criterion has the greatest influence on failure probability. Time-dependent material degradation and long-term exposure to cumulative stresses affect the entire network. In the pairwise comparison matrix, pipeline age is classified as having the most important impact.
- ❖ Pipe Material (23,8 %):
The material's mechanical properties and corrosion resistance determine its structural stability. Therefore, material characteristics are prioritized over historical damage rates and dynamic

traffic loads because the chemical and structural composition determine how the pipeline reacts to environmental stresses.

- ❖ **Specific Damage Rate (21,9 %):**
As an empirical, network-specific indicator, the historical failure rate provides direct calibration based on localized, real-world data.
- ❖ **Traffic load (15,4 %):**
Dynamic surface stresses and ground vibrations induced by road transport accelerate structural degradation. While this external factor is critical, it is a lower priority than pipe properties because of soil cover depth and pipe bedding protection.
- ❖ **Rail load (8,7 %):**
Localized structural vibrations from railway lines represent the lowest weight within the condition assessment dimension. This is justified by the highly limited spatial occurrence of rail crossings within the municipal area.

These derived weights establish the framework for the following condition assessment. The following subsections systematically describe the evaluation methodologies, scoring systems, and indexing scales for each criterion. To demonstrate the framework's practical application, each subsection uses operational data from Stadtwerke Freudensstadt's municipal water supply network. This localized dataset provides the absolute length in meters and the corresponding percentage distribution across all condition categories. Integrating these empirical metrics serves two primary purposes.

- It provides a clear visual representation of the local network's current physical state, material trends, and environmental stress factors.
- It establishes a baseline for structural evaluation in the absence of explicit guidelines or standard literature parameters by directly connecting the cited technical standards to the specific operational context.

Pipeline Age

The age of a pipeline section is a key indicator of time-dependent degradation processes, such as internal and external corrosion. To ensure methodological accuracy, this criterion is categorized according to established asset management frameworks in water supply engineering. Specifically, the definition of age intervals and their impact on pipeline degradation follows the classification proposed by (Al-Barqawi & Zayed, 2008). This approach models a nonlinear increase in failure probability. This increase occurs as infrastructure assets age. It accounts for the cumulative exposure to mechanical and chemical stresses over time. Within the evaluation framework, raw operational data is transformed into a standardized index ranging from 0 to 1, and the specific age intervals and their assigned progressive risk indices are systematically structured in Table 6.

TABLE 6: INDEX CLASSIFICATION AND AGEING INTERVALS FOR PIPELINE SECTIONS BASED ON (DVGW E.V. W 401, 1997) AND (AL-BARQAWI & ZAYED, 2008)

Pipeline Age [years]	Index	Absolute Length [m]	Percentage
< 20	0,00	28.081,8	16,9%
20 – 40	0,25	39.023,8	23,5%
40 – 60	0,50	51.390,4	30,9%
60 – 80	0,75	33.645,0	20,2%
> 80	1,00	14.250,6	8,6%

The classification reflects the technical service life of pipelines according to (DVGW e.V. W 401, 1997). As shown in Table 6, pipeline sections under 20 years old are assigned an index of 0 because significant time-dependent degradation is absent (compare with Figure 18). As age increases, the index rises steadily from 0,25 to 0,75, reflecting the accelerated degradation kinetics typically observed in midlife infrastructure. Assets that exceed the standard technical lifespan of 80 years receive the maximum index value of 1 due to the exponential increase in material wear and tear that puts the structural integrity at risk, requiring immediate consideration of rehabilitation.

Pipe Material

The material properties of a pipeline influence its physical integrity and long-term degradation behavior. Different materials have different mechanical properties, corrosion resistance, and aging mechanisms. To ensure methodological validity within the assessment framework, the "pipe material" criterion is categorized according to international technical literature. Table 7 summarizes the standardized technical service lives according to (DVGW e.V. W 401, 1997).

TABLE 7: STANDARDIZED TECHNICAL SERVICE LIVES FOR PIPE MATERIALS ACCORDING TO (DVGW E.V. W 401, 1997)

Pipe Material	Technical Service Life according to DVGW W 401
AZ	-
GG	60 - 120
1. Gen. GGG	40 - 100
2. Gen. GGG	100 - 140
PE	40 - 80
Stahl	60 - 100

Scientific literature shows that the selection and historical classification of materials directly correlates with the probability of failure. Modern ductile iron pipes and plastics, such as high-density polyethylene (HDPE), are highly resilient, however, older materials have significantly higher failure rates. For example, (Al-Barqawi & Zayed, 2008) and (Zyoud, 2017) identified GG as a critical material that greatly impact failure risk due to phenomena such as graphitization. The risk assessment of GGG, PE and PVC varies depending on the evaluation context. (Marzouk, Hamid, & El-Said, 2015) and (Nedjar, Djebbar, & Djemili, 2022) point out that early generations of PVC are prone to cracking and subsequent failure under specific loading conditions, while modern PE pipelines, on the other hand, typically exhibit the lowest inherent risk. This is also why they are grouped together in the general "PE" category and are no longer separated between PE 100 and PE-HD. Additionally, a differentiated view of technological development stages is necessary for cast iron materials because the introduction of the second generation of GGG substantially improved toughness and corrosion protection.

These material-specific risk profiles convert raw operational data into a standardized index ranging from 0,2 to 1,0. The specific indexing and material categorizations are organized systematically in Table 8.

TABLE 8: MATERIAL-SPECIFIC INDEX CLASSIFICATION AND STRUCTURAL RISK PROFILES

Pipe Material	Index	Absolute Length [m]	Percentage
PE	0,20	28.617,6	17,2%
2. Gen. GGG	0,40	55.087,2	33,1%
1. Gen. GGG	0,60	42.417,6	25,5%
GG	0,80	37.521,0	22,5%
AZ, PVC	1,00	2.748,2	1,7%

As shown in Table 8, PE has a minimum risk index of 0,2. This is due to its excellent flexibility and corrosion resistance. The scoring system for metallic pipelines reflects their evolution in terms of production quality, both chronologically and technologically. Second-generation GGG pipes receive an index of 0,4. First-generation GGG pipes have a risk index of 0,6. However, they are stronger than gray cast iron pipes, which have a high index value of 0,8 because of their graphite structure and tendency to break more easily. The maximum index value of 1,0 is allocated to AZ and PVC pipelines. AZ pipelines carry health risks during handling because inhaling the generated dust is highly toxic. However, the material is considered uncritical during standard operation as long as only water flows through it. Early generations of PVC experience material exhaustion and softening due to long-term plasticizer loss, necessitating this critical assessment.

Specific Damage Rate

Integrating the historical damage rate provides an evaluation of the existing infrastructure that is both empirical and network specific. This assessment provides a more accurate evaluation than generalized aging and material risks derived from standard literature. Guidelines and standard damage indices often fail to capture unique local boundary conditions, such as soil chemistry and historical installation quality. Thus, this localized analytical approach was developed for the evaluation framework. Damages are assigned via the logical clustering of homogeneous pipeline segments. When a damage event occurs, a specific section is identified as a weak point, and all identical sections within that network zone are included in the risk assessment. These sections' homogeneity and comparability are strictly defined by two criteria: the exact year of construction and an identical pipe type, characterized by material and nominal diameter.

To quantify this criterion, the total cumulative length L_{total} in meters is determined for each homogeneous cluster. Then, L_{total} is placed in relation to the absolute number of documented damages within that cluster $n_{damages}$. This mathematical relationship yields the damage rate, which is expressed in meters of pipeline per damage.

$$\text{Specific Damage Rate} = \frac{L_{total}}{n_{damages}}$$

A lower numerical value indicates a shorter pipeline length per failure, suggesting high damage density and acute failure risk. As the number of meters per damage event increases, the need for rehabilitation decreases correspondingly. To transform the data into a standardized index, the affected assets were divided into eight distinct condition categories. Table 9 summarizes the weighting parameters, empirical distributions, and quantitative boundaries underlying this transformation.

TABLE 9: SPECIFIC DAMAGE RATE CLASSIFICATION AND DISTRIBUTION FOR RISK INDEXING

Specific Damage Rate [m / Damage]	Index	Absolute Length [m]	Percentage
> 1.200	0,00	137.019,9	82,3%
500 – 1.200	0,10	5.328,5	3,2%
300 – 500	0,20	4.332,6	2,6%
200 – 300	0,30	5.052,8	3,0%
150 – 200	0,70	5.026,1	3,0%
100 – 150	0,80	5.154,9	3,1%
50 – 100	0,90	3.681,4	2,2%
0 – 50	1,00	795,4	0,5%

As shown in Table 9, the boundaries of these intervals are defined by the distribution of the overall dataset, which comprises 182 damages on 101 damaged pipeline sections. The classification and distribution of these sections across the intervals reveal a clear concentration in the high-risk categories. The first category has a damage rate of over 1.200 *meters* and a risk index of 0 because failures only occur beyond one kilometer, indicating negligible damage density. The second category, spanning 500 to 1.200 *meters*, indicates very low damage potential. This category includes four pipeline sections within the network. The 300 – 500 *meter* interval includes ten affected pipeline sections. The 200 – 300 *meter* interval marks the transition toward regular damage patterns and has an index of 0,3. This category includes 14 pipeline sections. A critical turning point in the evaluation framework occurs in the 150 – 200 *meter* category, where the risk index increases nonlinearly to 0,7. This sharp increase is due to the significant accumulation of 16 affected pipeline sections, indicating a severe concentration of failures. The empirical and mathematical peaks of the entire distribution are reached in the 100 – 150 *meter* category. This category has a high failure frequency and contains 21 affected pipeline sections, the most in the dataset. This critical trend continues in the 50 – 100 *meter* category, which has dense damage spacing and affects 20 pipeline sections. The 0 – 50 *meter* category has the highest failure risk, with an index of 1,0, as sections have experienced a damage event every 50 *meters* or less. Twelve pipeline sections in the dataset reach this peak risk level, indicating severe material failure and requiring the highest priority in the rehabilitation model.

Traffic Load

External mechanical influences, such as traffic loads, accelerate the degradation of pipeline infrastructure. Heavy vehicle traffic, frequent bus routes, and agricultural machinery generate cyclical surface stresses that propagate through the soil and result in ground vibrations. To quantify these influences within the evaluation framework, the local network structure was overlaid with municipal spatial data and classified into seven load categories. The traffic categories were identified by using the pipeline GIS, open-source road network databases, and regional digital traffic maps from (Landesamt für Geoinformation und Landentwicklung Baden-Württemberg, 2026) and (Stadtverwaltung Freudenstadt, 2026). The resulting indexing framework and the corresponding empirical network lengths are organized systematically in Table 10.

TABLE 10: TRAFFIC LOAD CLASSIFICATION, RISK INDICES, AND CORRESPONDING PIPELINE DISTRIBUTION

Traffic Load	Index	Absolute Length [m]	Percentage
No traffic load	0,00	120.857,0	72,6%
Main railway station	0,10	242,3	0,1%
Occasional bus routes	0,20	725,1	0,4%
Bus routes	0,40	11.259,4	6,8%
District road	0,50	8.538,1	5,1%
Rural road	0,70	8.608,1	5,2%
Agricultural / Forestry load	0,80	9.599,3	5,8%
Federal road	1,00	6.562,3	3,9%

As shown in Table 10, the classification system covers all types of urban and rural transportation interfaces. These interfaces are organized by traffic volume, vehicle capacity, and operational impact. Areas subject to public transit operations require detailed routing analyses using local transit schedules and line network maps from the regional transit authority to differentiate transport frequencies. Standard regional road networks are divided into "district roads" (Kreisstraßen), which span 8.538,1 *m*, and "rural roads" (Landstraßen) receive an elevated index of 0,7 due to higher permitted speeds and increased freight axle loads. With a high-risk index of 0,8, the "Agricultural/Forestry Load" category presented a unique methodological challenge. This index reflects the extreme loads placed on the ground by equipment used for harvesting and transporting timber. In the initial phase of the risk assessment, a conservative spatial approach was implemented, classifying all pipeline segments running through designated forest perimeters as high risk. However, this preliminary baseline model yielded a cumulative length of 21.165,1 *m*, which overrepresented the environmental risk. To optimize the model and ensure data accuracy, Stadtwerke Freudenstadt was requested to provide operational traffic data and actual route logs. After filtering, the length was reduced to 9.599,3 *m*. The "federal road" (Bundesstraße) category poses the greatest risk because these roads experience continuous, high-frequency traffic. Within the analyzed network, 6.562,3 *m* fall into this maximum load category. This extreme dynamic stress justifies peak weighting, making these sections key areas for preventing structural damage.

Rail Load

In addition to standard vehicular traffic, localized mechanical stress is induced by railway infrastructure. The methodology for identifying and evaluating these assets is like the one used for assessing traffic loads (Landesamt für Geoinformation und Landentwicklung Baden-Württemberg, 2026). However, due to the highly localized nature of these crossing points within the municipal area, this criterion plays a minor role. However, it is essential for identifying structural vulnerabilities. The assessment framework categorizes these rare interfaces into five risk classes based on structural proximity and loading intensity. These classes are systematically structured in Table 11.

TABLE 11: RAIL LOAD CLASSIFICATION AND ASSIGNED RISK INDICES

Rail Load	Index	Absolute Length [m]	Percentage
No rail load	0,00	161.810,4	97,2%
Near railway tracks	0,10	3.062,0	1,8%
Parallel to the tracks	0,70	294,9	0,2%
Bridge under rails	0,80	118,6	0,1%
Under rails	0,90	998,2	0,6%
Twice under the rails	1,00	107,5	0,1%

As shown in Table 11, the spatial distribution indicates that pipeline segments within the environmental buffer zone ("Near railway tracks") have a low-risk index because they are not subject to direct structural loading. However, as the spatial intersection becomes direct, the risk index increases substantially. This increase is due to the static and dynamic forces of passing trains, as well as the continuous structural vibrations. Pipelines running parallel to or intersecting standard have an index of 0,7. The risk profile increases to an index of 0,8 for segments crossing a "Bridge under rails." This accounts for complex structural interactions, confined space maintenance restrictions, and direct vibration transmission. The most critical risk exposures occur where pipelines run directly beneath active tracks. Consequently, the "Under rails" category receives an index of 0,9, and the "Twice under the rails" category receives an index of 1,0, the absolute maximum.

3.5.4 Damage Extent

While previous sections focused on assessing the structural condition to determine the probability of failure, the evaluation framework must also quantify the potential consequences of a supply disruption within the "damage extent" dimension. This chapter evaluates potential consequences, such as socioeconomic and environmental impacts. The focus shifts from identifying the cause of the defect to assessing its practical impact on supply security and surrounding urban assets. The AHP establishes an objective framework for weighing these consequence parameters. The core criteria are evaluated using a pairwise comparison matrix that balances immediate public safety priorities with localized physical and hydraulic risk factors.

The operational prioritization and relative importance of each consequence criterion are determined by the pairwise comparisons shown in Table 12. Then, the principal eigenvector is calculated using these comparisons to convert the qualitative expert judgments into a standardized priority vector.

TABLE 12: PAIRWISE COMPARISON MATRIX FOR DAMAGE EXTENT CRITERIA

	Critical Infrastructure	Expert-based Criticality	Criticality	Crucialness	Erosion Radius	Operating Pressure
Critical Infrastructure	1	1	1	2	6	8
Expert-based Criticality	1	1	1	1	5	7
Criticality	1	1	1	1	5	7
Crucialness	1/2	1	1	1	6	8
Erosion Radius	1/6	1/5	1/5	1/6	1	2
Operating Pressure	1/8	1/7	1/7	1/8	1/2	1

The resulting weight distribution for the damage extent criteria is defined by the quantitative hierarchy shown in Table 13.

TABLE 13: RESULTING WEIGHTS AND PRIORITIES FOR DAMAGE EXTENT

Damage Extent Criterion	Weight
Critical Infrastructure	26,9%
Expert-based Criticality	22,2%
Criticality	22,2%
Crucialness	21,2%
Erosion Radius	4,5%
Operating Pressure	2,9%

- ❖ **Critical Infrastructure (26,9 %):**
This criterion has the greatest influence on the total score. Disruptions to the supply of vulnerable or irreplaceable entities, such as healthcare facilities, retirement homes, and schools, pose an immediate threat to public health and safety.
- ❖ **Expert-based Criticality (22,2 %):**
This criterion captures repair complexity based on expert knowledge, site accessibility, and estimated shutdown durations. It is prioritized equally with criticality, reflecting the fact that difficulty of restoration and physical access directly increase the socioeconomic impact of any failure event.
- ❖ **Criticality (22,2 %):**
This factor quantifies the systemic dependency of downstream consumers on primary transmission lines and gravity mains. It reflects the scale of the socioeconomic impact, as a structural failure would immediately trigger a supply deficit that would affect entire pressure zones.
- ❖ **Crucialness (21,2 %):**
This metric evaluates the hydraulic transport capacity and operational importance of the main distribution grid ($DN \geq 200$). Failure in high-flow municipal arteries triggers immediate localized depressurization, which heavily destabilizes the surrounding network.
- ❖ **Erosion Radius (4,5 %):**
This parameter evaluates the physical hazard of subsurface soil washout, which endangers nearby building foundations and roads. Although erosion is technically significant, its lower weight is justified because it is a localized hazard rather than a threat to regional supply security.
- ❖ **Operating Pressure (2,9 %):**
The volumetric discharge rate is determined by operating pressure using the Torricelli equation. Although it determines the physical scale of a burst, it is given lower priority because the secondary consequences are accounted for by the erosion radius and the criticality of downstream consumers.

To prevent distortion of the pairwise matrices, Table 12 and Table 13 exclude redundancy from the weighted criteria. Rather than acting as a horizontal sub-criterion, redundancy acts as an independent factor that directly scales the final damage extent calculation. This approach ensures an objective evaluation of the structural impact.

The following subsections provide an organized overview of the evaluation methodologies, scoring systems, and indexing scales for each consequence criterion. As already discussed in the Condition Assessment, each evaluation matrix is supported by empirical data from the Stadtwerke Freudenstadt municipal water supply network, providing both absolute lengths in meters and length-based percentage distributions.

Critical Infrastructure

This evaluation module focuses strictly on main pipelines. This ensures that the assessment captures systemic risk to supply security at a broad level, since the failure of a main supply pipeline could simultaneously compromise entire sectors. To evaluate these consequences systematically, sensitive consumer types within the municipal area were identified and classified based on operational resilience and structural redundancy using GIS data.

As there is no standardized classification for identifying critical infrastructure, this selection is based on comprehensive strategic discussions and expert advice. Consequently, the framework defines key public and economic sectors as critical infrastructure. This includes healthcare facilities, such as hospitals and clinics, as well as retirement homes, where a reliable water supply is essential for human health and wellbeing. Educational institutions, such as schools, and critical industrial areas, like the food industry, are also included due to their vulnerability to supply interruptions and the potential for economic and social consequences. The framework uses a scoring system to identify critical facilities in the agricultural, educational, healthcare and industrial sectors. The classification boundaries and indices logic are systematically structured in Table 14.

TABLE 14: FRAMEWORK FOR INDEXING CRITICAL INFRASTRUCTURE AND SENSITIVE CONSUMER

Critical Infrastructure	Index	Absolute Length [m]	Percentage
No critical infrastructure	0,00	161.556,3	97,1%
Critical replaceable infrastructure	0,50	3.367,7	2,0%
Critical irreplaceable infrastructure	1,00	1.467,6	0,9%

As shown in Table 14, the scoring logic identifies three operational states that determine if a pipeline is classified as replaceable or irreplaceable critical infrastructure.

- No critical infrastructure (index 0,00)
- Critical replaceable infrastructure (index 0,50): This classification is assigned to vital facilities that have localized backup storage or alternative supply routes. Consequently, critical water demand can be temporarily replaced during a pipeline failure, reducing the extent of immediate damage.
- Critical irreplaceable infrastructure (index 1,00): This classification is assigned to facilities where a water supply interruption would directly endanger public health or safety or result in serious economic loss. There is no immediate alternative or redundant supply network at this level that can provide the required operational pressure or volume.

The classification applies a structural redundancy check to sensitive facilities within the municipal network, depending on whether their feeder line can be bypassed. To prevent the evaluation model from becoming overly sensitive, general municipal, commercial, and residential facilities are excluded from the critical infrastructure rating and given an index value of 0. This exclusion applies to many urban facilities and spaces, including transit stations, construction depots, concrete or biogas plants, landfills, and multifamily housing units. While these locations are vital to daily urban operations, temporary water outages do not immediately endanger public safety or human life. This ensures that the framework strictly prioritizes irreplaceable institutions.

Expert-based Criticality

"Expert-based criticality" uses a quantitative scoring system that combines empirical field knowledge and qualitative network observations. With this system, experienced operational

personnel can identify localized site conditions that could significantly worsen the consequences of a pipeline failure. This criterion's core logic focuses heavily on estimated repair duration and operational shutdown time. The most significant socioeconomic consequence of a pipe burst depends on how quickly utilities can locate the leak and perform repairs. Factors such as high traffic density, extreme installation depths, property ownership constraints, and specialized construction methods can hinder accessibility. These factors consider how long a supply zone remains cut off due to a longer location or fixing time, and they incorporate this into the framework. Unlike other utility companies, Stadtwerke Freudenberg does not need to hire outside contractors to repair large-diameter pipelines. This prevents multi-day supply disruptions. Its internal workforce has the technical capability to independently repair pipelines of all sizes. This organizational advantage minimizes baseline restoration time and eliminates the need for long-term temporary bridging solutions. Consequently, Stadtwerke Freudenberg's model prioritizes site-specific complexity parameters over contractor-induced delays. The classification model converts these qualitative field notes into a scale of five distinct risk levels. The index scale directly reflects the expected increase in complexity and repair duration. Table 15 systematically organizes the specific qualitative conditions and their corresponding expert-based indices.

