

## Article

# Operational Failures and Cost Implications in Water Distribution Networks: A Multi-Year Utility-Based Assessment

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## Abstract

Water distribution networks are often assessed mainly through the number of recorded failures, although this indicator does not fully reflect the technical and economic burden imposed on utilities. This study proposes an Operational Failure-Cost Assessment (OFCA) method for transforming routine utility records into a cost-informed assessment of water network failures. The method was applied to an anonymized municipal water distribution network using failure records from 2015 to 2025, annual repair cost data from 2016 to 2024, and technical information on pipe type, material, and diameter structure. Failures were classified by pipe type, material, nominal diameter, and failure mechanism, while repair cost dynamics were evaluated using total annual repair expenditures and the average repair cost per recorded failure. During the common analysis period 2016–2024, the number of recorded failures decreased by 25.9%, whereas reported nominal annual repair costs increased by 77.9% and the average repair cost per recorded failure increased by approximately 140.3%. These results demonstrate that decreasing failure frequency does not necessarily imply decreasing repair cost pressure at the utility level. The proposed OFCA method provides a reproducible utility-level procedure that can be implemented even when event-level repair costs are not available. It supports maintenance planning, budgeting and prioritization of diagnostics, rehabilitation, and replacement activities.

**Keywords:** water distribution network; operational failures; repair costs; failure mechanisms; asset management; maintenance planning



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## 1. Introduction

Water distribution networks are one of the fundamental components of urban technical infrastructure. Their reliable operation is necessary to ensure continuity of water supply, maintain sanitary safety, and support the functioning of households, public services, commercial facilities, and industry [1–4]. Unlike many other infrastructure systems, water supply networks operate continuously and under variable hydraulic, environmental, and operational conditions [3–6]. Their deterioration is usually gradual, spatially uneven, and difficult to observe directly, which makes the management of such systems particularly demanding [5,6]. In practice, water utilities are responsible for networks composed of

pipes that differ in age, material, diameter, hydraulic function, and exposure to external and internal degradation processes [5,6].

Failures of pipes, fittings, and appurtenances are among the most visible symptoms of technical deterioration in water distribution systems [7,8]. They may cause temporary interruptions in water supply, local pressure drops, water losses, emergency repair works, excavation, surface restoration, traffic disruption, and consumer complaints [7,9]. From the perspective of a water utility, every failure is also associated with direct and indirect costs. These costs include labor, materials, equipment, transport, site restoration, and organizational activities required to manage the intervention [9–11]. For this reason, failures should not be interpreted only as technical incidents. They are also events with measurable economic, organizational, and asset management consequences [10–15].

In operational practice, the annual number of failures is often used as a basic indicator of network condition and operational reliability [2,7,8]. This indicator is simple, intuitive, and relatively easy to obtain from routine utility records. However, failure frequency alone does not provide a complete picture of the actual burden imposed on the operator [10,11,15,16]. A large number of minor failures in water connections may have a different technical and economic meaning than a small number of failures in large-diameter main pipes. Similarly, failures caused by corrosion in metallic pipes may require different maintenance and rehabilitation strategies than mechanical damage, cracking, or joint leakage in plastic pipes [5,6,9]. Therefore, an assessment based only on the number of failures may lead to simplified conclusions and may not provide sufficient support for maintenance planning, budgeting, or long-term asset management [1,10,16,17].

A more informative assessment requires the integration of failure records with repair cost data [10,11,16,17]. Such integration makes it possible to determine whether the operational trend expressed by the number of failures is consistent with the economic trend expressed by repair expenditures. This distinction is important because a reduction in the number of recorded failures does not necessarily mean a reduction in maintenance pressure. Fewer failures may still generate higher expenditure if the remaining events are more complex, affect more important pipes, require longer repair times, involve larger diameters, occur under difficult site conditions, or take place in a period of increasing labor, material, and equipment costs [10,11,17–20]. In this context, the average repair cost per failure becomes a useful indicator that complements failure frequency and provides additional information for utility decision-making [16–18].

Despite the practical relevance of this issue, water utility technical and financial data are often collected and stored separately [1,10,16]. Failure registers usually contain operational information such as date, location, pipe material, nominal diameter, and failure cause. Repair costs, however, are frequently recorded in accounting systems and aggregated at the annual level. This separation limits the possibility of assigning a precise repair cost to each individual failure event. Nevertheless, such data limitations do not eliminate the possibility of conducting a meaningful assessment. Even when event-level repair costs are unavailable, the combination of multi-year failure records with annual repair expenditures can reveal whether the technical and economic burden of network operation follows the same or divergent trajectories.