TABLE 15: EXPERT-BASED CRITICALITY CLASSIFICATION AND INDEXING BASED ON OPERATIONAL REPAIR COMPLEXITY

Expert-based Criticality	Index	Absolute Length [m]	Percentage
Standard conditions (no specific constraints)	0,00	147.610,7	88,7%
Heavy traffic	0,60	2.028,9	1,2%
Very deep / Cured-In-Place Pipe	0,70	859,3	0,5%
Unknown routing / limited accessibility / private land	0,80	3.937,3	2,4%
Hard to access / construction year completely unknown	0,90	5.787,4	3,5%
Drilled / stream bed / heavily damaged / stoneware	1,00	6.168,0	3,7%

The heavy traffic interval identifies pipeline sections where excavation delays are caused by the need to set up emergency detours, control traffic, and secure equipment in densely populated areas. These factors are unrelated to the physical load, which has already been evaluated. This is also why pipelines buried at non-standard depths receive a higher index. Legal and administrative barriers further complicate pipeline segments that cross private properties with surface obstacles or inaccurate historical GIS documentation. These segments require more time-consuming digging. Uncertainty increases when a total lack of historical construction records is coupled with difficult physical access, leaving repair teams unaware of the exact material specifications. The absolute peak of operational complexity involves extreme civil engineering solutions, such as drilling or replacing fragile, old stoneware spring pipelines. Complicated replacements are necessary in these situations, resulting in the longest possible supply outages and justifying an immediate priority within the rehabilitation matrix.

Criticality

When assessing the extent of socioeconomic damage caused by a pipeline failure, it is important to consider the asset's structural significance. This metric quantifies the scale of supply disruption based on the number of affected consumers. Specifically, this module evaluates the central transmission mains and gravity lines that feed directly from elevated storage reservoirs into the distribution network. These transmission lines are the primary arteries of the water supply system, therefore, any structural failure along these lines triggers a supply deficit that affects entire pressure zones. To capture this risk systematically, the transmission lines must be isolated, filtered, and

mapped to their respective supply zones. Although the spatial allocation presented complex hydraulic overlaps, particularly in areas where multiple pipelines are interconnected to supply a single zone, the assignment was generalized by determining the total number of downstream consumers. This established a clear, conservative relationship between the asset and its maximum supply dependency.

To ensure accuracy, the numerical classification boundaries within this framework must be adjusted based on demographics and supply structures. The resulting scoring system converts raw consumer connectivity data within a supply zone into a standardized index. The exact consumer intervals and their associated risk weightings are systematically organized in Table 16.

TABLE 16: CRITICALITY INDEX CLASSIFICATION BASED ON THE DOWNSTREAM CONSUMER FOR STADTWERKE FREUDENSTADT'S NETWORK

Criticality [Inhabitants]	Index	Absolute Length [m]	Percentage
< 100	0,00	148.446,4	89,2%
101 – 1.000	0,20	9.053,0	5,4%
1.001 – 2.000	0,40	5.869,6	3,5%
2.001 – 3.000	0,60	516,1	0,3%
3.001 – 4.000	0,80	1.130,0	0,7%
> 4.000	1,00	1.376,5	0,8%

As shown in Table 16, the scale linearly increases with growth in the affected supply area and rise in socioeconomic consequences. As the number of consumers increases through the intermediate ranges, the risk index rises by 0,2 intervals. The smaller classification accounts for peripheral districts and smaller villages, transitioning to medium-sized distribution zones. It also captures heavily integrated municipal sectors within the range of 2.001 to 3.000 consumers. The upper tier of the framework targets zones with a high impact on core municipal infrastructure. This is due to the high density of residential and commercial dependency on a single pipeline. This complicates short-term bypass procedures. The maximum risk level is assigned to the absolute peak of network criticality. A structural failure of any backbone pipeline supplying over 4.000 consumers could disrupt major municipal sectors or multiple districts. Therefore, it receives the highest index in the framework due to the threat to public welfare and network stability.

Crucialness

In addition to the structural importance of primary transmission arteries, the socioeconomic impact of damage must also consider the operational capacity and hydraulic significance of the distribution pipes as determined by the "crucialness" criterion. This module evaluates and ranks primary distribution mains operating directly within the municipal network grid. The focus is mainly on the analysis of distribution pipelines with a nominal diameter of at least $DN\ 200$. Furthermore, specialized transmission lines were excluded from this subset. The classification framework evaluates the operational importance of these pipelines based on their peak hydraulic capacity, measured in cubic meters per hour (m^3/h). To transform these continuous hydraulic flow rates into a standardized scoring system, the framework establishes five discrete capacity intervals. The exact volumetric boundaries and their corresponding risk indices are systematically organized in Table 17.

TABLE 17: CLASSIFICATION OF CRUCIALNESS AND PEAK HYDRAULIC CAPACITY FOR PIPELINES (DN ≥ 200)

Crucialness [m ³ /h]	Index	Absolute Length [m]	Percentage
< 1	0,00	149.644,5	89,9%
1 – 5	0,25	2.081,5	1,3%
5 – 10	0,50	1.927,1	1,2%
10 – 20	0,75	2.163,2	1,3%
> 20	1,00	1.205,6	0,7%

The distribution of the evaluated pipeline network shows that most falls into the baseline category. This category includes assets with peak flows of less than 1 m³/h and / or a diameter of less than 200 mm. These sections represent 89,9 % of the total. In contrast, the remaining hydraulic capacity intervals reflect the critical distribution backbone. The low-flow interval (1 – 5 m³/h) accounts for 1,3 % of the total network length, and the intermediate class (5 – 10 m³/h) marks the transition to standard municipal supply volumes. This class covers 1,2 % of the total. The elevated category, which covers major high-flow arteries within the urban core, comprises 1,3 %. Finally, the peak interval for flows exceeding 20 m³/h targets the most critical backbone mains, making up 1.205,6 m of the network. This maximum weighting is technically justified by the significant hydraulic energy and extensive downstream dependency of these large-diameter assets. Any structural damage at this level would lead to severe localized depressurization.

Erosion Radius

A critical consequence of a high-pressure pipeline failure is subsurface soil erosion. This erosion can quickly damage surrounding urban infrastructure, including foundations and roadways. A major structural failure creates a high-velocity water jet that washes away the surrounding soil. To quantify the potential damage, the maximum size of the washout zone must be calculated. This assessment is based on technical standards for water loss and pipeline failure analysis. Specifically, it references the empirical principles detailed in (DVGW e.V. W 401, 1997) and (DVGW e.V. W 402, 2021). The maximum erosion radius for each pipe is calculated using an empirical formula that links operational network pressure, structural dimensions, and kinetic energy. The mathematical relationship is defined as follows:

$$R_{erosion} = 8 \cdot \left((P_{mean} \cdot 10)^3 \cdot \left(\frac{DN}{1000} \right)^5 \right)^{\frac{1}{8}} \quad (3.3)$$

Where:

$R_{erosion}$	Maximum potential erosion radius in [m]
P_{mean}	$\left(\frac{P_{max} + P_{min}}{2} \right)$ Mean operational network pressure in [bar]
DN	Nominal diameter of the pipeline, normalized into [mm]

In this formula, the term representing the mean operating pressure is calculated using an average of the maximum and minimum pressure zone values recorded. This nonlinear relationship demonstrates that potential erosion increases drastically with an increase in inner diameter. The exact geometric boundaries and their corresponding risk indices are organized systematically in Table 18.

TABLE 18: EROSION RADIUS CLASSIFICATION, INTERVAL BOUNDARIES, AND PIPELINE DISTRIBUTION

Erosion Radius [m]	Index	Absolute Length [m]	Percentage
0 - 3 m	0,00	30.712,3	18,5%
3 - 7 m	0,25	14.818,5	8,9%
7 - 10 m	0,50	76.904,1	46,2%
10 - 15 m	0,75	40.070,6	24,1%
> 15 m	1,00	3.886,1	2,3%

A calculated erosion radius only triggers a hazard index if it intersects structural elements, such as urban buildings. However, if a pipeline with a calculated erosion radius runs through unpopulated areas, such as forests or open agricultural fields, where localized soil washout does not threaten structural stability, the asset's hazard index is automatically downgraded to zero. The baseline class includes sections with low operational pressure and small nominal diameters that have a minimal impact, as well as sections where the pipeline runs through open land that does not endanger infrastructure. Peak categories highlight zones with high consequences where the erosion radius poses a significant threat to the surrounding area. The maximum weighting is justified by the danger of foundation collapse.

Operating Pressure

Operating pressure is the primary hydraulic factor that determines the extent of a pipe burst. In the evaluation framework, this criterion focuses on operational pressure in the grid because it directly affects the initial velocity and volume of water that escapes during a failure event. Although the spatial effects of a burst are evaluated separately, including operating pressure in the risk matrix ensures that the network's potential energy is considered. The framework uses the maximum operational pressure of the supply zone to convert these continuous hydraulic states into a standardized scoring system.

The direct impact of operating pressure on resulting failure volume is mathematically defined by the Torricelli equation for leakage discharge rates:

$$Q = C_d \cdot A \cdot \sqrt{\frac{2 \cdot \Delta p}{\rho}} \quad (3.4)$$

Where:

- Q Leakage volumetric flow rate in cubic meters per second [m^3/s]
- C_d Dimensionless discharge coefficient, standardly assumed between 0,60 and 0,65 for sharp-edged holes in pipeline systems
- A : Cross-sectional area of the pipe failure opening in square meters [m^2]
- Δp Fluid pressure differential in Pascal (Pa), where $1 \text{ bar} = 100.000 \text{ Pa}$
- ρ Density of water, standardly approximated at 1.000 kg/m^3

TABLE 19: OPERATING PRESSURE CLASSIFICATION, RISK INDICES AND CALCULATED LEAKAGE DISCHARGE RATES BASED ON TORRICELLI

Operating Pressure [bar]	Assumed Design Pressure [bar]	Hole Ø 12 mm [m ³ /h]	Hole Ø 5 cm [m ³ /h]	Joint displacement DN 100 - 1 cm [m ³ /h]	Index	Absolute Length [m]	Percentage
< 2	2	5,1	87,7	45,6	0,00	16.161,5	9,7%
2 – 4	4	7,1	124,0	64,5	0,25	32.411,1	19,5%
4 – 6	6	8,7	151,8	79,0	0,50	45.761,2	27,5%
6 – 8	8	10,1	175,3	91,3	0,75	37.032,7	22,3%
> 8	10	11,3	196,0	102,1	1,00	35.025,1	21,0%

To ensure empirical validity, these theoretical classifications were cross-referenced with experimental research on pressurized pipeline leaks. (Darvini, Gambadori, & Soldini, 2024) conducted parametric laboratory investigations on cast iron systems and confirmed that hole diameters of up to 12 mm could simulate severe localized point corrosion. Scaling these parameters to large-scale failures, such as a 5 cm blowout or 1 cm total joint displacement, ensures that the framework prioritizes high-pressure zones in asset management. Even minor geometric failures in these zones can cause significant hydraulic secondary damage. Table 19 provides an overview of the calculated discharge rates for all analyzed failure types and hole sizes, thereby justifying the assigned indices.

In cases of complex structural damage, the cross-sectional failure area (A) must first be determined by calculating the geometry of the hole. For vertical joint displacement, the opening area no longer covered by the counterjoint is mathematically defined by the intersecting segment areas of two offset circles when the pipe segments shift a distance h . For minor displacements when h is small compared to the nominal pipe diameter (d), an approximation can be applied. This approximation assumes that the opening area behaves as a rectangle across the diameter.

$$A \approx d \cdot h$$

For a DN 100 pipeline with a vertical joint displacement of $h = 0,01 \text{ m}$ (1 cm) and a diameter of $d = 0,10 \text{ m}$, the precise geometric calculation of the intersecting segment areas yields an actual failure opening area of $A \approx 815 \text{ mm}^2$. This opening is hydraulically equivalent to a single circular punch hole with a diameter of approximately 32 mm.

The scale in Table 19 categorizes operational pressure into two-bar intervals to systematically classify operational risks and assign standardized risk indices. These intervals directly reflect the nonlinear progression of volumetric loss derived from the Torricelli formula. To demonstrate the derivation of the scoring matrix, the volumetric flow rate corresponding to a pipe burst is calculated step by step using a 12 mm ($A = 0,0001131 \text{ m}^2$) hole and an average discharge coefficient (C_d) of 0,62.

$$\begin{aligned}
 \Delta p &= 2 \text{ bar} = 200.000 \text{ Pa} \\
 A &= \frac{\pi \cdot d^2}{4} = \frac{\pi \cdot (0,012 \text{ m})^2}{4} \approx 0,0001131 \text{ m}^2 \\
 Q &= C_d \cdot A \cdot \sqrt{\frac{2 \cdot \Delta p}{\rho}} = 0,62 \cdot 0,0001131 \text{ m}^2 \cdot \sqrt{\frac{2 \cdot 200.000 \text{ Pa}}{1.000 \text{ kg/m}^3}} \\
 &\approx 0,001402 \text{ m}^3/\text{s} \approx 5,05 \text{ m}^3/\text{h}
 \end{aligned}$$

This calculation generates specific discharge values for defined pressure intervals. These values are used in the risk assessment framework in Table 19.

Redundancy

A significant structural factor in determining the ultimate socioeconomic consequences of a pipe failure is the network's operational redundancy. While previous criteria quantify the initial physical and hydraulic parameters of a failure event, the "Redundancy" module evaluates the system's capacity to withstand failure by rerouting the supply. The module determines if the affected pipeline is an irreplaceable link or if a temporary outage can be bypassed via meshed network rings or interconnected pressure zones. These pipeline segments are classified into five distinct categories for systematic classification. The indices increase progressively based on the difficulty of replacing the asset during an emergency shutdown.

Table 20 outlines the precise index assignments based on the alternative routing options of the respective network components.

TABLE 20: CLASSIFICATION OF REDUNDANCY INDEX BASED ON IMPORTANCE OF PIPELINE TYPE

Redundancy	Index	Absolute Length [m]	Percentage
Pipeline DN < 200	0,60	120.211,5	72,2%
Main Pipeline DN ≥ 200	0,70	9.500,7	5,7%
Interconnection Pipeline Between Reservoirs	0,80	2.948,8	1,8%
Downstream Gravity Lines	0,90	18.936,8	11,4%
Spring Source Pipelines / Raw Water Transmission Mains	1,00	14.793,8	8,9%

- Pipeline DN < 200 (Index 0,60):
This baseline category represents standard, localized distribution pipelines within the city grid that have smaller nominal diameters. The highly meshed nature of these smaller rings enables utility teams to quickly reroute flow through nearby loops, thereby minimizing the socioeconomic impact of a failure.
- Main Pipeline (Index: 0,70):
This baseline category represents the distribution pipelines found in city grids. Although these lines carry significant volumes, the design of the distribution network usually enables utility teams to reroute flow through nearby loops, which reduces the impact of widespread failure.
- Interconnection Pipeline Between Reservoirs (Index: 0,80):
This category covers transmission mains that connect elevated storage tanks. While these lines enable regional water balancing, failure results in the loss of secondary backup reserves between zones, thereby increasing operational risk.
- Downstream Gravity Lines (Index: 0,90):
This high-risk category includes lines that supply isolated urban subzones or peripheral districts. Therefore, a physical disruption to these lines results in the termination of supply to all downstream consumers.
- Spring Source Pipelines/Raw Water Transmission Mains (Index: 1,00):
This category indicates the greatest network vulnerability. It assigns the highest index value to primary raw water intakes and transmission mains. The peak weighting is justified because these pipelines form the basis of the supply infrastructure. Since some elevated reservoirs depend entirely on these lines, and internal network loops cannot replace them, structural failure would stop primary water generation and their supply. This would cause a system collapse and pose an absolute threat to supply security.

The systematic allocation of the maximum redundancy index (1,00) to this primary water infrastructure is based on specific economic and sociocultural justifications. In theory, one could argue that purified drinking water has a higher material value due to the cumulative costs of

treatment and refinement. However, Stadtwerke Freudenstadt operates within a unique financial framework in which using local spring and well resources is significantly more cost-effective than buying water from ZVKK. Disruptions to this self-supply structure incur immediate opportunity costs because deficits in the supply must be compensated for by purchasing more expensive external water volumes. Furthermore, these local resources provide vital systemic redundancy and strategic independence in the event of water scarcity induced by climate change, thereby increasing their value beyond standard market prices.

The distinct topography of the Black Forest region, where Freudenstadt is located, heavily influences another complex factor: the geodetic elevation and the resulting potential energy of the water. Water stored in or pumped to highly elevated reservoirs has a significantly higher potential energy value than water in pipelines in lower-lying pressure zones. Differentiating the assets based on this elevation-dependent energy footprint would introduce a highly dynamic component to the model that depends heavily on fluctuating electricity prices and variable pumping cycles. Therefore, to maintain a robust and standardized evaluation matrix, the topographic energy profile is excluded from direct indexing. This ensures a consistent focus on the technical and structural condition of the system.

3.6 Methodological Calibration of the Strategic Pyramid Approach

The methodology uses a strategic pyramid approach (Figure 13), an interactive process necessary for sustainable network management. This process ensures that short-term actions align with long-term financial and technical goals. The long-term strategy establishes a vision for the next 20 to 50 years to determine the total rehabilitation volume required and the necessary long-term budget, ensuring asset value preservation. Medium-term planning involves sequencing specific measures over a five-year period based on the prioritization matrix that will be developed. The short-term implementation plan involves identifying risks and immediately executing individual measures.

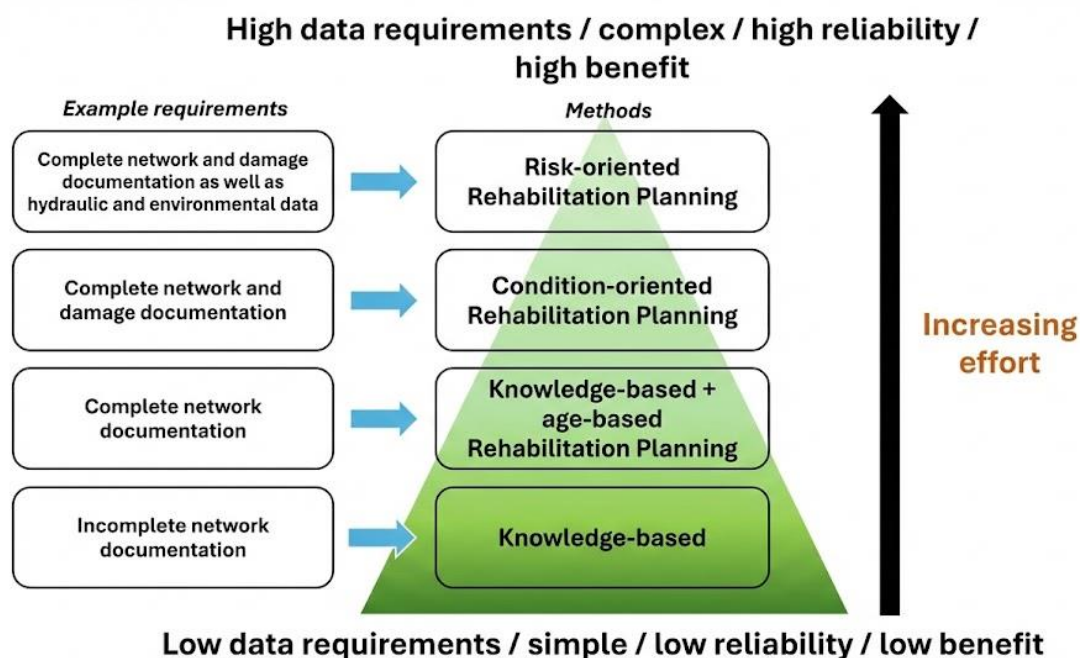


FIGURE 13: PYRAMID MODEL FOR REHABILITATION PLANNING (DVGW E.V. W 403, 2025)

A critical component of this methodology is the integration of economic constraints and resilience. Budgeting ensures that the proposed rehabilitation rates are feasible over the next decades. A robust, data-driven framework can be developed by balancing economic limitations with resilience targets. This framework will enable the city's water supply network to withstand future shocks,

such as major technical failures, while remaining economically sustainable until 2050 and beyond. Figure 14 illustrates the systematic hierarchical alignment of these long-term economic targets with medium- and short-term operational planning.

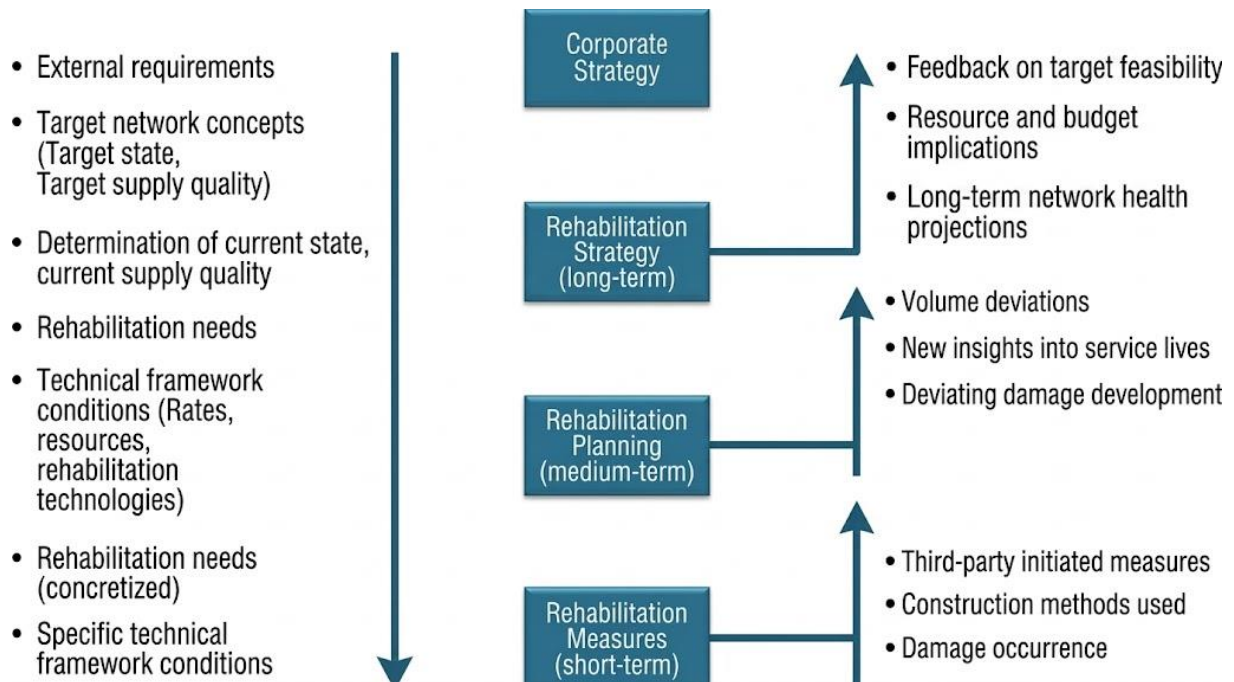


FIGURE 14: STRUCTURE OF REHABILITATION MANAGEMENT (DVGW E.V. W 403, 2025)

The determination of necessary rehabilitation rates is grounded in the pyramid approach (Figure 13), which aligns long-term strategic goals with available technical data. This methodology involves first establishing the expected technical service life for individual asset groups and subsequently deriving the annual renewal requirements. The accuracy of these forecasts depends on the availability and depth of the data. While simplified methods are useful for establishing a foundation, advanced simulation models are preferable for maximizing economic efficiency and ensuring reliable planning.

4. Results and Discussion

4.1 Empirical Baseline Evaluation of the Current Network State

4.1.1 Historical Network Evolution and Volumetric Age Distribution

The first step in developing a risk-based rehabilitation strategy is converting the adjusted inventory data into a structured analysis. The goal of this chapter is to identify statistical patterns in Stadtwerke Freudenberg's Municipal Utilities network by closely examining the digital twin. The analysis describes the network's current state and identifies correlations between technical attributes and observed damage events.

A well-founded assessment of the network's condition is based on multidimensional analysis. In this step, parameters correlated and verified in the previous step, are examined alongside the damage history from 1998 to 2026. This step provides the basis for decision-making, as required by (DVGW e.V. W 403, 2025), for planning sustainable renovations. Figure 15 illustrates the trend in the average age of the entire grid system over a period of more than 130 years.

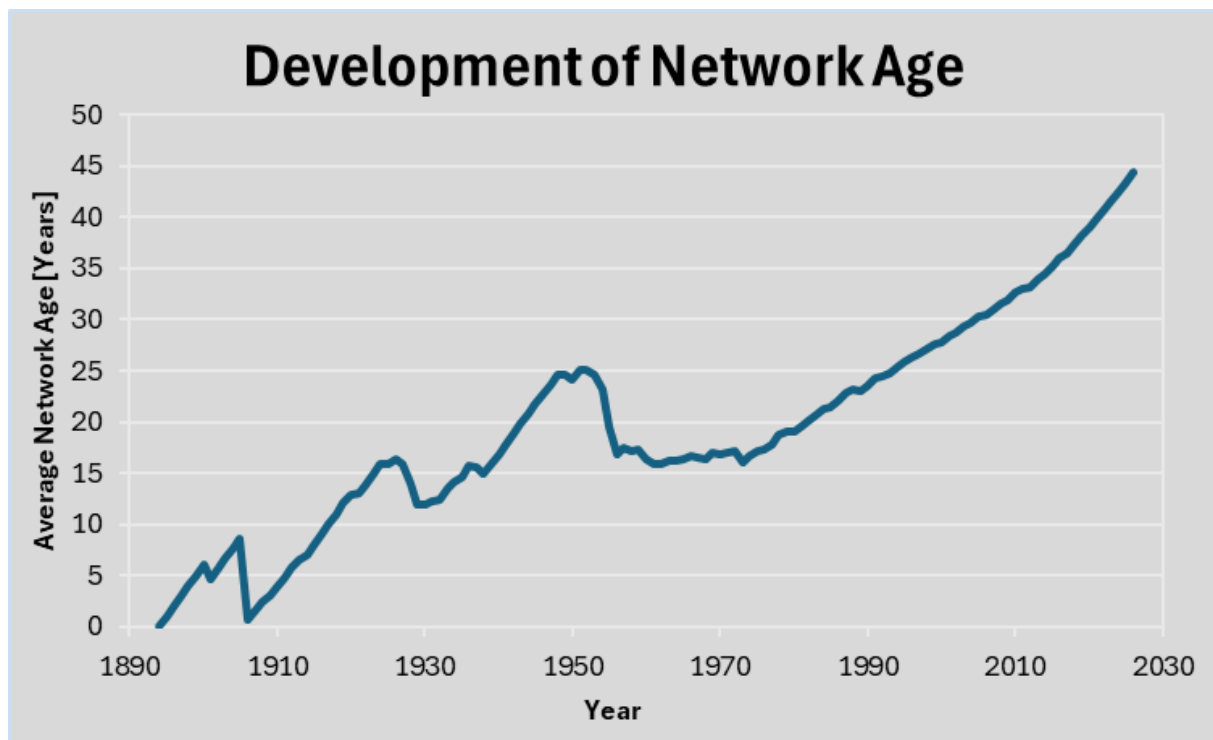


FIGURE 15: HISTORICAL DEVELOPMENT OF AVERAGE NETWORK AGE (1894 - 2026)

The curve shows a steady increase in grid age, interrupted only by phases of significant grid expansion. A significant rise is evident beginning in the 1970s, with the average grid age reaching approximately 45 years by 2026. A critical limitation of this representation is the lack of documentation regarding line replacements. Since information on the age of the removed lines is missing, the model cannot accurately represent the effect of targeted renewals on overall grid age. The dip in the curve during certain time periods primarily results from the installation of new pipelines. Since the model only knows the construction year of the "new" pipelines, the renewal effect is statistically visible only when the volume of new pipelines outweighs the aging of the existing stock.

Figure 16 shows the relationship between the age of the water network and its growth over time. It uses length-weighted construction year in its calculations:

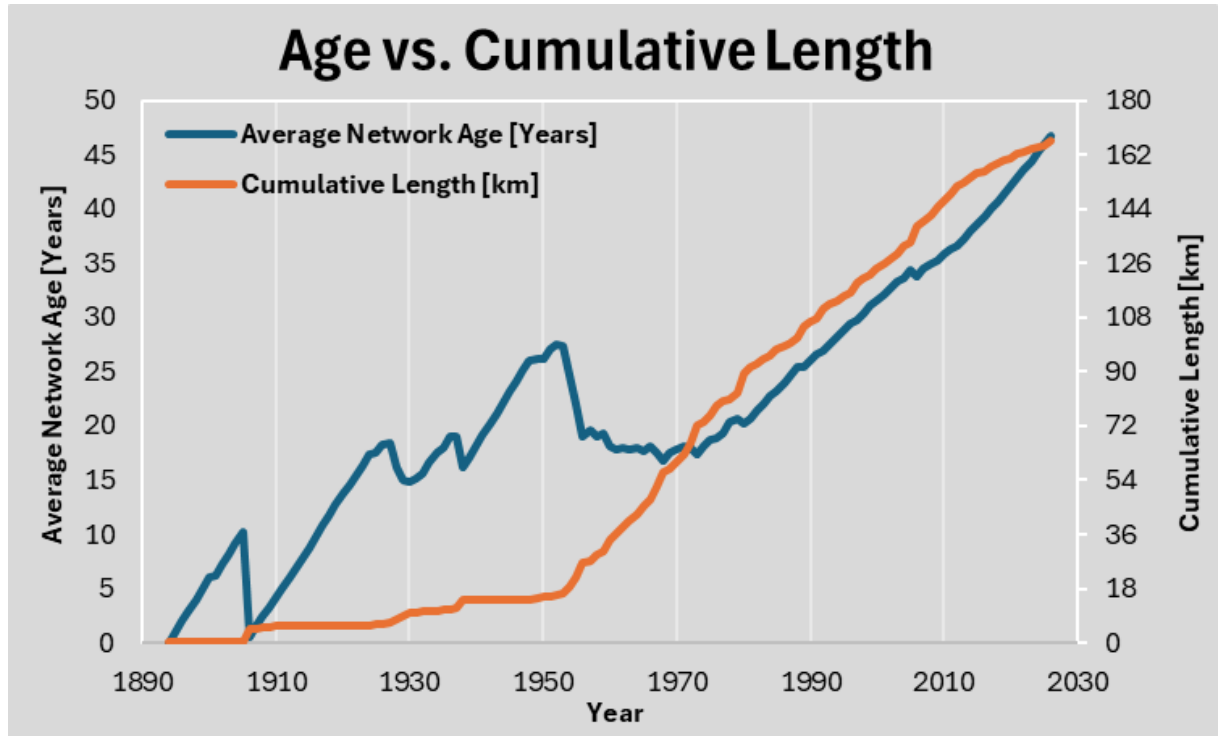


FIGURE 16: WATER NETWORK EVOLUTION: AGE VS. CUMULATIVE LENGTH

The cumulative network length steadily increases, reaching a maximum of approximately 163km by 2026. A particularly steep increase is evident between 1960 and 1980, indicating a period of intensive expansion. The blue line proportionally weights the age according to the pipeline length using the formula shown below:

$$\text{Length-Weighted Year} = \frac{\sum_{i=1}^n (\text{Year}_i \cdot \text{Length}_i)}{\sum_{i=1}^n \text{Length}_i} \quad (4.1)$$

Where:

Year_i Construction year of individual pipeline section i

Length_i The length of the individual pipeline section i

Correlation analysis reveals that physical network expansion is the only factor pushing the average age down statistically. Without a significant increase in new pipeline length, the age curve would linearly increase because the age of the replaced line is not recorded in the data.

4.1.2 Statistical Classification of Historical Failure Trends

The most labor-intensive aspect of the basic evaluation was processing historical damage data. Datasets spanning from 1998 to the present were provided in various formats, including different shapefiles. These were then converted into a spatial format and overlaid onto the updated network model using QGIS, an open-source geographic information system. While records from the last 15 years provided exact dates and coordinates, older entries often lacked specific locations, resulting in varying degrees of precision in the raw data. A great deal of additional work was required to allocate historical damage points to the correct pipeline IDs based on coordinates and technical descriptions. The damage entries included valuable qualitative information, such as the specific mode of failure (e.g. longitudinal cracks, corrosion or leaking joints). These descriptions were manually reviewed to differentiate between technical defects and systemic material ageing. A critical step in this evaluation was to exclude historical damage located on pipes that had been replaced since the data was collected. The model avoids overestimating the failure probability in recently rehabilitated zones by filtering out ghost damages. However, damage hotspots were identified in the remaining network segments due to frequent failures. These segments will be

assigned a higher weighting factor to reflect the engineering principle that a pipe with a history of failure is statistically more likely to experience subsequent localized instability. Figure 17 illustrates the trend in damage frequency over time.

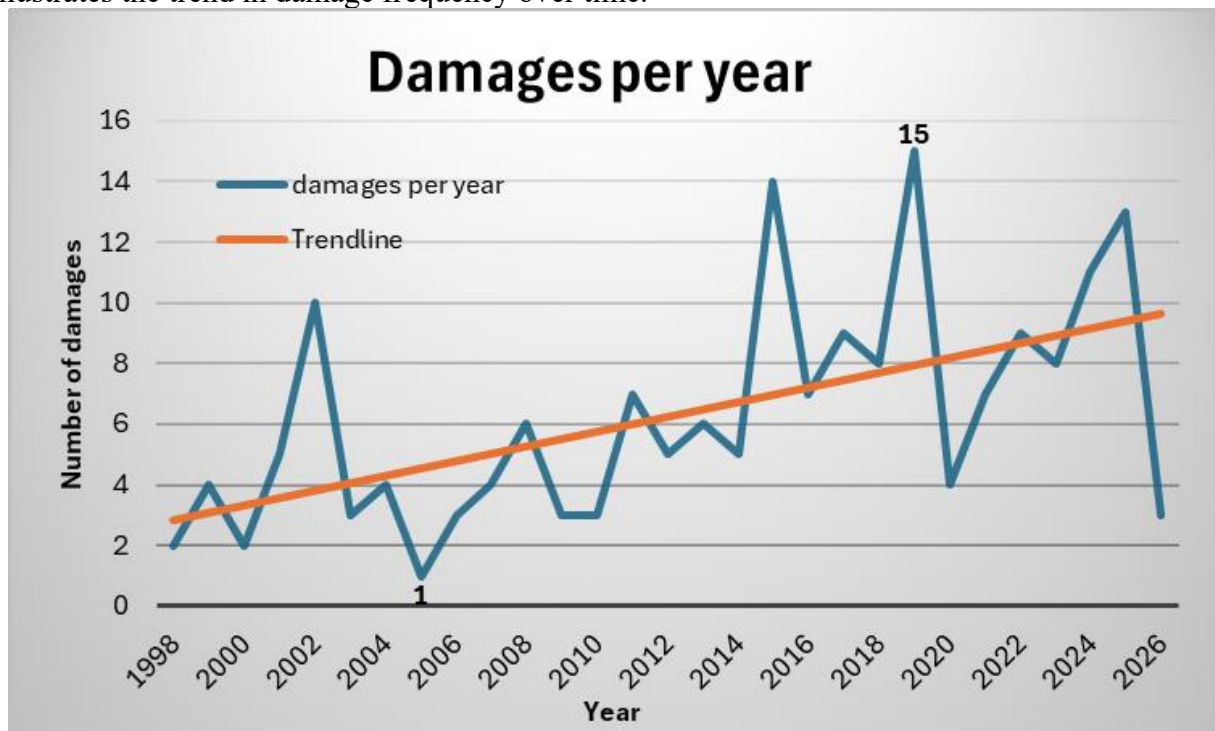


FIGURE 17: ANNUAL DAMAGES TO STADTWERKE FREUDENSTADT'S WATER DISTRIBUTION NETWORK FROM 1998 TO 2026, WITH A LINEAR TREND LINE

The orange trend line clearly shows an upward trend. While failures were moderate in the early 2000s, there has been an increase in absolute numbers since around 2012. The upward slope of the trend line indicates that the current renewal rate is insufficient to compensate for the network's ongoing wear and tear. The growing number of pipe bursts per year indicates an increasing rehabilitation deficit. The analysis is based on verified damage data from 1998 to 2026. Peaks (e.g., in 2018) suggest external influences, such as extreme weather conditions or systemic weaknesses in certain age groups.

The quality of failure predictions and resulting rehabilitation rates depends directly on the integrity of historical damage data. Since accurate predictions require assigning each event to a specific location and pipeline, integrating the data was one of the most labor-intensive steps of the inventory process. The analysis of the Stadtwerke Freudenstadt's municipal utility's water supply network was based on a dataset of 328 documented damage cases.

TABLE 21: SAMPLE LIST OF DAMAGES IN THE CASE OF THE Kniebis DISTRICT

X-coordinate	Y-coordinate	District	Street	Revision Date	Type of damage
448.668	5.368.284	Kniebis	Rimbachweg	09.02.2005	Burst
448.849	5.369.502	Kniebis	Kohlwaldweg	29.01.2008	Burst
449.262	5.369.068	Kniebis	Am Zollacker	13.12.2011	Leaky coupling
449.022	5.369.094	Kniebis	Kohlwaldweg	14.12.2011	Burst
449.022	5.369.098	Kniebis	Kohlwaldweg	14.12.2011	Burst
448.714	5.368.994	Kniebis	Alte Pass-Straße	19.12.2012	Burst
449.263	5.369.068	Kniebis	Am Zollacker	12.06.2013	Burst
448.991	5.369.219	Kniebis	Kohlwaldweg	29.10.2015	Corrosion
448.112	5.369.193	Kniebis	Alter Weg	13.04.2016	Corrosion
448.822	5.368.341	Kniebis	Rimbachweg	18.08.2016	Leak
449.284	5.368.928	Kniebis	Baiersbronner Sträßle	24.01.2017	Unknown
448.959	5.369.280	Kniebis	Kohlwaldweg	30.08.2018	Corrosion
448.640	5.368.300	Kniebis	Rimbachweg	20.09.2018	Leak
448.305	5.369.219	Kniebis	Alter Weg	05.07.2021	Burst
448.822	5.369.136	Kniebis	Alter Weg	21.02.2024	Burst
448.684	5.368.435	Kniebis	Rimbachweg	20.10.2025	Burst

A qualitative analysis of the damage descriptions from the district Kniebis, listed in Table 21, reveals information beyond spatial mapping. In-depth notes about the technical causes of failure and sometimes the condition of the pipeline network can be seen. Interpreting specific terms, such as "Leaky coupling" provides clear signs of installation or assembly errors. Since joints are the most robust component of a pipe, a break in this area indicates wrong installation during construction. Distinguishing between damage types, such as "pipe burst," "leak," or "corrosion," provides insight into the relationship between the material and the environment. Signs of corrosion often indicate a defective pipe bed, which can result from foreign objects or unsuitable materials damaging the pipes' protective coating. Failure behavior depends heavily on the material. Gray cast iron develops sudden cracks or complete fractures due to its fragility. PVC pipes often exhibit characteristic longitudinal cracks when under stress. First-generation ductile cast iron exhibits specific corrosion phenomena, while PE pipe failure is often due to welded joints or localized mechanical impacts from stones in the pipe bed.

Documented comments from Stadtwerke Freudenstadt are essential for this technical classification because they help distinguish between systemic material failure and one-time installation incidents. However, the review revealed that this valuable information was often missing from historical statistics, requiring a time-consuming manual plausibility check for each event. After spatial assignment and technical filtering, only 182 of the original 328 reported events were considered relevant for evaluation in the strategic rehabilitation model. Almost 45 % of the damages were excluded.

The basic damage evaluation concludes with the integration of these refined datasets into a three-phase lifecycle model, also known as the "bathtub curve", shown in Figure 18. Categorizing the verified damage data by the age and material of the pipes allows the mapping of the network's current state across three distinct phases of failure probability.

- **Phase 1 (infant mortality):** Failures occur early in the lifecycle and are usually caused by installation errors or material defects. These failures are often characterized by leaking joints.
- **Phase 2 (Operational Stability):** A period of low, constant failure rates where the pipe performs as intended under standard hydraulic stress.

- **Phase 3 (Wear-Out Phase):** There is an exponential increase in age-related damage as the material reaches the end of its technical service life.

Identifying which assets have transitioned from Phase 2 to Phase 3 enables the model to consider factors other than age when planning replacements. This ensures Stadtwerke Freudenstadt's limited rehabilitation budget is spent on segments where the probability of failure and potential extent of damage converge to pose the greatest risk to supply security, rather than solely on aging pipes.

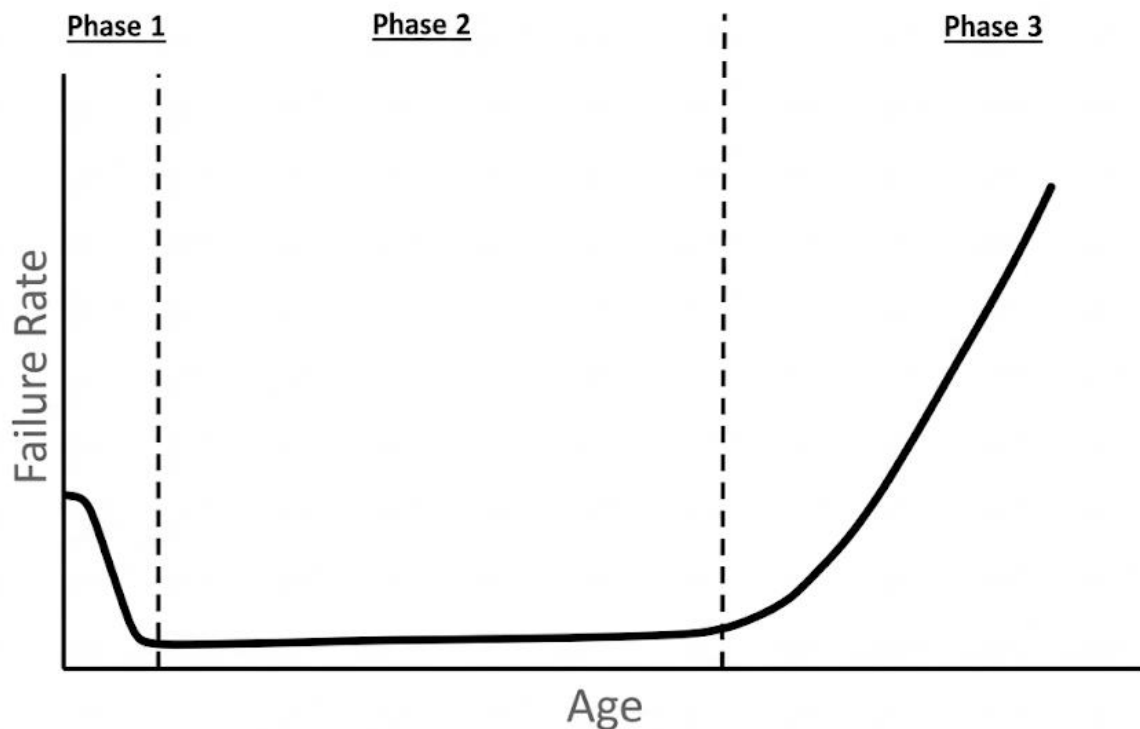


FIGURE 18: SCHEMATIC REPRESENTATION OF THE TREND IN FAILURE RATES (BATHTUB CURVE)

The following examples illustrate common defects that were identified and corrected. Some special cases were also resolved, but due to their uniqueness, they will not be discussed further. Many of these incidents occurred during the early failure phase of the lifecycle model and were caused by installation errors, such as missing gaskets or loose screw connections. To ensure the quality of the model, damages to pipeline sections that were decommissioned or rerouted due to grid restructuring were excluded. Similarly, no assessment was made in cases involving the replacement of short sections only, except when precise material documentation was available. This was done to prevent unknown variables from biasing material-specific failure rates. Current rehabilitation projects planned from Freudenstadt itself in 2026 were also considered. Furthermore, data sets with insufficient spatial precision or missing network references were eliminated to increase the model's robustness.

The damage list in Table 21 provided by the municipal utility contains detailed information on coordinates, districts, repair dates, and types of damage, such as corrosion, pipe bursts, or leaks. To standardize the database, all datasets underwent the previously described coordinate transformation from Gauss-Krüger to UTM. After the transformation, the damage points were often offset from the actual pipeline due to surveying tolerances, which required precise spatial assignment, visible in Figure 19. Each damage point (marked with a red "X") was manually assigned to the corresponding pipeline segment. The light blue digital pipeline network plan from Stadtwerke Freudenstadt was used as a reference for verification.