In response to this gap, the present study introduces the Operational Failure-Cost Assessment (OFCA) method as a practical procedure for linking routinely collected failure records with reported annual repair expenditures. The method is not intended to replace advanced predictive failure models or life-cycle cost optimization tools. Instead, it addresses a more basic but common situation in utility practice, where technical failure registers and financial records exist but are not integrated at the level of individual events. In its basic application, the OFCA can be implemented when a utility has access to failure records,

pipe type or nominal diameter, pipe material, failure cause, annual failure counts, and total annual repair costs. Additional information, such as repair duration, water-supply interruption time, construction year, or network length by material and diameter, may improve interpretation but is not required for the basic version of the method.

Existing approaches to water distribution network management include failure prediction and deterioration models, rehabilitation strategies, whole-life costing, replacement scheduling, cost-benefit assessment, and risk-based renewal methods [1,5,6,9,10,16,17,21]. These approaches are valuable for detailed asset management, but they commonly require technical, spatial, hydraulic, or event-level economic data that may not be consistently available in routine utility records. The OFCA method is positioned differently. It does not estimate the probability of failure for individual assets, calculate the consequence of a specific failure event, or optimize replacement schedules. Instead, it provides a preliminary diagnostic layer for utilities that have annual failure records and reported annual repair expenditures, but do not maintain integrated event-level cost databases. In this sense, OFCA complements existing predictive and optimization approaches by identifying whether operational and repair cost trends diverge and where more detailed asset management analysis may be justified.

The contribution of the proposed OFCA method lies in formalizing a minimum-data, utility-level procedure for interpreting water network failures from both operational and repair cost perspectives. Existing asset management, pipe failure prediction, and rehabilitation planning approaches often rely on detailed technical, spatial, or event-level economic data, which may not be consistently available in routine utility records [16–22]. OFCA therefore provides an intermediate step between descriptive failure statistics and advanced asset management models, enabling utilities to move from simple failure counting towards a cost-informed interpretation of network performance while remaining applicable to incomplete or fragmented operational datasets.

The aim of this study is to apply the OFCA method to an anonymized municipal water distribution network and to evaluate whether failure frequency and reported repair cost indicators follow consistent or divergent trends. The analysis combines multi-year failure records from 2015 to 2025, common failure and repair cost data from 2016 to 2024, and technical classification by pipe type, material, nominal diameter, and failure mechanism. The study also demonstrates how the OFCA method can support maintenance budgeting, diagnostic planning, and preliminary screening of rehabilitation or replacement needs.

The methodological value of OFCA lies not in proposing a complex predictive model, but in defining a minimum-data procedure that can be applied when technical and financial records are not integrated at the event level. This reflects the real data structure of many utilities and provides an operationally feasible bridge between descriptive failure statistics and advanced asset management models.

The main contribution of the paper is to show that failure frequency and reported repair cost pressure may evolve in different directions. A decreasing number of recorded failures does not necessarily indicate decreasing repair expenditures or lower maintenance pressure. By linking operational failure records with annual repair cost indicators, the study provides a practical basis for greater cost-informed management of water distribution infrastructure.

## 2. Materials and Methods

### 2.1. Study Design and OFCA Method

The study was designed as a multi-year utility-level assessment of failure occurrence and repair cost dynamics in a municipal water distribution network. The proposed Operational Failure-Cost Assessment (OFCA) method integrates two complementary per-

spectives: a technical assessment of recorded failures and an interpretation of reported annual repair expenditures. In routine utility practice, failures are often evaluated mainly through the number of recorded events. Although this measure is useful, it does not fully represent maintenance pressure when repair expenditures follow a different trajectory from failure frequency.

The OFCA approach was developed as an operational-cost assessment procedure that can be applied by water utilities using data commonly available in operational and financial records. Its basic version does not require advanced predictive modeling [23–30] or repair costs assigned to each individual failure. Instead, it uses annual failure counts, failure classification criteria, and reported annual repair expenditures to determine whether the operational trend expressed by failure frequency is consistent with the repair cost trend expressed by annual costs and average repair cost per recorded failure.

The OFCA method was structured into seven consecutive analytical steps, from data collection to maintenance-oriented interpretation. To improve transparency and reproducibility, each step was defined in terms of its analytical stage, main input data, main output, and methodological role. The detailed methodological structure of the OFCA procedure is summarized in Table 1.