FIGURE 19: DEVIATION OF THE DAMAGE POINT FROM THE PIPELINE IN STANET

During the detailed inspection, it became clear that not all recorded events could be used to evaluate long-term conditions. Figure 20 illustrates a classic example of an installation error. One damage is explicitly documented in the database as a defect in the joint. Since these failures occurred immediately after installation, they are not due to material degradation but rather to wrong construction. To prevent external factors from distorting the statistical calculation of the technical service life, such events were consistently excluded from the assessment.

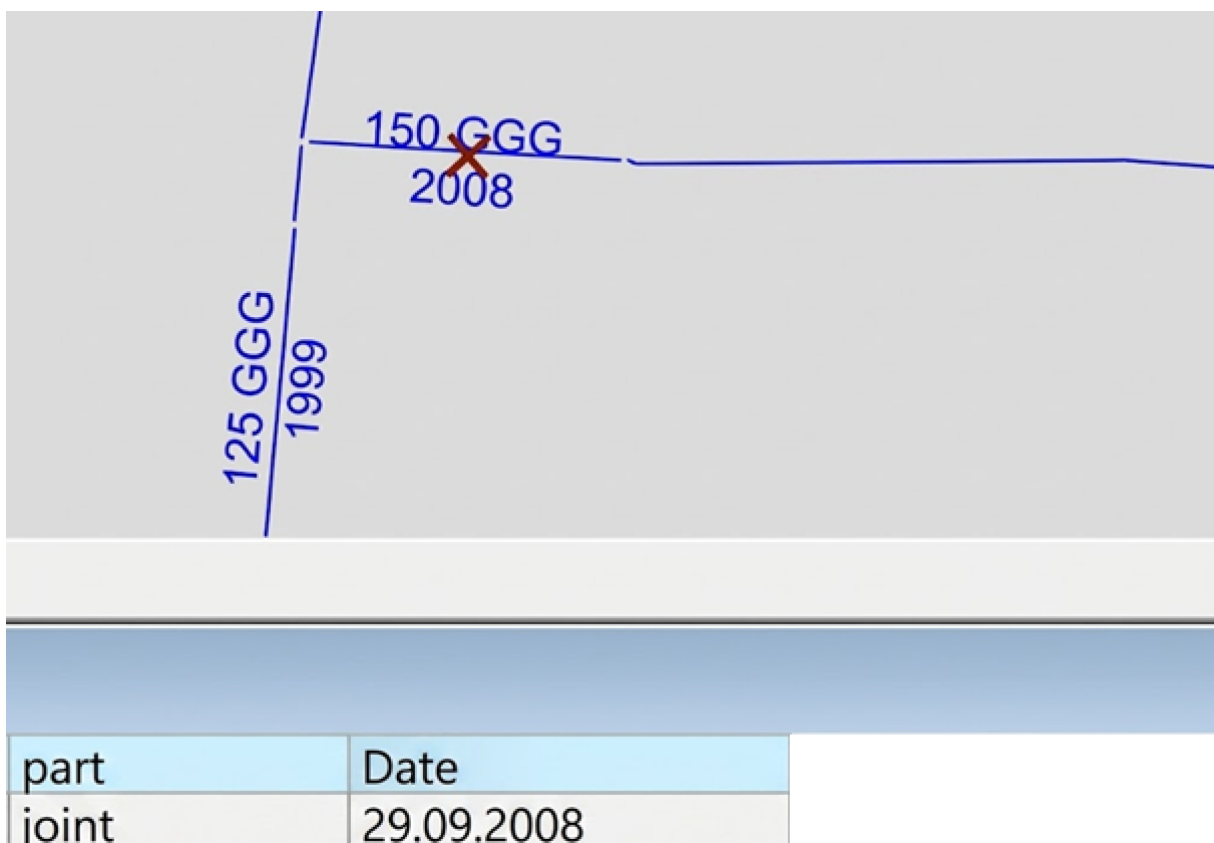


FIGURE 20: EXAMPLE OF AN INSTALLATION MISTAKE (BUILT IN 2008, DAMAGE OCCURRED IN 2008) WITH DOCUMENTATION OF DAMAGE TO A JOINT

Figure 21 illustrates the importance of manual plausibility checks. In this case, a damage event was identified whose documentation date predates the construction year of the pipeline currently listed in the system. Although the defect statistics record 1998 as the defect date for this entry, the

pipeline in the model is listed as having been constructed in 2003. After consulting Stadtwerke Freudenstadt, it was verified that the damage concerned the former pipeline, replaced by the current one in 2003. Since the damaged component has been removed, it is irrelevant to the condition assessment of the new pipeline segment and has been removed from the statistics.

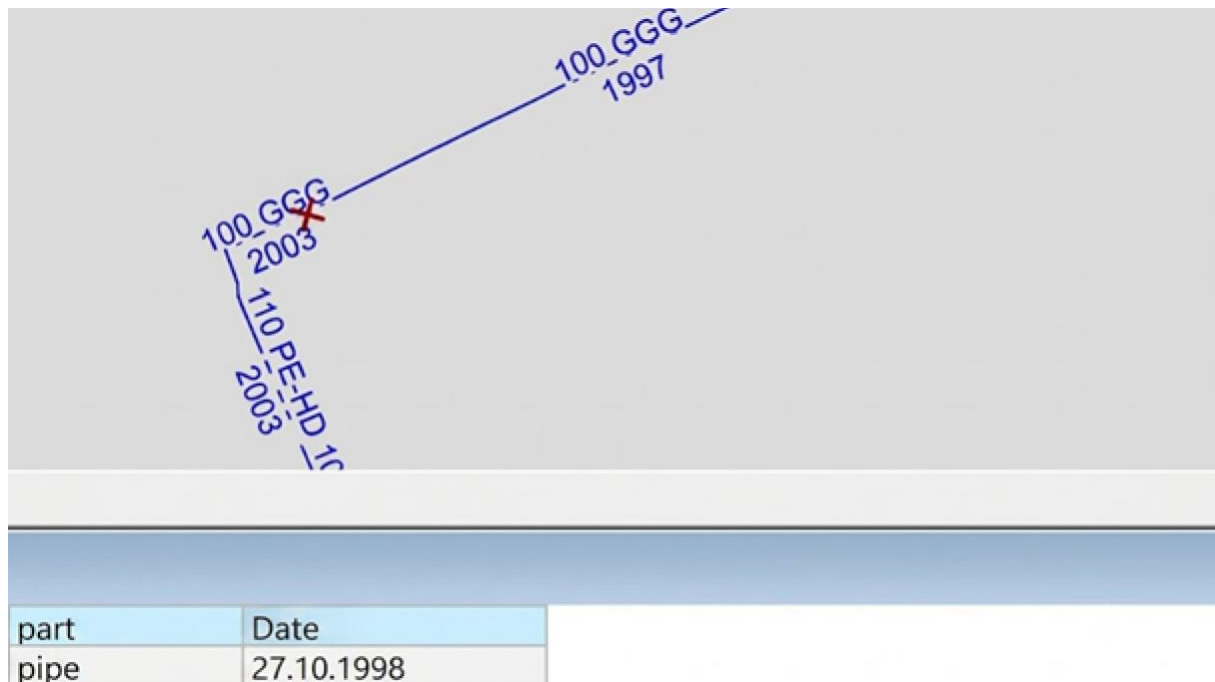


FIGURE 21: CHRONOLOGICAL INCONSISTENCY (DAMAGE DATE FROM 1998 ON A LINE FROM 2003) INDICATES THAT RENOVATIONS HAVE ALREADY TAKEN PLACE.

4.1.3 Material-Specific Generations and Diameter Analysis

This analysis relates damage incidents to the age of the affected pipeline at the time of damage.

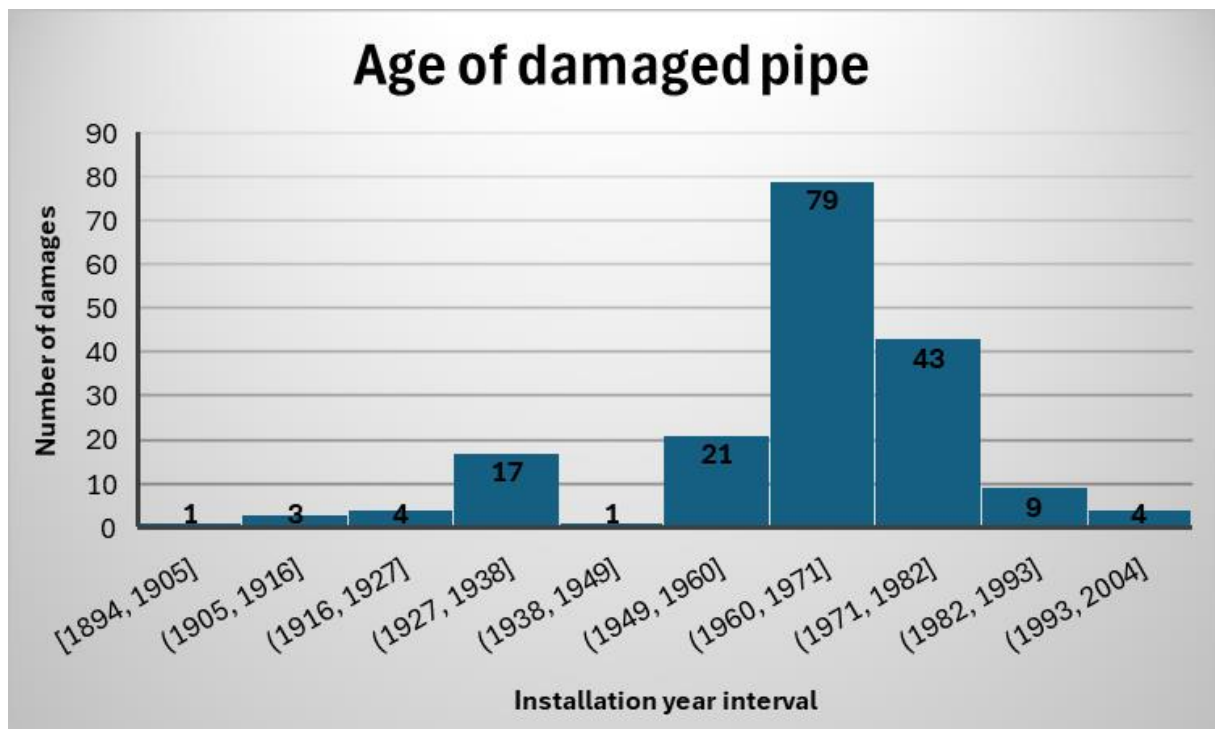


FIGURE 22: DISTRIBUTION OF DAMAGE BY DECADE OF CONSTRUCTION

Figure 22 shows a significant concentration of damage in pipelines built between 1960 and 1982. The 1970s account for the highest number of incidents, at 79. This peak results from two factors. First, this period represents one of the most intensive construction phases in the network. Second, the materials used during this time, particularly the first generation of GGG, are now reaching the end of their technical service life. Pipelines from the 1960s and 1970s are the most frequent cause of failure today, confirming that these assets have entered the "wear phase" (phase three of the bathtub curve; see Figure 18 above). In contrast, newer lines (from 1993 onward) show hardly any damage, underscoring their current operational stability. Newer types of pipes are significantly less affected because they are not yet that old. The following analysis provides a detailed examination of damage characteristics, considering both diameter and material resistance.

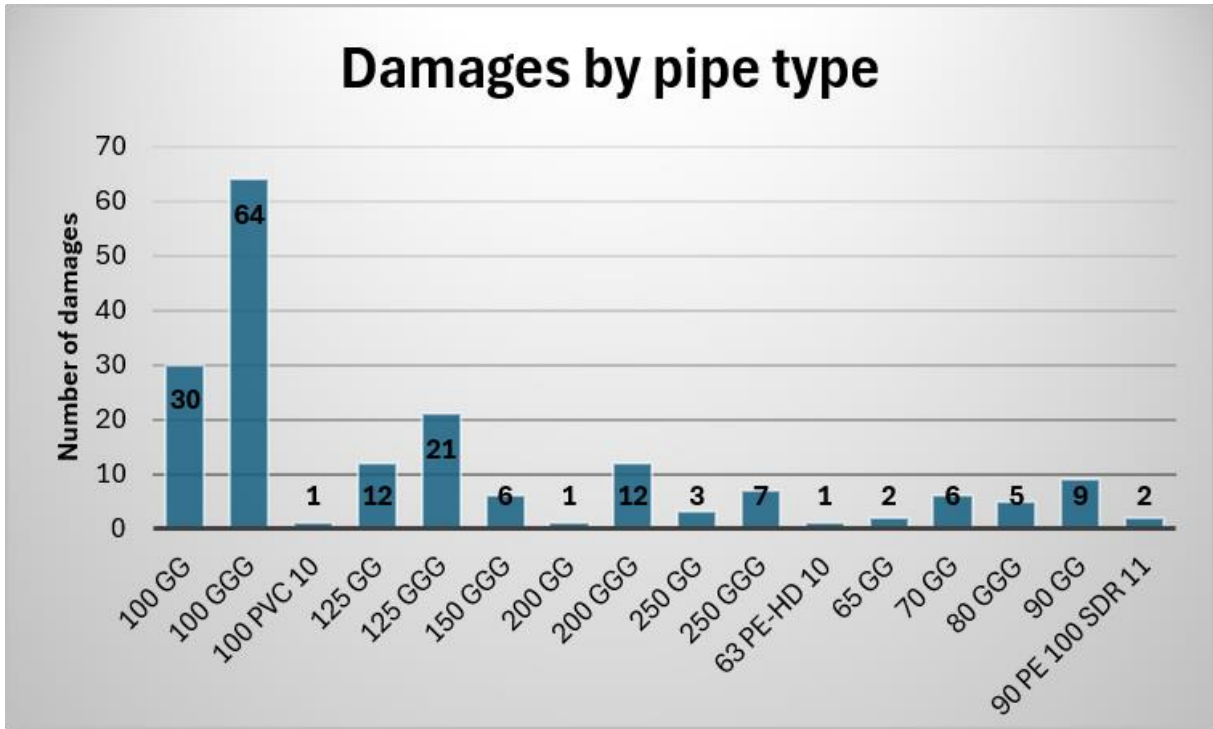


FIGURE 23: DISTRIBUTION OF DAMAGES BY MATERIAL AND DIAMETER

Figure 23 shows the number of damage incidents broken down by combinations of material and nominal diameter. 100 GGG (64 incidents) and 100 GG (30 incidents) dominate the chart. Notably, damage to plastics is rare, and PE pipes barely appear in this statistic. However, it is difficult to determine from this graph alone whether one technical failure mode predominates over another (such as corrosion versus mechanical failure), since the data primarily shows which pipes were affected.

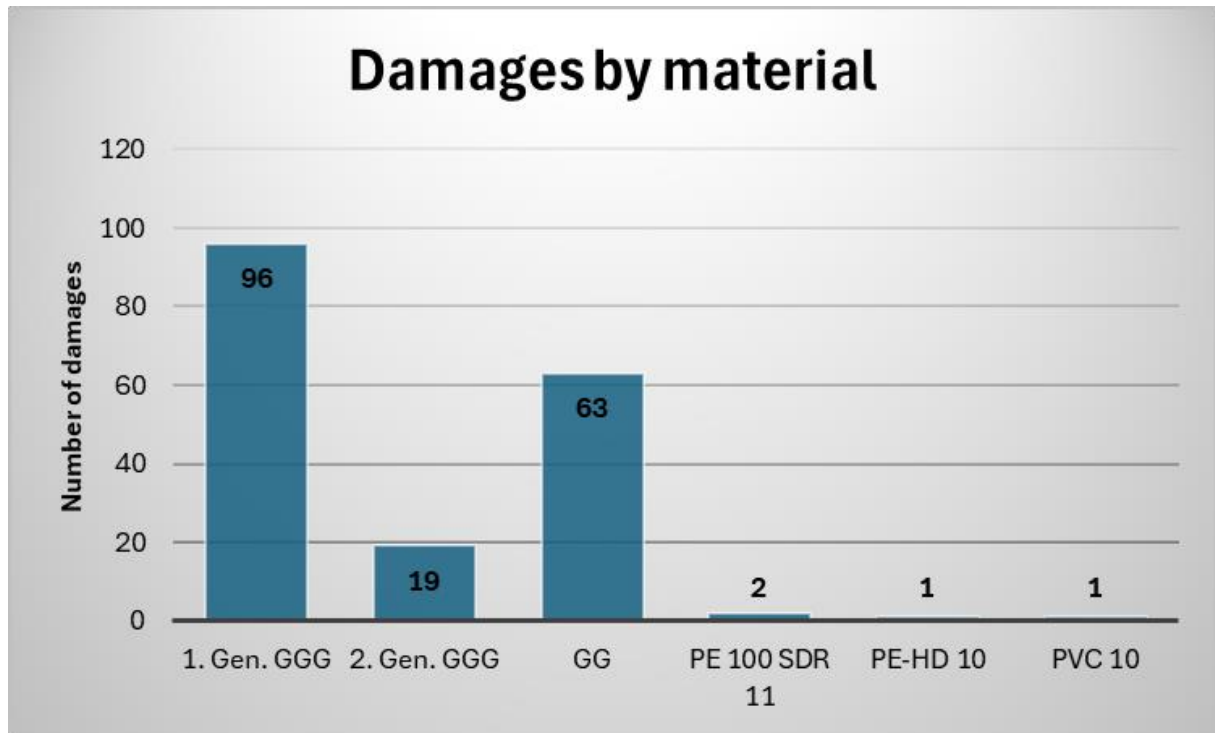


FIGURE 24: FREQUENCY OF DAMAGE BY MATERIAL GROUP

Figure 24 shows that "1. Gen. GGG" had the most failures, with 96 cases, GG is second with 63 cases. In contrast, modern plastic materials have very low failure rates, with only four incidents in total. However, these low frequencies must be understood in the context of asset age and network proportions. The low number of failures in PE pipelines is primarily due to their shorter operational lifespan. These modern pipes are significantly newer than cast iron pipes. The low absolute failure count for PVC is due to the limited total length of PVC pipes installed across the network, which prevents a statistically representative determination of its failure behavior. As previously discussed in the Asset403 evaluation (Figure 11), the structural context of the length distribution remains critical. "2. Gen. GGG" forms the backbone of the inventory and is the most prevalent material group in the network. Thus, the high absolute number of failures is the result of a combination of material aging and the large quantity of these pipes in the network.

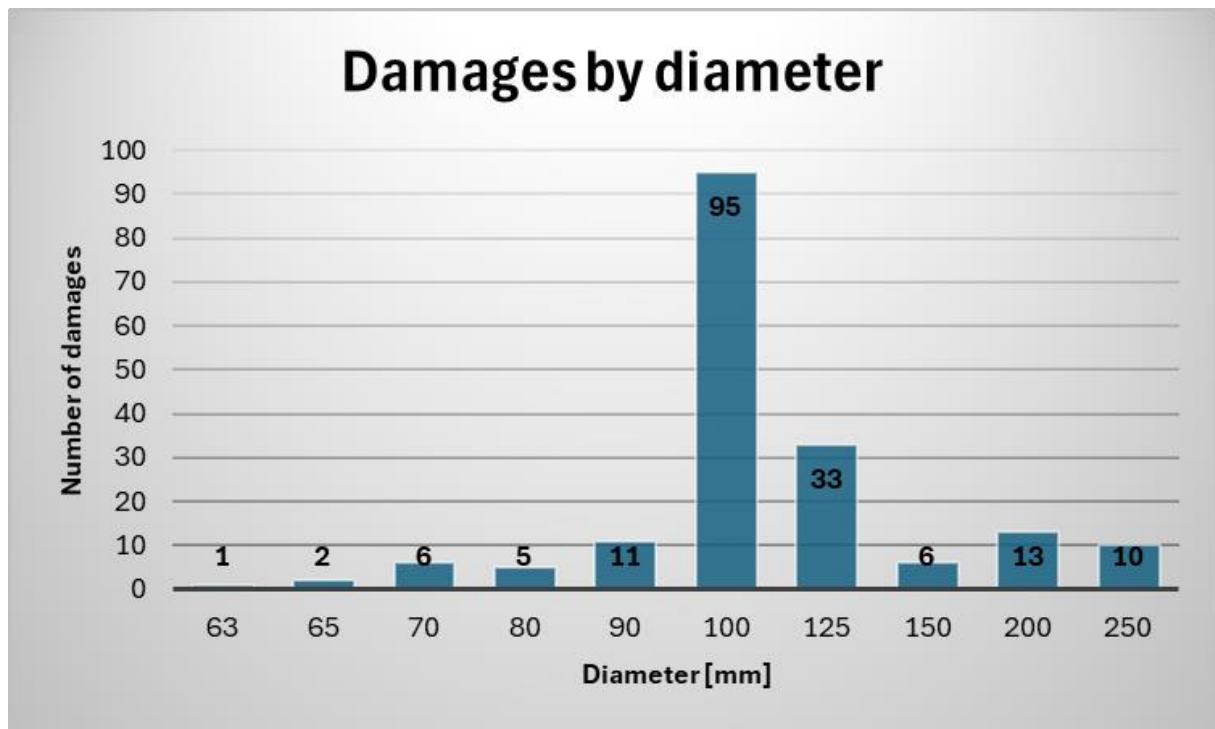


FIGURE 25: FREQUENCY OF DAMAGE BY NOMINAL DIAMETER

After analyzing the pipe diameters (Figure 25), a significant concentration of damage in the DN 100 range is found, with a total of 95 documented incidents. At first glance, the DN 100 diameter appears to be significantly more prone to breaking than larger or smaller diameters. However, the following Figure 26 is crucial for putting this figure into perspective.

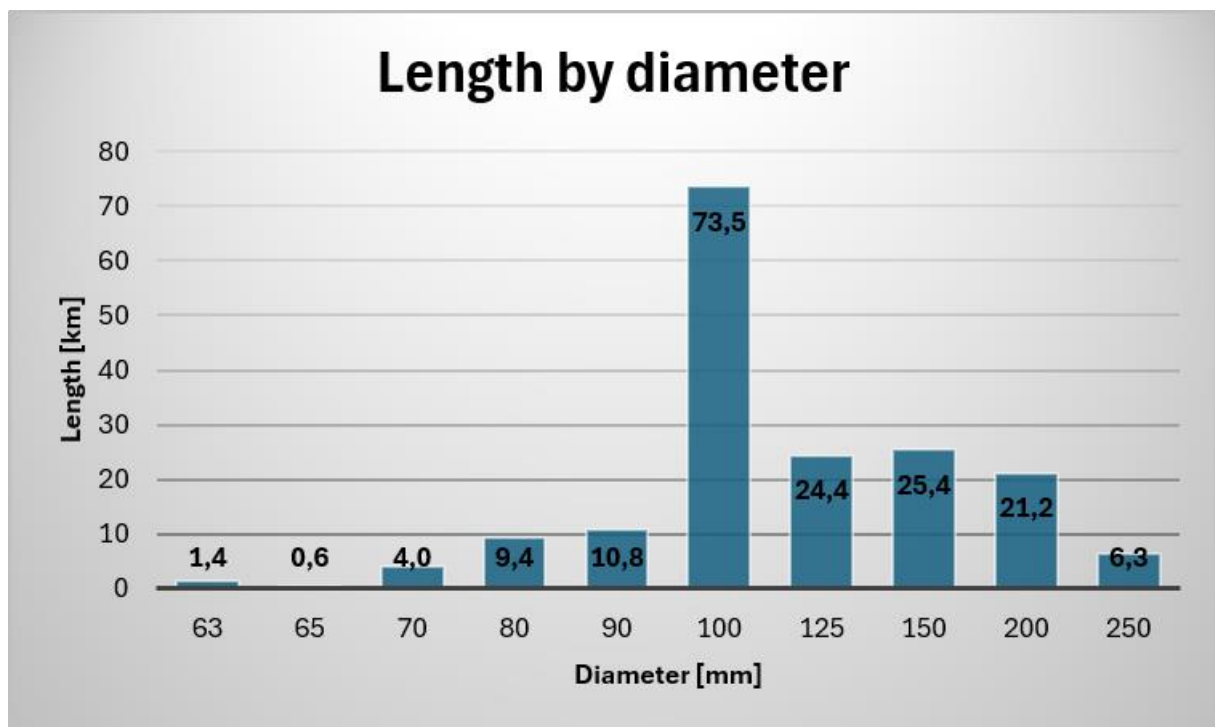


FIGURE 26: CORRELATION BETWEEN LENGTH AND DIAMETER

Comparing the damage figures with Figure 26 shows how significant the peak at *DN 100* is. With a total length of about *73,5 kilometers*, *DN 100* is the most used nominal diameter in Stadtwerke

Freudenstadt's service area. It is the standard size for distribution lines. Since this diameter is installed most frequently, statistically speaking, the highest absolute number of damages occurs here as well.

4.2 Spatial Execution of the Risk Model and Asset Prioritization

The AHP framework, when applied to Stadtwerke Freudenstadt's actual pipeline network, enables the objective, risk-oriented prioritization of individual pipe segments. To demonstrate the model's process and the mathematical derivation of the risk scores transparently, a detailed sample calculation is performed for a highly critical network element. The evaluated asset is an old distribution pipeline with a nominal diameter of 200 mm that exhibits significant technical vulnerabilities and severe environmental exposure.

The final risk index (RI) is dependent on the predefined combination of local condition assessment and localized damage extent.

$$RI = \left(0,6 \cdot \sum_{i=1}^n I_{CA,i} \cdot W_i + 0,4 \cdot \left(\sum_{i=1}^n (I_{DE,i} \cdot W_i) \cdot R_i \right) \right)$$

Where:

RI	Overall Risk Index for one pipe segment
$I_{CA,i}$	Index of Local Condition Assessment Criteria
$I_{DE,i}$	Index of Local Damage Extent Criteria
W_i	Weight of the Criteria
R_i	Redundancy factor based on the pipeline type

1. Step: Calculating the Condition Assessment Sub-Index

This evaluation quantifies the probability of structural failure of the pipe segment. It does so by multiplying each index value by its respective AHP weight. The asset's specific attribute profile and resulting scoring distribution are structured within the following framework:

TABLE 22: PARAMETER MATRIX FOR LOCAL CONDITION ASSESSMENT

Condition Assessment	Age of Pipeline	Pipe Material	Specific Damage Rate	Traffic Load	Rail Load
Attribute Value	61 years	1. Gen. GGG	89,075 m / Damage	No traffic load	Under rails
Value	0,75	0,6	0,9	0	0,9
Criteria Weight	30,2%	23,8%	21,9%	15,4%	8,7%
Lokal Weight	22,7%	14,3%	19,7%	0,0%	7,8%

As shown in Table 22, the evaluation of technical and environmental stress factors yields the following components.

- Pipeline Age Component: The pipe has an active service age of 61 years, reflecting accelerated midlife degradation kinetics according to nonlinear aging intervals. Multiplying this component by the criteria weight of 30,2 % results in a contribution of $0,75 \cdot 0,302 = 0,2265 \approx 22,7 \%$
- Pipe Material Component: The pipe consists of "1. Gen. GGG". This material has older coating standards and an increased failure probability compared to newer generations. This results in

a material-specific index of 0,6. Multiplying this by the 23,8 % criteria weight yields a contribution of 14,3 %.

- **Specific Damage Rate Component:** The homogeneous network cluster has an empirical failure density of 89,075 *meters per damage event*. This indicates a critical concentration and a high local risk score of 0,9. Multiplying this by the historical damage criteria weight of 21,9 % yields 19,7 %.
- **Traffic Load Component:** Since the pipeline runs through a zone free of surface vehicle traffic, the value is 0.
- **Rail Load Component:** The segment crosses directly underneath active railway tracks, triggering a severe mechanical stress index of 0,9 due to continuous structural vibrations. Multiplying this by the rail criteria weight of 8,7 % yields 7,8 %.

Summing up the five weighted products from Table 22 yields the Local Condition Assessment Index.

$$\sum_{i=1}^n (I_{(CA,i)} \cdot W_i) = 0,2265 + 0,1428 + 0,1971 + 0 + 0,0783 = 0,6447 \approx 64,5 \%$$

2. Step: Derivation of the Damage Extent Sub-Index

The consequence-related evaluation calculates the socioeconomic, hydraulic, and physical impacts of a potential structural rupture. The unadjusted localized damage value is calculated by adding the weighted environmental parameters defined in Table 23 below.

TABLE 23: PARAMETER MATRIX FOR LOCAL DAMAGE EXTENT

Damage Extent	Critical Infrastructure	Expert-based Criticality	Criticality	Crucialness	Erosion Radius	Operating Pressure	Redundancy
Attribute Value	No critical infrastructure	Poor pipe bedding	-	15,977 m ³ /h	15,532 m	8,576 bar	Main pipeline ≥ 200
Value	0	1	0	0,75	1	1	0,7
Criteria Weight	26,9%	22,2%	22,2%	21,2%	4,5%	2,9%	-
Lokal Weight	0,0%	22,2%	0,0%	15,9%	4,5%	2,9%	70,0%

A critical analysis of the matrix elements in Table 23 reveals the following consequence profiles:

- **Critical Infrastructure Component:** This pipe segment does not supply critical healthcare, educational, or industrial facilities. Therefore, the contribution is 0.
- **Expert-Based Criticality Component:** Operational personnel documented severe constraints due to poor pipe bedding conditions. This resulted in a maximum risk index of 1,0. Multiplying this by the expert judgment weight of 22,2 % yields a contribution of 22,2 %
- **Criticality Component:** The pipeline does not act as a central gravity transmission line feeding a downstream zone.
- **Crucialness Component:** The asset is defined as a primary grid distribution main ($DN \geq 200$) operating directly within the interconnected urban ring network. Hydraulic network calculations indicate a peak transport capacity of 15,977m³/h through this large diameter pipeline. The asset is assigned an index of 0,75. Multiplying this by the weight of 21,2 % yields 15,9 %.
- **Erosion Radius Component:** The combination of internal grid pressure and nominal diameter yields a calculated physical washout zone of 15,532 *meters*. This threatens urban building

foundations and triggers a maximum hazard index of 1,0. Multiplying this by the physical risk weight of 4,5 % results in a contribution of 4,5 %:

- Operating Pressure Component: The network zone operates at a high hydraulic pressure of 8,576 bar. The operational consequence is 2,9 %.

Summing up, the localized factors from Table 23 yields an unadjusted cumulative score of 45,5 %. According to the model's structural hierarchy, this baseline consequence is adjusted by the redundancy multiplier (R). Since the pipeline is a main grid artery in the distribution network where nearby loops can reroute some of the flow, it receives an R value of 0,7. The total adjusted Damage Extent Sub-Index is derived as follows:

$$\left(\sum_{i=1}^n (I_{(DE,i)} \cdot W_i) \right) \cdot R = 0,455 \cdot 0,7 = 0,3185 \approx 31,9 \%$$

3. Step: Core Multi-Criteria Risk Index Fusion (RI)

The final priority layer is determined by combining the aggregated condition-related index with the adjusted consequence-related index. The 60/40 macro-weighting distribution primarily governs the management of assets based on technical decay, considering localized risk consequences.

TABLE 24: CORE SUB-INDEX INTEGRATION AND FINAL RISK INDEX RESULT

Condition Assessment	Unadjusted Damage Extent	Adjusted Damage Extent	Riskindex
64,5%	45,5%	45,5 % · 0,7 = 31,9 %	0,5142 = 51,4 %

As summarized in Table 24, the strategic combination of the distinct index layers is calculated as follows:

$$RI = 0,6 \cdot 0,6447 + 0,4 \cdot 0,4550 \cdot 0,7$$

$$RI = 0,3868 + 0,1274 = 0,5142 \approx 51,4 \%$$

The mechanical execution of the multi-criteria calculation yields an RI of 51,4 %. An asset with such a high RI requires immediate intervention. Therefore, this pipe segment will be classified under the short-term rehabilitation scenario, which indicates the urgent need for technical renewal investments within a one-year planning window. These investments are necessary to ensure the security of the municipal water supply network.

Using the calculated asset distribution, a risk matrix was created to evaluate the mathematical relationship of the multicriteria model (see Figure 27). Figure 27 shows the distribution of prioritized pipeline segments within the water supply network. To preserve visual clarity and prevent information overload, duplicate data points and pipeline segments on the axes ($x = 0$ or $y = 0$) were filtered from the figure. Figure 28 provides an optimized close-up focusing strictly on the high-density asset clusters. In this matrix visualization, the y-axis represents the local condition assessment score, and the x-axis represents the local damage extent score. These matrices exclude the systemic vertical redundancy factor. Diagonal boundaries represent risk thresholds based on 60/40 macro-weighting, which categorizes assets into four priority bands: Zone Very Low (green), Zone Low (blue), Zone Medium (yellow), and Zone Elevated (red).

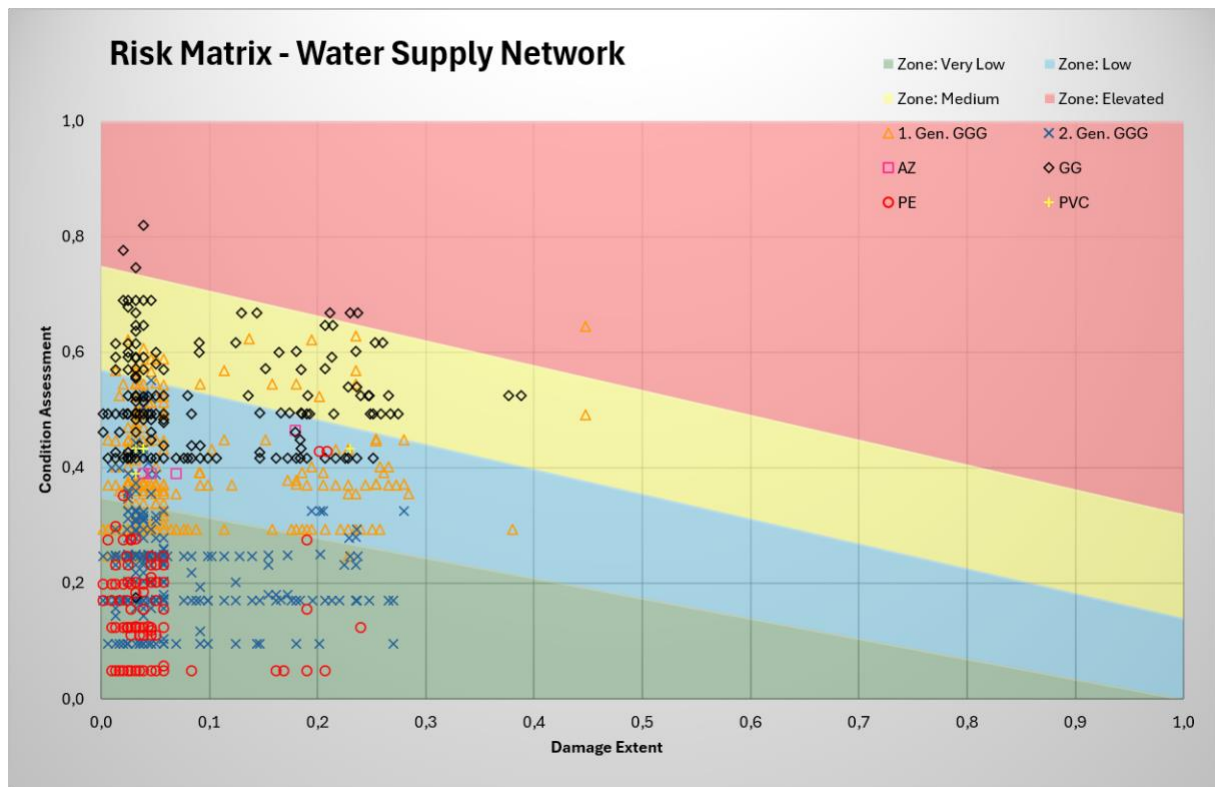


FIGURE 27: RISK MATRIX: NETWORK ASSET DISTRIBUTION ACROSS THE ENTIRE MUNICIPAL GRID

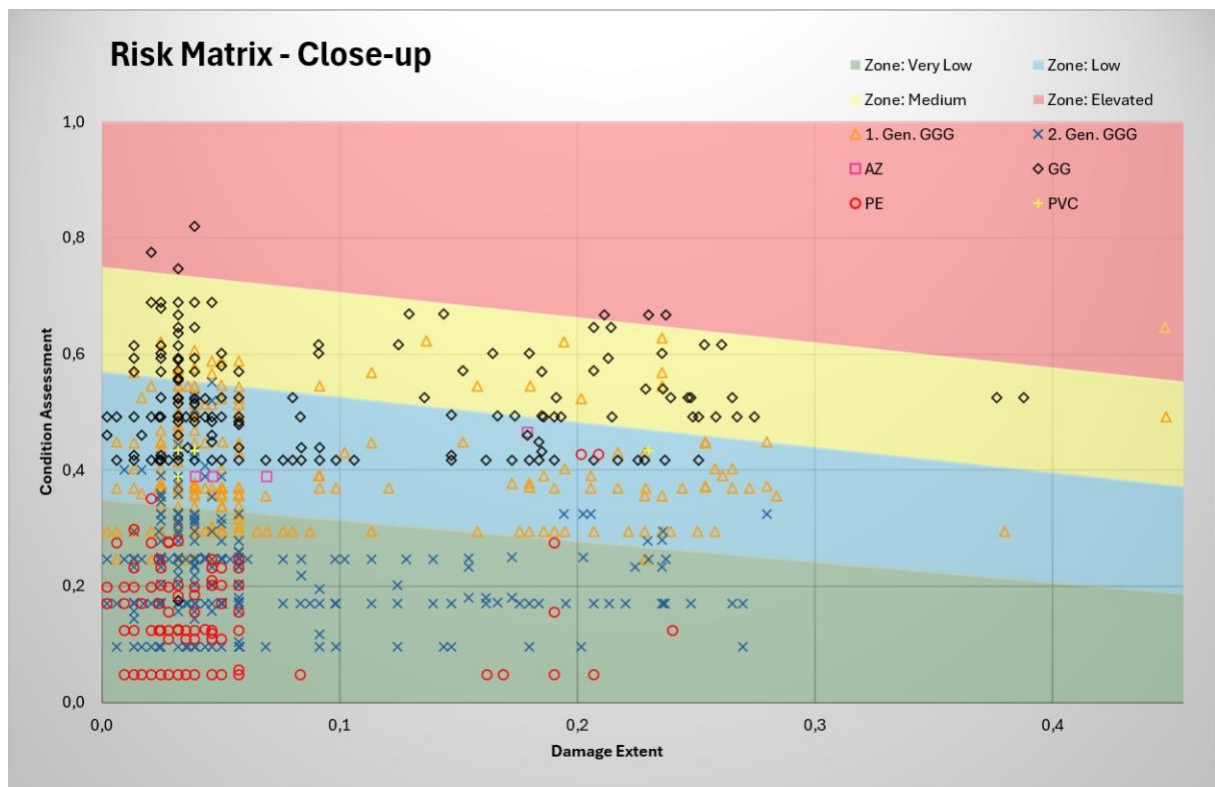


FIGURE 28: RISK MATRIX: CLOSE-UP OF DENSE ASSET CLUSTERS AND MATERIAL-SPECIFIC CATEGORIZATION

The distribution of assets across the matrix reveals clear, material-specific patterns determined by each pipe type's technological generation and structural role. Second-generation ductile cast iron pipes, represented by blue crosses, cluster at lower condition assessment values between 0,1 and

0,4 due to their modern coating standards and younger age. However, they exhibit extreme horizontal variability along the damage axis, ranging from 0,0 to nearly 0,3, since they often serve as primary distribution arteries with large diameters. First-generation ductile cast iron pipes, marked as orange triangles, exhibit significantly higher vertical displacement, with condition assessment scores ranging from 0,3 to 0,7, reflecting older manufacturing standards and higher failure rates. At the same time, they maintain a wide horizontal distribution that includes a critical outlier extending beyond 0,45 in the elevated damage zone. Grey cast iron pipes, represented by black diamonds, exhibit a distinct dual distribution pattern. Many of them are clustered on the far left of the matrix and function as localized distribution loops with local damage scores below 0,1. However, numerous critical outliers extend far to the right, reaching nearly 0,4 on the damage extent axis. These high-consequence segments represent vital infrastructure, including older gravity mains and large-diameter distribution lines. Their physical failure would trigger widespread systemic and socioeconomic disruptions. All gray cast iron assets are heavily elevated vertically, with condition assessment scores ranging from 0,4 to over 0,8. This emphasizes that their advanced structural decay poses an acute threat to grid operations when combined with these high-consequence profiles. Polyethylene pipelines, represented by red circles, are concentrated almost entirely in the bottom left corner. They have low scores in both dimensions due to their excellent material flexibility, low age, and standard residential grid dimensions. Finally, the asbestos cement and polyvinyl chloride pipelines, represented by pink squares and yellow plus signs, respectively, appear as isolated points because these legacy materials are not part of the current network. While most of these assets are confined to low localized damage zones below 0,1, a closer inspection reveals a few critical outliers with significantly higher scores in both dimensions. These outliers shift upwards and to the right into the medium-risk zone due to advanced structural aging combined with higher operational consequence profiles. This notable material classification is directly tied to the mathematical framework in which pipeline age and pipe material account for 54,0 % of the condition assessment sub-index. This places these legacy assets higher on the vertical axis, regardless of other local environmental variables.

4.3 Predictive Lifespan Simulation and Renewal Needs

To develop a forward-looking maintenance strategy, the focus of the analysis must shift from historical data to simulated predictions of network behavior. While historical damage data records past events, predictive modeling forecasts future performance and pinpoints upcoming renewal needs across the network.

4.3.1 Method 1: Flat-rate Rehabilitation Rates

This approach is utilized as a primary approximation for water distribution systems that have developed evenly over long periods but lack detailed, age-related inventory data. The annual rehabilitation rate is determined by calculating the reciprocal of the expected technical service life, or the remaining service life if little prior maintenance has occurred. For example, a target service life of 50 years results in a strategic rehabilitation rate of 2% per year, while a 100-year lifecycle implies a 1% rate. By aggregating these calculations across all groups, a long-term rehabilitation volume for the entire system can be estimated.

4.3.2 Method 2: Age-Dependent Rehabilitation Rates

When specific inventory lengths and construction years are known, the age-dependent method provides a more detailed projection of renewal needs over time. Each individual asset within a system group is assigned a technical service life, and the required rehabilitation date is calculated based on its specific installation year. Because historical construction activities often occurred in waves, the resulting raw data typically shows significant annual fluctuations. To ensure operational

and financial feasibility, these rates are smoothed over 5-10-year intervals by calculating mean values for the respective system groups. By integrating the network inventory with these mathematical functions, the model calculates required rehabilitation lengths year by year for each asset group and the total inventory. This stochastic methodology ensures that renewal strategies remain economically sustainable while preserving long-term supply security.

4.3.3 Estimating the Service Life and Determining the Need for Renewal

The document establishes the need for renewal and estimates the technical service life by considering damage development, permissible damage rates, and the procedures used to derive rehabilitation rates. The need for rehabilitation is largely determined by age-dependent damage development and technical service life. Technical service life is defined as the intersection of a specified permissible damage rate and the age-dependent damage rate. Service life ends as soon as age-dependent damage development exceeds the permissible damage rate. This service life can be determined using technical literature, internal empirical values, damage documentation, or special investigations, such as material tests or the evaluation of cathodic corrosion protection.

4.4 Technical and Economic Analysis of Strategic Rehabilitation Scenarios

4.4.1 Short-Term Rehabilitation Measures

Short-term rehabilitation measures relate to the concrete implementation of work derived from strategy and planning. These measures are strictly based on current local conditions and previously identified priorities. The goal is to rehabilitate individual pipe sections promptly while considering economic and technical aspects. These measures include decisions regarding dimensioning, rehabilitation technology, and materials. Depending on the situation, open or trenchless construction, rehabilitation, or complete renewal methods are selected. The regulations refer to many specific technical standards, including those for relining, pipe jacking, and flush drilling. Short-term measures have a clear objective: to swiftly mitigate the risks identified during the planning stage and ensure the network's functionality. These measures are the first step in the rehabilitation process and form the operational level at which strategic decisions are carried out.