**Table 1.** Analytical steps of the OFCA method.

| Step | Analytical Stage                    | Main Input Data                                                                                         | Main Output                                                                                    | Methodological Role                                                                                                  |
|------|-------------------------------------|---------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------|
| 1    | Data collection and preparation     | Failure records; annual or monthly failure summaries; annual repair cost data; basic network inventory. | Defined source dataset and analysis periods.                                                   | Establishes the minimum dataset and temporal scope of the assessment.                                                |
| 2    | Anonymization and harmonization     | Original operational and financial records.                                                             | Harmonized analytical database.                                                                | Removes or protects identifiers and standardizes material names, pipe descriptions, diameters, and failure causes.   |
| 3    | Technical characterization          | Pipe function, material, nominal diameter, and, where available, pipe length.                           | Technical structure of the analyzed network.                                                   | Provides the background for interpreting failure patterns in relation to the network structure.                      |
| 4    | Failure classification              | Harmonized failure records.                                                                             | Failure counts and shares by pipe type, material group, diameter class, and failure mechanism. | Identifies dominant technical categories beyond total failure counts.                                                |
| 5    | Temporal failure analysis           | Annual, and, where available, monthly failure counts.                                                   | Annual failure trends and possible seasonal patterns.                                          | Provides the operational baseline for comparison with repair cost indicators.                                        |
| 6    | Repair cost indicator calculation   | Annual failure counts and reported annual repair expenditures.                                          | Total repair cost trends; ARCF; relative changes; indexed values.                              | ARCF is an annual aggregate indicator and not the cost of an individual failure event.                               |
| 7    | Maintenance-oriented interpretation | Failure trends, repair cost indicators, and technical classification results.                           | Identification of consistent or divergent operational and repair cost trends.                  | Supports budgeting, diagnostic planning, and preliminary prioritization of rehabilitation or replacement activities. |

In this study, OFCA was applied in its basic form, reflecting the structure and limitations of the available utility dataset. The analysis was therefore based on annual failure counts, technical failure classification, reported annual repair expenditures, and the average repair cost per recorded failure. Because repair costs were not assigned to individual failure events, the method was not used to estimate repair costs for specific materials, diameter classes, pipe sections, or failure mechanisms. Similarly, length-normalized failure and cost indicators were treated as possible extensions rather than as part of the core assessment presented in this paper.

## 2.2. Data Requirements and Source Categories

The data requirements of the OFCA method can be divided into three levels: minimum data required for the basic assessment, recommended data improving technical interpretation, and extended data enabling more advanced asset management applications. This distinction is important because not all utilities maintain the same level of detail in their operational and financial records. The basic OFCA requires only those variables that are necessary to compare annual failure occurrence with reported annual repair expenditures. Additional technical, spatial, and cost-component data improve interpretation but are not required for the basic utility-level analysis. Table 2 shows the data types and data requirements for the OFCA method.

**Table 2.** Minimum, recommended, and extended data requirements for the OFCA method.

| Data Level                         | Required or Recommended Information                                                                                                                                | Role in OFCA                                                                                                                  | Analytical Implication                                                                                        |
|------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------|
| Minimum dataset                    | Failure year or failure date; annual number of failures; pipe type or nominal diameter; pipe material; failure cause or description; total annual repair cost.     | Enables annual failure trends, basic technical classification, and calculation of average repair cost per recorded failure.   | Sufficient for the basic OFCA using annual aggregated repair costs.                                           |
| Recommended technical data         | Month of failure; repair duration; water-supply interruption time; construction year of pipe sections; pipe length by material, nominal diameter or pipe function. | Improves interpretation of temporal patterns, operational consequences, aging effects, and exposure of different pipe groups. | Enables more robust technical discussion and, where pipe lengths are available, length-normalized indicators. |
| Extended economic and spatial data | Internal spatial identifiers; labor costs; material costs; equipment and transport costs; surface restoration costs; administrative and other site-related costs.  | Enables more detailed cost allocation, spatial diagnostics, and rehabilitation prioritization.                                | Required for event-level cost analysis, cost modeling, and advanced asset management applications.            |

For the purposes of OFCA, the source data were organized into operational failure records, annual or monthly failure summaries, annual repair cost data, and technical inventory data. The method distinguishes between the failure observation period, denoted as  $T_f$ , and the repair-cost analysis period, denoted as  $T_c$ . These periods do not have to be identical, because utilities may maintain longer failure registers than financial datasets suitable for repair cost analysis. The base year,  $y_0$ , should be selected as the first year within  $T_c$  for which both failure and repair cost data are complete and internally consistent.

### 2.3. Data Confidentiality, Anonymization, and Aggregation

Before applying the OFCA method, the source data should be reviewed not only for completeness and consistency, but also for confidentiality and the risk of re-identification. This is particularly important when real utility records include exact failure locations, street names, pipe-section identifiers, internal asset codes, or cost information that may be commercially or operationally sensitive. In the present method, detailed spatial and asset-level identifiers may be retained for internal utility analyses, but scientific reporting should be based on anonymized and aggregated datasets. The level of aggregation should be selected so that the technical interpretation of failure and repair cost patterns is preserved, while the identity of the utility, specific network sections, and sensitive operational information remain protected. The adopted data scope and anonymization rules are summarized in Table 3.