4.4.2 Medium-Term Rehabilitation Planning

Medium-term planning usually covers a period of about five years. It identifies which pipe sections need rehabilitation and establishes a priority order. The decisive factor is the risk of damage, which consists of the probability and extent of potential damage. The probability of occurrence and extent of damage are determined by the parameters discussed earlier. Other influencing factors can include hydraulic performance, customer complaints, operating experience, and measured values. Assessments are carried out section by section, using systems in which criteria are weighted and linked mathematically. The result is a priority list that specifies the order of the measures. However, coordination with measures taken by other divisions may result in lower-priority pipes being given priority if it makes economic sense. Nevertheless, external influences must not dilute the basic rehabilitation strategy.

4.4.3 Long-Term Rehabilitation Strategy

By integrating the network inventory with these mathematical functions, the model calculates the required rehabilitation length for each pipeline group and the total inventory year by year. It is crucial to distinguish the mathematically calculated stochastic failure probability, which is a survival model that forecasts future performance, from empirical, historical pipe failure rates, which are recorded past events. Consequently, an individual pipeline asset may have a high

calculated probability of failure due to its age and the characteristics of its material, even if that specific section has never experienced any damage.

The long-term strategy spans 20 – 50 *years* and aims to determine total future renovation and renewal requirements. The strategy consists of four steps:

1. Strategy guidelines
2. Formation of asset groups
3. Determination of condition development
4. Derivation of rehabilitation requirements

Asset groups are formed based on criteria such as material, year of construction, nominal diameters, location, operating conditions, and corrosion protection. Condition development can be determined by using technical literature, internal experience, damage documentation, technical investigations, or mathematical models. The age-dependent damage rate is particularly important because it is often used to determine the technical service life. The reliability of the results increases with improved data quality. The long-term strategy serves as the basis for budget planning and medium-term measures. It is typically reviewed and adjusted every five years.

4.4.4 Budget Determination

The sustainable management and structural preservation of a water distribution network requires the precise quantification of long-term financial commitments and technical prioritization. However, municipal utilities often have strict budget constraints, so the ideal annual rehabilitation rate needed to prevent network decay cannot be achieved. Consequently, available financial resources must be allocated optimally to maximize system resilience and supply security. The subsequent sections calculate the exact budget baseline available, which is then used to determine the maximum feasible length of pipelines in meters that can realistically be rehabilitated yearly within these economic boundaries. To ensure a high degree of economic forecasting accuracy up to the year 2050, the cost structures are differentiated by surface categories, pipe materials, and nominal diameters. In practice, actual renewal expenditures depend heavily on whether construction measures are carried out within strengthened roadways or on unpaved surfaces. To provide a transparent overview of these multidimensional financial parameters, costs are structured as follows for all relevant pipe dimensions and surface conditions.

TABLE 25: SPECIFIC REHABILITATION COSTS FOR DIFFERENT PIPE MATERIALS, DIAMETERS, AND SURFACE CONDITIONS PER METER

Pipe [€/ m]	PE 63	PE 110	PE 160	PE 180	PE 225	PE 250	PE 315	GGG 100	GGG 125	GGG 150	GGG 200	GGG 250	GGG 300
Civil engineering work on paved surfaces up to 14 cm of asphalt	494,90	501,90	526,90	529,90	627,51	667,51	707,51	581,73	594,73	614,73	732,39	762,39	832,39
Civil engineering involving water-bound surfaces	303,12	310,12	335,12	338,12	442,22	482,22	522,22	388,04	401,04	421,04	545,98	575,98	645,98

The investment forecast is based on two primary materials: PE and GGG ranging from 63 to 315 millimeters. These materials represent most of the distribution network infrastructure. The costs differentiate between paved asphalt surfaces and unpaved surfaces. Table 25 shows the cost breakdowns for standard construction, which illustrate how these rates are derived. The cost rates of these primary materials form the basis of the entire investment forecast. Analyzing the cost breakdowns for PE pipeline construction in detail is crucial to illustrate how these rates are derived, since these pipelines are currently used most often for replacement and rehabilitation.

TABLE 26: DETAILED COST BREAKDOWN ON ASPHALTED SURFACE (STADTWERKE FREUDENSTADT, 2026)

Trade	Item	Quantity	Unit	Unit Price [€]	PE 110 [€]	PE 160 [€]	PE 180 [€]
Civil Works	Civil works on 14 cm Asphalt	100,0	m	298,55 €	29.855,00 €	29.855,00 €	29.855,00 €
Civil Works	Pipe Embedding	2,0	pcs	351,45 €	702,90 €	702,90 €	702,90 €
Installation	Installation PE Pipe DN ≤ 180	100,0	m	23,54 €	2.354,00 €	2.354,00 €	2.354,00 €
Installation	Embedding PE Pipe DN ≤ 180	2,0	pcs	592,87 €	1.185,74 €	1.185,74 €	1.185,74 €
Civil Works	Connecting Pipe to the System	1,0	pcs	6.292,03 €	6.292,03 €	6.292,03 €	6.292,03 €
Planning & Construction	Project Engineer	20,0	h	82,50 €	1.650,00 €	1.650,00 €	1.650,00 €
Planning & Construction	Construction Coordinator	60,0	h	82,50 €	4.950,00 €	4.950,00 €	4.950,00 €
Technical Documentation	Surveying and Documentation	1,0	pcs	500,00 €	500,00 €	500,00 €	500,00 €
Warehouse	Pipeline Materials	100,0	m		1.000,00 €	2.200,00 €	2.500,00 €
Warehouse	Manhole Material	1,0	pcs		1.200,00 €	2.500,00 €	2.500,00 €
Approval	Permits	1,0	pcs	500,00 €	500,00 €	500,00 €	500,00 €
Total (per 100 m)					50.189,67 €	52.689,67 €	52.989,67 €
Total (per meter)					502,00 €	527,00 €	530,00 €

As shown in Table 26 and Table 27, total expenditures per meter include costs associated with asphalt demolition, surface restoration, trench excavation, pipe installation, shaft connections, engineering, surveying, and regulatory fees.

TABLE 27: DETAILED COST BREAKDOWN FOR UNPAVED SURFACES (STADTWERKE FREUDENSTADT, 2026)

Trade	Item	Quantity	Unit	Unit Price [€]	PE 110 [€]	PE 160 [€]	PE 180 [€]
Civil Works	Civil works on unpaved Surface	100,0	m	112,70 €	11.270,00 €	11.270,00 €	11.270,00 €
Civil Works	Pipe Embedding	2,0	pcs	351,45 €	702,90 €	702,90 €	702,90 €
Installation	Installation PE Pipe DN ≤ 180	100,0	m	23,54 €	2.354,00 €	2.354,00 €	2.354,00 €
Installation	Embedding PE Pipe DN ≤ 180	1,0	pcs	592,87 €	592,87 €	592,87 €	592,87 €
Civil Works	Connecting Pipe to the System	1,0	pcs	6.292,03 €	6.292,03 €	6.292,03 €	6.292,03 €
Planning & Construction	Project Engineer	20,0	h	82,50 €	1.650,00 €	1.650,00 €	1.650,00 €
Planning & Construction	Construction Coordinator	60,0	h	82,50 €	4.950,00 €	4.950,00 €	4.950,00 €
Technical Documentation	Surveying and Documentation	1,0	pcs	500,00 €	500,00 €	500,00 €	500,00 €
Warehouse	Pipeline Materials	100,0	m		1.000,00 €	2.200,00 €	2.500,00 €
Warehouse	Manhole Material	1,0	pcs		1.200,00 €	2.500,00 €	2.500,00 €
Approval	Permits	1,0	pcs	500,00 €	500,00 €	500,00 €	500,00 €
Total (per 100 m)					31.011,80 €	33.511,80 €	33.811,80 €
Total (per meter)					310,00 €	335,00 €	338,00 €

The standardized unit prices can be reconstructed step by step using the exemplary calculations presented in Table 26 Table 27. Directly comparing the individual costs shows that open trench civil engineering work and surface restoration are the main financial considerations in urban areas.

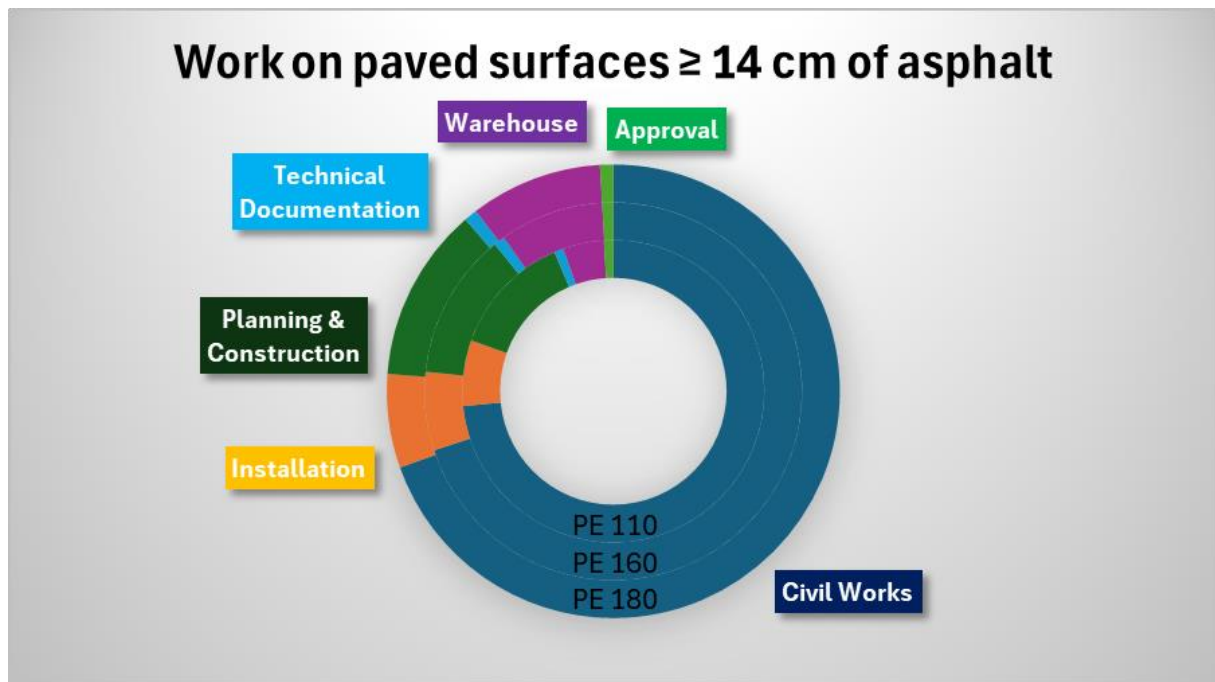


FIGURE 29: COST BREAKDOWN FOR PIPELINE REHABILITATION ON ASPHALTED SURFACES (≥ 14 CM)
(STADTWERKE FREUDENSTADT, 2026)

Figure 29 illustrates the proportions of total expenditures for renewal measures in asphalted zones. Civil work is the primary financial driver, significantly outweighing the costs of material installation and engineering services.

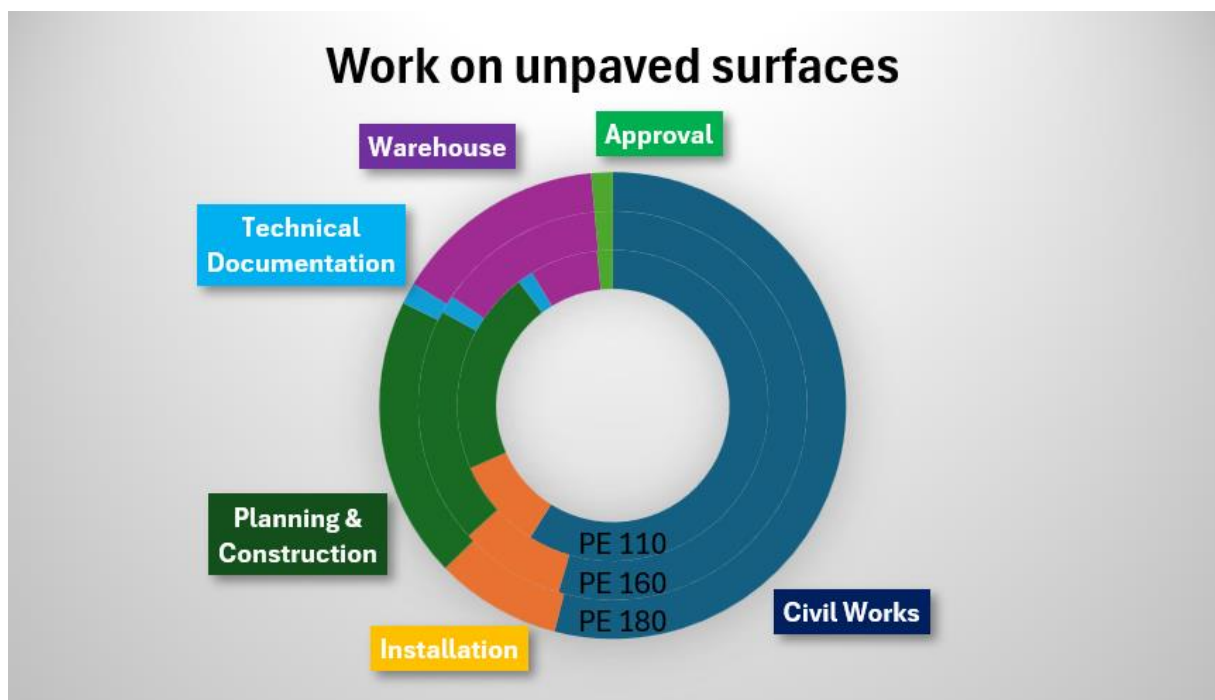


FIGURE 30: COST BREAKDOWN FOR PIPELINE REHABILITATION ON UNPAVED (STADTWERKE FREUDENSTADT, 2026)

Figure 30 shows the cost breakdown for unpaved or unpaved surfaces. Compared to paved roads, the share of civil work decreases slightly due to reduced surface restoration efforts. Consequently, the financial weight of installation and technical documentation increases. Since historical and strategic network analyses confirm that most upcoming construction sites will be on asphalted

public roads, a specific reference price must be established for macro-level budget simulations. The most frequently used polyethylene pipe dimensions under asphalt are used to derive this generalized reference rate, which is a weighted average. Considering the cost distribution of PE pipes, the strategic model defines an average baseline price of 500,00 € *per meter* for the standard urban rehabilitation scenario.

In addition to defining structural unit costs, the economic model should base its financial predictions on the utility provider's actual financial framework and historical funding allocations. A seven-year retrospective analysis of funding distribution provides valuable insight into the allocation capabilities of Stadtwerke Freudensstadt.

TABLE 28: HISTORICAL BUDGET ALLOCATION AND REHABILITATION SHARE (2018-2024)

Year	Total Budget [€]	Rehabilitation [€]	Rehabilitation [%]
2018	400.000 €	395.000 €	99%
2019	400.000 €	399.000 €	100%
2020	500.000 €	431.900 €	86%
2021	500.000 €	369.000 €	74%
2022	700.000 €	352.000 €	50%
2023	700.000 €	676.557 €	97%
2024	500.000 €	252.000 €	50%
Average	528.571 €	410.780 €	78%

As shown in Table 28, the relationship between total available resources and the portion allocated to infrastructure rehabilitation has fluctuated over time. A critical evaluation of the chronological sequence reveals that the rehabilitation budget was significantly smaller in 2022 than in previous years. During this period, Stadtwerke Freudensstadt prioritized new development and connection projects, which required a temporary reduction in capital allocated to rehabilitation. However, there was insufficient data from 2019 and 2024 to draw conclusions about outliers with extremely high or low percentages. The exact figures for 2025 are not yet available because some construction projects have not been fully settled yet. Despite these fluctuations, an empirical evaluation establishes a consistent long-term performance baseline, yielding an average rehabilitation share of 78 % per year over the historical period under investigation. Figure 31 illustrates the resulting percentage-based and absolute allocations of the annual fund.

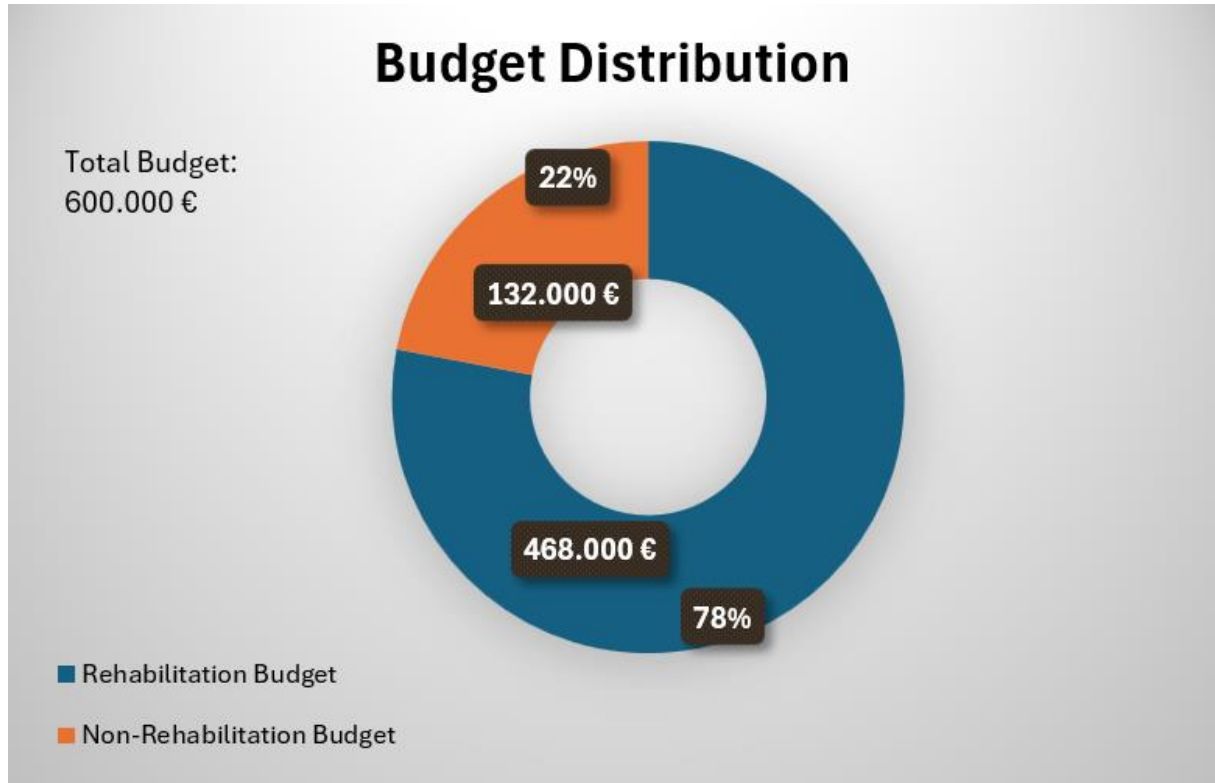


FIGURE 31: FIXED ANNUAL INFRASTRUCTURE BUDGET FOR 2025-2029, DISTRIBUTED BETWEEN REHABILITATION AND NON-REHABILITATION ALLOCATIONS

This forms the basis of the short- and medium-term financial planning framework. The framework covers the next five operational years, from 2025 to 2029. Within this planning horizon, the total annual corporate budget for network infrastructure remains fixed at 600.000,00 €. The annual fund dedicated to systematic network rehabilitation is derived mathematically by applying the empirically established dedication rate to the total global budget allocation.

$$B_{Reha} = B_{Total} \cdot R$$

Where:

B_{Reha}	Specific annual budget available for rehabilitation [€/a]
B_{Total}	Fixed total annual corporate infrastructure budget [600.000,00 €/a]
R	Empirical long-term rate of dedication [78 %]

$$B_{Reha} = 600.000,00 \text{ €/a} \cdot 0,78 = 468.000,00 \text{ €/a}$$

Applying the established rate of 78 % to the budget results in an annual rehabilitation fund of approximately 468.000 €. This establishes the economic boundary condition for all subsequent mathematical simulation models and strategic calculations. To bridge the gap between financial constraints and technical execution, this annual budget must be converted. The total feasible annual renewal distance can be calculated by dividing the available annual rehabilitation fund by the established urban baseline reference cost per meter. This calculation determines exactly how many meters of pipeline can be rehabilitated systematically each year within the given financial limit. The annual physical execution length is calculated using the following mathematical relationship:

$$L_{Reha} = \frac{B_{Reha}}{C_{Baseline}}$$

Where:

L_{Reha}	Maximum feasible annual pipeline rehabilitation length [m/a]
------------	--

B_{Reha}	Specific annual budget available for rehabilitation [€/a]
$C_{Baseline}$	Standard unit cost baseline [500 €/m]

Substituting the standard operational parameters into the equation yields the following capacity:

$$L_{Reha} = \frac{468.000,00 \text{ €/a}}{500,00 \text{ €/m}} = 936,00 \text{ m/a}$$

To evaluate the impact of this rehabilitation capacity on the overall long-term network lifespan, the feasible renewal volume must first be converted into an annual network renewal rate. The rehabilitation rate represents the proportion of the entire water distribution infrastructure that can be modernized annually within the given financial constraints. Based on Stadtwerke Freudenstadt's total verified distribution network length of 166.392 *meters*, the relative performance metric is defined as follows:

$$Reha = \frac{L_{Reha}}{L_{Total}} \cdot 100 \%$$

Where:

$Reha$	Relative annual percentage rehabilitation rate [%]
L_{Reha}	Maximum feasible annual pipeline rehabilitation length [936,00 m/a]
L_{Total}	Total length of the water distribution network infrastructure [166.392 m]

Substituting the specific local parameters into the equation yields the relative renewal capacity:

$$Reha = \frac{936,00 \text{ m/a}}{166.392 \text{ m}} \cdot 100 \% = 0,5625 \%$$

The mathematical evaluation shows that the fixed annual allocation of 468.000 € enables an annual rehabilitation rate of 0,56 % of the network's total length. From an engineering standpoint, this percentage significantly falls below the long-term sustainability recommendations of the DVGW guidelines, indicating a substantial long-term investment gap (according to (DVGW e.V. W 403, 2025) and (DVGW e.V. W 1003 (A), 2022)). Subsequent chapters will present comparative scenario data to determine if this funding level is sufficient or if a higher rehabilitation rate is necessary to maintain the network's integrity. They will also evaluate the long-term impact of this deficit on grid stability.

Methodologically, Stadtwerke Freudenstadt's financial planning must strictly separate the rehabilitation budget from the strategic expansion budget. Costs associated with connecting new development zones, resolving localized hydraulic bottlenecks, or executing emergency repairs following acute pipe bursts should not be financed through the systematic network renewal budget. Since the economic scenarios cover an extended planning horizon up to 2050, the static base values must be adjusted dynamically within the continuous financial framework. This dynamic approach realistically accounts for future inflation. It secures the long-term value of the infrastructure while minimizing the risk of failure of the entire supply system.

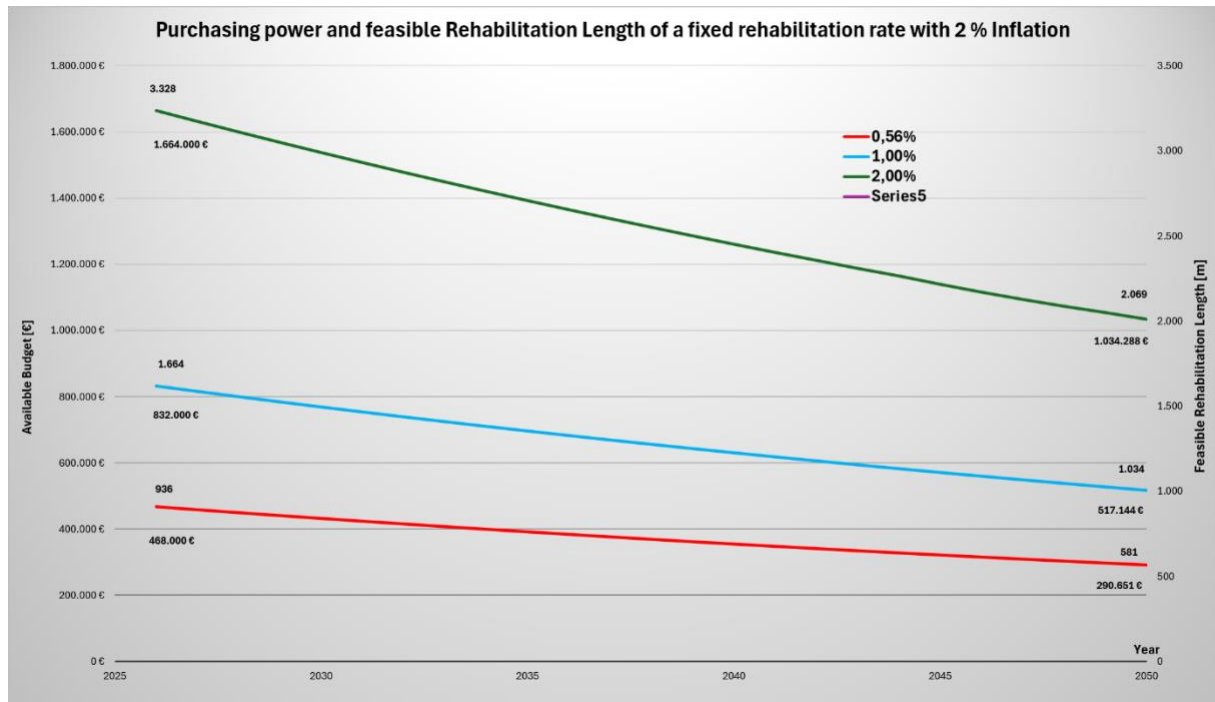


FIGURE 32: LONG-TERM PROJECTION OF AVAILABLE REHABILITATION BUDGET AND FEASIBLE RENEWAL LENGTH UNDER A 2% ANNUAL INFLATION RATE (2026–2050)

Figure 32 shows the long-term effects of inflation on financial planning and execution capacity. Assuming a constant annual inflation rate of 2 %, the real purchasing power of the fixed budget allocation decreases significantly over the forecasting horizon. In the baseline scenario with a rehabilitation rate of 0,56 %, the available real budget shrinks from 468.000 € in 2025 to 290.651 € in 2050. Consequently, the feasible annual renewal length falls substantially, from 936 *meters* to 581 *meters* per year. To address this deficit, Figure 32 presents two alternative strategic pathways. A targeted rehabilitation rate of 1,00% requires an initial real budget of 832.000 €, which enables 1.664 *meters* of renewal. However, this deflates to a purchasing power of 517.144 € (1.034 *meters*) by 2050. A 2,00 % comprehensive sustainability rate requires an initial budget of 1.664.000 € (enabling 3.328 *meters* of renewal), which decreases to an effective real value of 1.034.288 € (2.069 *meters*) by 2050. This modeling illustrates that a static nominal budget accelerates the technical rehabilitation deficit.

4.4.5 Rehabilitation Scenarios

According to the technical frameworks in (DVGW e.V. W 403, 2025) and the strategic resilience principles in (DVGW e.V. W 1003 (A), 2022), Stadtwerke Freudensstadt’s pipelines are divided into localized investment windows based on structural urgency and systemic criticality. To bridge the gap between immediate hazard mitigation and long-term preservation, the network is divided into short-, medium-, and long-term segments. A distinct subgroup that requires no rehabilitation is also included.

Immediate structural intervention is required under the short-term rehabilitation scenario, which has a one-year planning horizon. Assets fall into the highest-priority category if their calculated overall risk index exceeds the critical threshold of 46,5 %. This threshold indicates acute physical degradation combined with the potential for localized or systemic failure. An empirical evaluation of Stadtwerke Freudensstadt’s digital twin reveals that the critical, high-risk group encompasses 1.161,7 *meters*. This distance accounts for a minor yet highly sensitive 0,70 % of the total evaluated network length. The critical threshold was calibrated to approximate the technically

feasible annual rehabilitation volume and aligns closely with the budget-driven rate of 0,56 % calculated for Stadtwerke Freudenstadt's network. Since pipeline segments cannot be subdivided during execution of civil engineering projects and abandoning a rehabilitation measure mid-pipe is operationally and economically impractical, the cumulative length of prioritized assets naturally fluctuates slightly above or below the strict theoretical budget limit. This practical adjustment framework was applied to determine risk index thresholds for all other planning horizons. Within this short-term window, the operational focus is swiftly eliminating structural weak points while maintaining system integrity. Table 29 also shows the other categorizations, which are organized by the type and timeframe of rehabilitation.

TABLE 29: CATEGORIZATION OF PIPELINE ASSETS AND RISK INDEX THRESHOLDS BY PLANNING HORIZON, ACCORDING TO (DVGW E.V. W 403, 2025)

Risk Index	Network Length [m]	Rehabilitation [%]	Type of Rehabilitation	Rehabilitation Period [years]
> 46,5 %	1.161,7	0,70%	Short-Term	1
41,6 % – 46,5 %	5.439,8	3,27%	Medium-Term	5
31,1 % – 41,6 %	20.047,5	12,05%	Long-Term	20
< 31,1 %	139.743,0	83,98%	No Rehabilitation	-

Pipeline assets with elevated yet non-immediate structural risk profiles are allocated to the medium-term rehabilitation planning horizon. This period spans five years. It includes all segments with a multi-criteria risk index between 41,6 % and 46,5 %. A total of 5.439,8 *meters* of pipeline were identified as being in this intermediate category, representing 3,27 % of the municipal pipeline grid. In these cases, the localized damage rate clearly indicates that the asset has entered the wear-out phase of its lifecycle.

The long-term rehabilitation strategy spans 20 *years*. It is designed to ensure the network's sustainability and preserve its structures. To improve visual understanding and provide an efficient diagnostic overview of the strategic plans, the long-term rehabilitation is divided into two ten-year periods based on the risk index. The first period, Long-Term Phase I, includes structures with a risk index between 35,4 % and 41,6 % This phase includes 9.860,2 *meters* of infrastructure, accounting for 5,93 % of the total network. The second phase, Long-Term Phase II, includes segments with an index value between 31,1 % and 35,4 % . This phase includes 10.187,3 *meters*, representing 6,12 % of the municipal inventory. These two phases are color-coded dark green and light blue, respectively, on the STANET overview maps in Appendix 1. The map fully illustrates the geographic distribution and localized visual network mapping for the southern sector, including the year when rehabilitation should take place. This allows engineering staff to quickly identify critical pipeline segments and long-term staging areas. The other types of rehabilitation and their corresponding colors are shown in Table 30.

TABLE 30: VISUAL MAPPING FRAMEWORK AND EXTENDED RISK INDEX RANGES FOR LONG-TERM REHABILITATION PHASES

Risk Index	Network Length [m]	Rehabilitation [%]	Type of Rehabilitation	Rehabilitation Period [years]		Color
> 46,5 %	1.161,7	0,70%	Short-Term	1		Dark Red
41,6 % – 46,5 %	5.439,8	3,27%	Medium-Term	5		Light Red
35,4 % – 41,6 %	9.860,2	5,93%	Long-Term I	20	10	Dark Green
31,1 % – 35,4 %	10.187,3	6,12%	Long-Term II		10	Light Blue
< 31,1 %	139.743,0	83,98%	No Rehabilitation	-		Black

The remaining backbone of the water supply network is classified as functional inventory (No Rehabilitation). This classification does not indicate an absence of defects or risks. Rather, it

highlights the severe limitations of available funding. This group is defined by a risk index below 31,1 % and comprises 83,98 % of the total network length, including 139.743 *meters* of Stadtwerke Freudenstadt's infrastructure. While many of these pipeline segments include resilient materials, such as modern polyethylene, some should be rehabilitated before 2050 to prevent grid failure. However, the utility company cannot afford these measures due to financial constraints. Consequently, these segments are excluded from capital expense allocations, so no rehabilitation measures can be planned for them in the near future. This forced exclusion ensures that the strictly capped municipal budget remains focused on the highest-priority risk zones, even though significant structural deficits remain throughout the rest of the network.

4.5 Comprehensive Engineering Evaluation and Discussion of Findings

To apply the multi-criteria risk index and hydraulic twin data to practical engineering, it is necessary to conduct a comparison with other regional utilities. A robust, objective baseline was established for Stadtwerke Freudenstadt. The analysis used 42 comparable water distribution networks in Germany and Austria as a point of reference.

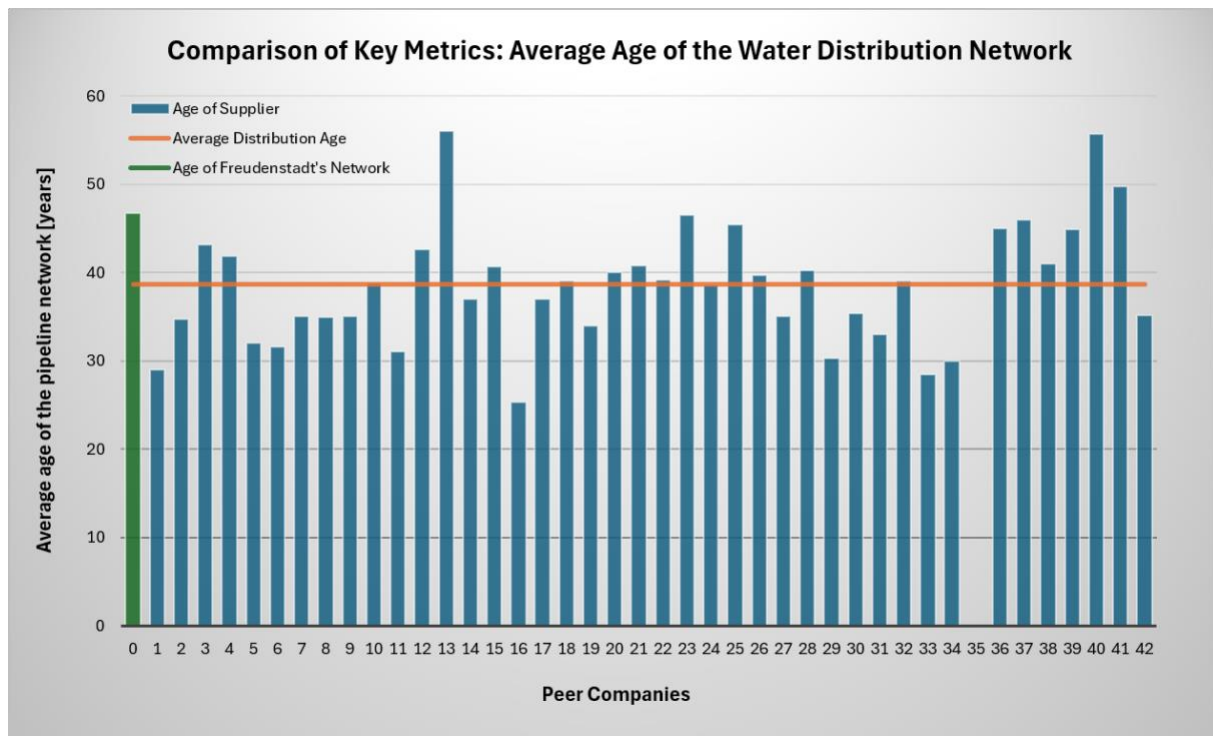


FIGURE 33: COMPARISON OF THE AVERAGE AGE WITH OTHER REGIONAL UTILITIES

Figure 33 shows that the length-weighted asset age indicates a significant infrastructure deficit in the local system. While the peer group average is 38,67 *years*, the validated digital twin of Stadtwerke Freudenstadt's municipal network, illustrated as "Peer Company 0" in green, is, on average, 46,7 years old. Among these peer companies, only three utility suppliers have a pipeline system that is older on average than the one from Stadtwerke Freudenstadt. Additionally, no data was available for Peer Company 35's network age evaluation. The absence of these records indicates missing chronological data rather than a network age of zero. These results highlight the state of advanced asset aging and confirm that the historical core of the network has surpassed its standard technical lifespan. Methodologically, excluding the external long-distance transmission lines owned by the ZVKK ensures that this evaluation considers only assets that are directly managed and maintained by the local municipal utility. A significant engineering challenge

emerges when comparing this advanced structural age with empirical failure statistics recorded in recent decades.

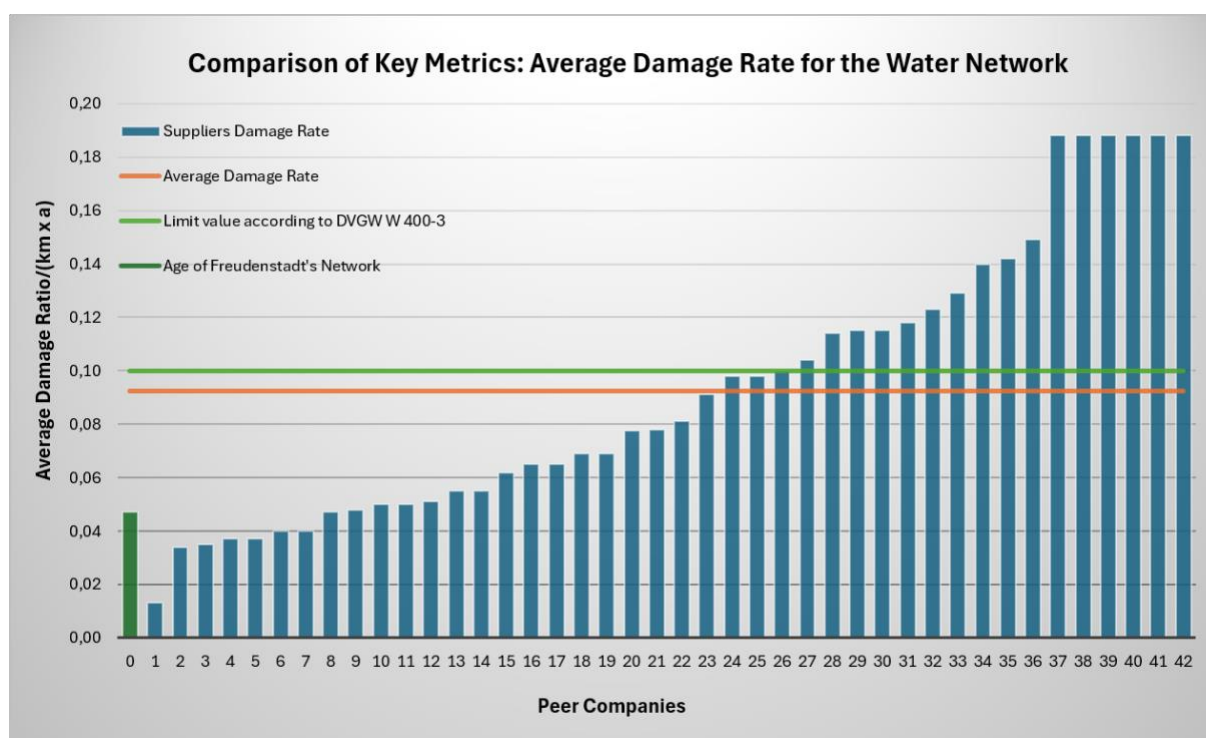


FIGURE 34: COMPARISON OF THE AVERAGE DAMAGE RATE WITH OTHER REGIONAL UTILITIES

This operational indicator in Figure 34 is significantly lower than the peer group average of $0,092 \text{ damages}/(\text{km} \cdot \text{a})$. It remains well below the $0,10 \text{ damages}/(\text{km} \cdot \text{a})$ threshold defined by (DVGW e.V. W 400-3, 2004) for low-risk networks. However, from a strategic asset management perspective, this favorable damage rate should not be misinterpreted as justification for postponing investments. However, this favorable benchmark position is largely due to the data framework applied to historical damage data. During the data cleaning process, the number of documented events was reduced from 328 to 182 system-relevant failures by strictly excluding house connections and damages to decommissioned lines. Using the complete, unverified raw database directly in the active calculation model would cause the grid's empirical failure rate to exceed the critical (DVGW e.V. W 403, 2025) limit of $0,10 \text{ damages}/(\text{km} \cdot \text{year})$. Consequently, the network's visual positioning would shift significantly above the average of its peers.

From a methodological standpoint, it is important to note that peer companies 1 through 42 represent the municipal utility systems depicted in Figure 33 and Figure 34. A cross-sectional correlation analysis of these parallel datasets reveals no direct, linear relationship between advanced network age and empirical failure rates. For example, some peer systems have low asset decay despite high age, while others have high damage rates within relatively young grids. Additionally, the current state of this network is a classic example of a latent crisis, the calm before the storm. The robust GGG pipelines of the first and early second generations, which were installed during the high-growth expansion phases, form the backbone of the current distribution grid. These groups are simultaneously transitioning from the operational stability phase to the wear-out phase of the traditional bathtub curve lifecycle (Figure 18). Because these pipe lengths are reaching their technical boundary conditions, a sudden, exponential increase in localized failures is highly probable in the near future if rehabilitation volumes remain stagnant. Translating these lifecycle simulations into long-term strategic planning up to the year 2050 reveals significant financial and operational limitations. Based on the economic framework established for the standard scenario,

the fixed annual budget of 468.000 € allows for approximately 936 *meters* of rehabilitation each year. This equates to an annual rehabilitation rate of 0,56 % of the total network length. Interestingly, this value nearly aligns with the regional macroeconomic reality: the average annual water main rehabilitation rate in Baden-Württemberg is approximately 0,54% (DVGW e. V., 2020). While this comparison shows that the funding limitations from Stadtwerke Freudenstadt reflects standard regional engineering practices rather than unique deficits, it also reveals a notable long-term investment gap. In order to counteract the aging of the cast iron pipes and prevent the accumulation of physical risks, the rehabilitation rate must be higher. Maintaining the current static budget cap will result in an increasing asset renewal deficit by 2050.

Figure 35 and Figure 36 illustrate the impact of certain investment choices on the system's structure and configuration over time. Figure 35 illustrates an upward trend in average asset age, increasing from less than 30 years in 2000 to nearly 47 *years* in 2026. The simulation of future scenarios up to 2050 illustrates the decisive role of strategic renewal volume.

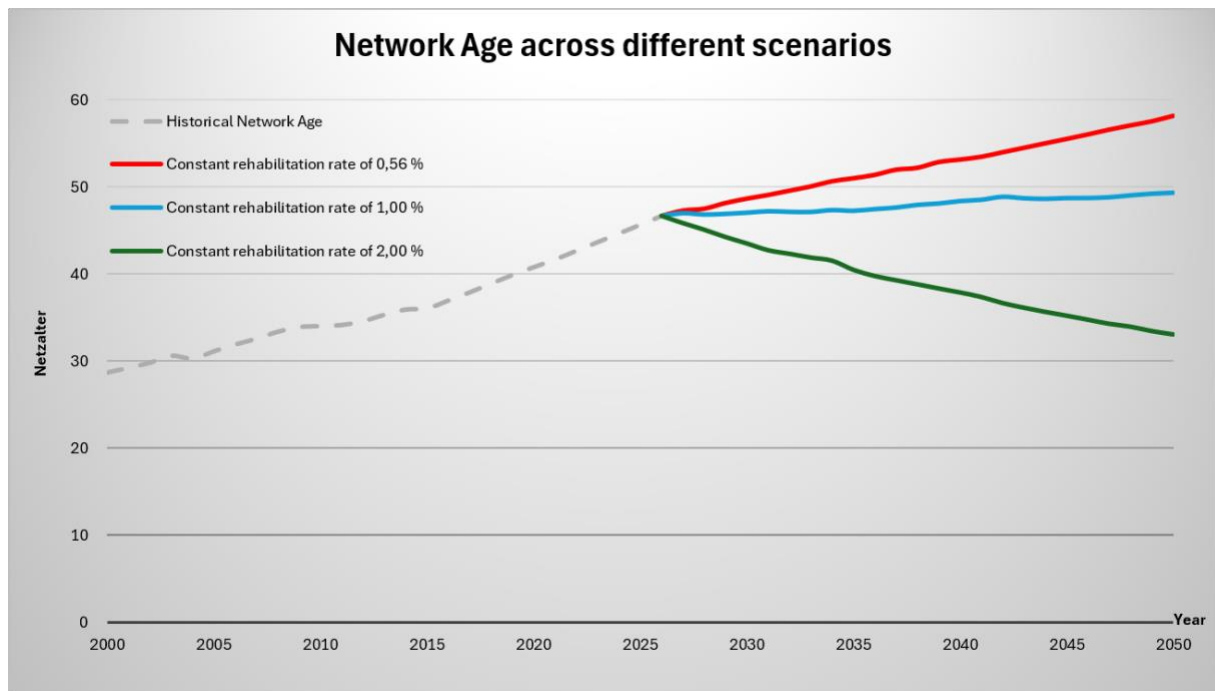


FIGURE 35: TRENDS IN THE AVERAGE NETWORK AGE ACROSS DIFFERENT SCENARIOS (2000–2050)

Figure 36 illustrates how the average network age changes over time when accounting for the significant impact of inflation on a fixed budget. Even with a constant rehabilitation rate of 0,56 % (solid red line), the average network age increases to nearly 58 years by 2050, indicating an unsustainable aging process. However, the newly introduced scenario of maintaining a constant nominal budget under a 2 % annual inflation rate (dashed red line), which accurately reflects Stadtwerke Freudenstadt's real-world operational planning, shows an even worse outcome. Because inflation continuously reduces purchasing power and feasible annual renewal lengths, as demonstrated in Figure 32, the average network age accelerates. It reaches 60 years by 2050. This highlights that a static nominal budget worsens the long-term rehabilitation deficit and accumulates severe structural risks within the infrastructure. Conversely, a rehabilitation rate of 1,00 % (solid blue line) stabilizes the average network age within the manageable range of 47 to 49 years. The 2,00 % scenario (solid green line) is the only one that achieves active asset restoration, reducing the average system age to approximately 33 years by 2050.

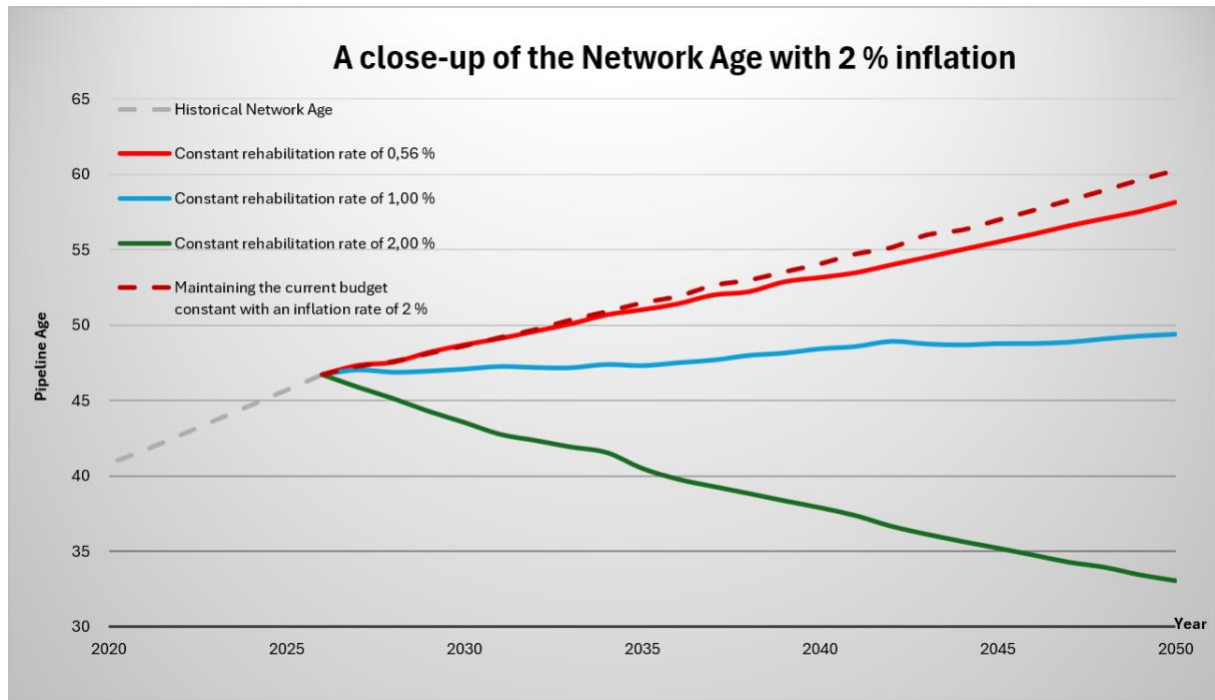


FIGURE 36: CLOSE-UP OF THE NETWORK AGE DEVELOPMENT WITH 2 % INFLATION (2020–2050)

Consequently, the multi-criteria optimization provided by the AHP model is essential for operations. Under strict financial constraints, this multilayered indexing model is the only objective mechanism that can ensure that the capital budget is allocated to high-risk sections where the probability of failure and potential socioeconomic damage are greatest. However, the reliability and long-term accuracy of these strategic scenarios are limited by the quality of the underlying geographic information and asset management systems' data. Uncertainties within the baseline parameters must be carefully considered when executing the engineering plan. Gaps in historical documentation required the use of material-age proxies and urban development correlations. While this validation significantly reduces macro-level model distortion, it introduces localized tolerances that may alter specific pipe prioritizations. Furthermore, the framework's practical traceability was demonstrated during the final validation phase when an error involving swapped risk parameters for the first and second generations of the GGG was discovered. Due to the framework's systematic and transparent architecture, the discrepancy was quickly identified and corrected. This proves that the model can be efficiently verified, calibrated, and validated. Additionally, qualitative filtering of historical damage data reduced the raw database from 328 to 182 failure events. Furthermore, the socioeconomic consequence parameters are tied to demographic distributions and municipal water consumption profiles recorded in 2025. Ongoing sociodemographic structural transformations increase peak hydraulic demands and introduce dynamic variables up to the year 2050 due to changing commercial network dynamics. These long-term dynamics require continuous updates to the digital twin to ensure the model remains useful.

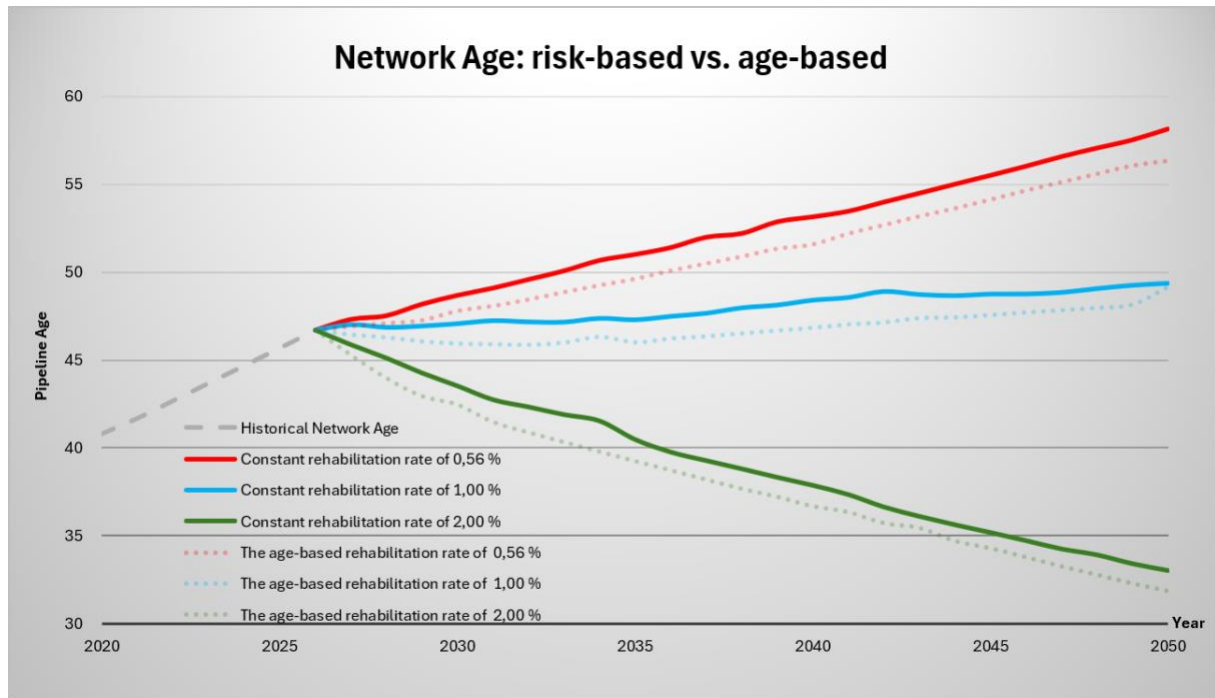


FIGURE 37: LONG-TERM PROJECTION SHOWING HOW THE NETWORK WOULD DEVELOP UNDER RISK-BASED VS. TRADITIONAL AGE-BASED REPLACEMENT ACROSS DIFFERENT SCENARIOS

A detailed analysis of the simulation results shown in Figure 37 reveals a critical operational paradox. At first glance, the age-based rehabilitation strategies (represented by the dotted lines) seem preferable to a non-expert because they result in a lower average network age than the risk-based models (represented by the solid lines). However, the discrepancy occurs because the traditional strategy strictly targets the oldest pipelines, maximizing grid renovation. Still, this conventional approach introduces a severe structural blind spot because it ignores localized failure probability and potential socioeconomic damage. Relying solely on an asset's age means that highly critical, high-risk pipeline segments remain operational even if they have not reached a rigid age-based threshold. Consequently, while the risk-based strategy results in a slightly higher average network age, it eliminates the most dangerous failure points. Failing to implement this risk-oriented prioritization results in an increased frequency of unpredictable pipe bursts, a greater number of affected consumers, and escalating long-term reactive repair expenditures. These factors severely compromise overall supply security.

5. Conclusions

A transition from intuitive or reactive maintenance to data-driven, risk-oriented asset management is essential to preserving municipal water distribution infrastructure. This master's thesis presents a scientifically based, transferable evaluation framework that links technical resilience requirements to strict economic constraints.

5.1 Summary of Core Contributions

The primary aim of this thesis was to develop a risk-oriented decision model for rehabilitation planning in water distribution networks that balances economic efficiency with supply security. The developed framework was successfully applied to Stadtwerke Freudenberg's municipal network, demonstrating the methodology's practical feasibility, transferability, and strategic value. To evaluate the framework's core contributions and practical efficiency, the empirical findings were mapped directly to the primary research questions.

Sub-question 1 was answered using a multi-criteria prioritization matrix. The AHP matrix successfully establishes a localized risk index by systematically weighing technical condition indicators at 60 % against localized socioeconomic and hydraulic consequences at 40 %.

- **Condition assessment (60 %):** This dimension integrates asset age, material classifications, and empirical pipe burst records to quantify the structural probability of failure. This dimension provides a mathematical methodology to analyze how multiple generations of robust infrastructure simultaneously enter the wear-out phase of their lifecycles (phase three of the traditional bathtub curve Figure 18).
- **Damage Extent (40 %):** This dimension shifts the focus toward supply security. It considers the proximity of critical infrastructure, the complexity of expert-based repairs, the overall criticality to consumers, peak hydraulic capacity, operating pressure, and the potential for subsurface soil erosion.

Consequently, the model surpasses traditional, age-based asset management strategies.

Sub-question 2 was addressed by examining long-term investment scenarios up to the year 2050. Dynamic lifecycle and financial simulations demonstrate that the current budget-driven rehabilitation rate of 0,56 % (936 *meters per year*) could lead to a structural deficit. The model shows that seemingly stable, low damage rates today often mask a potential crisis of latent degradation. This crisis would increase the average network age to an unsustainable 58 years by 2050. Conversely, the model identifies the following strategic pathways:

- **Grid Stabilization:** A minimum target renewal rate of 1,00 % is required to counteract grid decay and stabilize the average network age within the manageable range of 47 to 49 years.
- **Active Asset Restoration:** An enhanced sustainability rate of 2,00 % is necessary for long-term structural recovery. This would reduce the average system age to approximately 33 years by 2050.

The primary research question addresses a transferable strategy. This framework converts raw operational parameters into a dimensionless mathematical risk index that ranges from 0,0 to 1,0. This decouples the evaluation logic from local geographic specifics. It provides municipal water utilities around the world with an objective, universal, algorithmic strategy that balances severe cost restrictions with long-term supply security.

Operational Value and Strategic Conclusion

A key strength of this methodology is its ability to account for the specific characteristics of a supply network, such as pipe attributes, failure history, and hydraulic simulation results, while

maintaining a high degree of standardization. Implementing this methodology in Freudenstadt shows that combining multi-criteria prioritization with strategic rehabilitation planning under fixed financial constraints creates a consistent, transparent, and structured basis for municipal decision-making.

Furthermore, the long-term simulation up to the year 2050 underscores the model's strategic value by demonstrating the long-term impact of current budget limitations on network performance. The findings show that maintaining the baseline rehabilitation rate will result in progressive infrastructure decay. In contrast, the optimized allocation strategy maximizes risk reduction per euro invested. Thus, the model serves as a powerful communication tool that helps utility managers justify necessary capital expenditures to political decision-makers and regulatory bodies.

5.2 Key Insights for Network Asset Management

The management of water supply infrastructure is shifting from traditional, financially driven accounting methods to dynamic, condition-based engineering practices. For decision-makers and executive teams at municipal utilities, this thesis offers valuable insights for optimizing capital expenditures and maintaining long-term supply resilience despite severe budget constraints. Implementing a multi-criteria risk model reveals that relying solely on the age of assets or their theoretical lifespans is both economically inefficient and technically inadequate. Utilities must transition to a standardized framework in which structural degradation parameters and localized asset consequences dictate rehabilitation priorities. Simply replacing pipelines based on their age can result in the premature decommissioning of fully functional assets. Conversely, delaying intervention on highly critical transport segments can drastically increase systemic vulnerability. Decision-makers should not interpret low network failure rates as justification for postponing capital investments or reducing renewal budgets. Robust pipelines, such as early ductile cast iron ones, experience long periods of operational stability before entering an exponential wear-out phase. However, significant statistical uncertainty exists due to gaps in historical recordkeeping and decommissioned infrastructure assets. Documented failure events that occurred on pipelines already taken out of service are naturally absent from the active STANET calculation model and cannot be factored into current evaluation matrices.

Directly applying the complete historical archive of 328 damages to the 166-kilometer distribution grid would increase the theoretical, network-wide damage rate above the critical limit of 0,1 damages per kilometer and year defined in (DVGW e.V. W 400-3, 2004). Relying on unverified total statistics introduces severe inaccuracies because it is impossible to verify the localized structural relevance of missing or outdated entries. Consequently, the prioritization model must focus strictly on verified, system-relevant failures to eliminate these mathematical biases.

Taking advantage of open trenches from third-party municipal projects, such as sewer extensions or Gas pipeline installations, can provide significant cost savings in civil engineering. However, executive management must actively monitor this process to ensure these co-laying measures do not consume the core rehabilitation budget intended for priority assets. Clear internal thresholds must be established to balance cost-sharing opportunities with systematic, risk-driven renewal projects. The transformation of the network dataset shows that the accuracy of any model for asset management depends on continuous data engineering. Systematically removing misleading placeholder data from legacy archives (e.g., generic construction years) and carefully filtering defect statistics is not an administrative burden, but rather a financial requirement.

Furthermore, it should be noted that the transferability of this framework's methodology relies heavily on manual data engineering. Essential steps that cannot be skipped or fully automated include time-consuming processes such as cleaning geometric network data, performing coordinate transformations, and manually integrating localized spatial data (e.g., specific highways and railway infrastructures and damages).

High-quality digital twins are the only objective mechanism that can prevent the misallocation of millions of euros in limited public funds. Sustainable asset management requires evaluating the distribution network as a highly integrated system rather than as a collection of separate pipeline segments. Technical renewal planning should consider risks to linear pipelines as well as the localized condition of vertical infrastructure components, such as storage reservoirs, to ensure the safety and reliability of these critical systems. Identifying overlapping criticalities enables utilities to implement structural improvements, such as replacing outdated storage structures with optimized central facilities. These improvements will ensure regional supply security until the year 2050 and beyond.

6. Future Perspectives

6.1 Transferability of the Decision Model to Distributed Utilities

The risk-oriented asset management framework developed for Stadtwerke Freudensstadt's water supply network provides a generalized approach that can be applied to other medium-sized public utilities facing similar structural and financial constraints. The model separates the prioritization logic from specific geographic boundary conditions by converting localized environmental and hydraulic parameters into a dimensionless mathematical structure. The model successfully integrates zone-specific calibrations in accordance with technical regulations, such as (DVGW e.V. W 1003 (A), 2022). External utility companies can input their specific system attributes directly into the underlying hydraulic capacity and formulas to evaluate localized network stress. Additionally, converting raw, heterogeneous asset attributes into a standardized index ranging from 0,0 to 1,0 enables the uniform processing of various pipeline asset groups. This allows utilities to analyze different material generations within a single, consistent failure probability matrix.

The Analytic Hierarchy Process provides a highly flexible tool for corporate decision-makers (Saaty, 1980). While the baseline balance is fixed at 60 % for condition assessment and 40 % for damage extent at the macro level. In alignment with present risk frameworks such as (DVGW e.V. W 403, 2025), local engineering teams have the ability to adjust sub-criteria weights as needed to address particular regional issues. The model clarifies general definitions by establishing clear numerical classification boundaries, such as for critical infrastructure. These thresholds can be scaled proportionally to match the specific sociodemographic distributions and structural configurations of any municipal supply grid. Finally, the matrix developed in this study relies entirely on standardized data exchange formats. This enables engineering teams to replicate the optimization methodology across different software systems.

6.2 Recommendations for Engineering Practice and Future Research

In order to maximize the long-term validity of predictive lifespan simulations and optimize municipal asset management, specific procedures must be integrated into standard engineering workflows. According to (DVGW e.V. W 402, 2021), structured data collection should be initiated in the presence of data gaps. Water utilities should transition from unstructured field documentation to digital databases that adhere to this standard. These databases must be more precise. Field teams that record exact spatial coordinates, detailed technical failure categories, precise pipe bedding parameters, and soil attributes provide a robust foundation for stochastic survival analysis. Additionally, Asset403's automated predictive modules successfully illustrated and visualized baseline portfolio charts and material generation distributions. However, the tool's stochastic lifespan simulation capabilities did not produce plausible results. Automated degradation models based on survival functions usually need at least 100 verified damage events per material group to generate reliable degradation curves. While the 1. Gen GGG nearly met these conditions, the remaining material asset groups had too few historical failures. This caused the software to output inaccurate lifecycles that could not be manually validated. Thus, a custom, empirically calculated, risk-prioritizing framework was developed instead. Additionally, operating teams at municipalities must systematically eliminate errors in historical documentation, such as in GIS. To prevent significant inaccuracies in material-specific damage statistics, qualitative filters must distinguish between minor defects and historical damage. Furthermore, it is necessary to distinguish between grid pipelines and active distribution mains.

Future scientific research should incorporate dynamic civil engineering cost indices into fixed nominal budget scenarios. Modeling annual inflation up to the year 2050 shows that reduced real

purchasing power significantly shortens the length of feasible renewal projects. This shift requires transitioning from static funding caps to flexible infrastructure budgets that preserve value. Using modeling parameters such as digital soil chemistry and conductivity maps, as well as groundwater levels, restoration times, and local pH variations, the accuracy of material-specific degradation kinetics could be significantly improved. These improvements would surpass the standardized technical service lives defined in (DVGW e.V. W 401, 1997). However, the present case study could not incorporate these parameters due to the absence of localized data from Stadtwerke Freudenstadt and public online sources.

Furthermore, future research should establish a dynamic correlation between structural failure risks and water quality parameters within highly meshed ring networks. Incorporating factors such as stagnation, volumetric water losses, unplanned supply interruptions, and physical pipeline rehabilitation transforms asset management from a conventional replacement strategy into a comprehensive approach to ensuring regional supply security. Integrating these water loss metrics into the multi-criteria risk matrix enables the implementation of the framework and allows for targeted economic analyses across asset categories. This approach addresses a critical operational paradox: High-volume bursts in transmission mains are promptly detected and repaired, but minor background leaks in localized service connections often have extensive runtimes and generate the highest cumulative water losses across the distribution grid (International Water Association, 2011). Incorporating these distinct runtime dynamics into the predictive model enables utilities to systematically reduce non-revenue water and avoid the high cost of purchasing additional water from ZVKK.

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Appendix

Appendix A: STANET Overview Map (Freudenstadt South)

Appendix B: Pairwise Comparison Matrices and Consistency Verification

The consistency check was performed using the mathematical eigenvalue methodology described in Section 2.3.2. This verification is based on calculations using Equations (2.2) and (2.3), which are used to determine the consistency index (CI) and the consistency ratio (CR) respectively. This section outlines the fundamental principles and definition of the random index (R_I) and the overall verification process. Table 4 explicitly documents the underlying criteria comparisons for the condition assessment parameters (Section 3.5.3), and Table 12 documents them for the damage extent parameters (Section 3.5.4). The calculated metrics and final evaluation for both key dimensions are summarized in Table B1.

TABLE B1: OVERVIEW OF THE CONSISTENCY CHECK FOR THE PAIRWISE COMPARISON MATRICES

Pairwise Comparison Matrix	Number of Criteria (n)	Largest Eigenvalue ($\lambda_{\max}$)	Consistency Index (CI)	Random Index (R_I)	Consistency Ratio (CR)	Evaluation
Condition Assessment	5	5,231	0,058	1,120	0,052	consistent ($\leq 0,10$)
Damage Extent	6	6,192	0,038	1,240	0,031	consistent ($\leq 0,10$)

The consistency ratio (CR) for both pairwise comparison matrices is well below the strict limit of 0,1. Therefore, the matrices successfully meet the mathematical consistency requirements of the Analytic Hierarchy Process (AHP).



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