**Table 3.** Data scope and anonymization rules in the OFCA method.

| Element                            | Methodological Rule                                                                                                                      |
|------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------|
| Failure observation period, $T_f$  | Defined as the period in which failure records are complete and comparable.                                                              |
| Repair-cost analysis period, $T_c$ | Defined as the period in which annual repair cost data are complete and comparable.                                                      |
| Data overlap                       | Cost indicators are calculated only for years with both failure and repair cost data.                                                    |
| Internal utility use               | Spatial identifiers may be retained for operational diagnostics and asset management.                                                    |
| Scientific or public reporting     | Street names, exact failure locations, network section identifiers, and utility-identifying information should be removed or aggregated. |
| Reporting level                    | Results should be presented in aggregated form by year, month, pipe type, material group, diameter class, or failure mechanism.          |

The purpose of anonymization is not to remove the technical value of the dataset, but to separate operationally useful attributes from sensitive location-specific information. This ensures that the OFCA method can be implemented using real utility records while maintaining confidentiality and allowing comparison of failure and cost patterns at an aggregated level.

### 2.4. Network Classification and Technical Data Harmonization

The OFCA method requires the analyzed network to be classified into technical categories that are relevant for interpreting failure occurrence and structure. The basic technical classification includes pipe function, pipe material, and nominal diameter. In the present application, these categories were used primarily to contextualize failure patterns, because repair costs were available only as aggregated annual expenditures and could not be assigned to individual pipe groups.

Pipe function may be assigned using the utility's own classification or, if such classification is not available, on the basis of nominal diameter. In this study, pipe function was assigned according to the diameter-based classification presented in Table 4. The same classification was used consistently for network characterization and for the interpretation of failures by pipe type.

**Table 4.** Diameter-based pipe function classification used in the case study application of the OFCA method.

| Pipe Function      | Diameter Range | Interpretation                                                               |
|--------------------|----------------|------------------------------------------------------------------------------|
| Water connections  | DN 20–DN 63    | Local connection pipes supplying individual consumers or buildings.          |
| Distribution pipes | DN 65–DN 200   | Pipes forming the main distribution structure within supply zones.           |
| Main pipes         | DN 250–DN 1200 | Large-diameter pipes with a transmission or strategic distribution function. |

Pipe materials and nominal diameters were harmonized before analysis to ensure consistency between records and years. Material descriptions recorded under different spelling variants, abbreviations, or combined labels were assigned to common material groups. In this study, the harmonized material groups included cast iron, steel, galvanized steel, PE, PVC, asbestos cement, ductile cast iron, mixed materials, and unknown materials. If more than one material was recorded for a pipe or failure event, the dominant material was assigned only when it could be identified unambiguously; otherwise, the record was classified as mixed or unknown.

Nominal diameter was retained whenever available and was used either as a numerical variable or as a standardized diameter class. Records with missing or unclear diameter information were not forced into predefined classes and were excluded only from analyses requiring diameter-specific information. This conservative harmonization procedure reduces the risk of overinterpretation and keeps uncertain records visible in the dataset.

The technical classification described above provides a consistent basis for the subsequent analysis of failure occurrence, failure mechanisms, and repair cost dynamics. It also ensures that the OFCA method can be transferred to other utilities, provided that the adopted classification thresholds and material harmonization rules are clearly documented.

### 2.5. Failure Database Preparation and Harmonization

Each failure included in the analytical database was defined as a distinct operational event requiring corrective intervention on a pipe, fitting, or appurtenance. Before analysis, the source records were reviewed to verify whether individual entries represented separate failures or duplicate descriptions of the same event. Where several entries referred to the same location, date, and failure description, they were treated conservatively to avoid double counting. The preparation of the failure database included three main operations. First, the original records were reviewed, and each failure event was assigned to a unique analytical record. Second, technical attributes such as pipe type, material, and nominal diameter were standardized. Third, descriptive information regarding the cause of failure was transformed into harmonized failure mechanism categories.

For each failure event, the analytical database included, where available, the year and month of occurrence or removal, pipe type, pipe material, nominal diameter, diameter class, original failure description, harmonized failure mechanism, repair duration, and water-supply interruption time. Location-specific information was excluded from the manuscript or retained only in the internal utility database, according to the anonymization rules described in Section 2.3.

The use of a structured analytical database ensures that failure records collected over several years can be compared consistently. It also allows the same dataset to be analyzed at different levels of detail, including annual trends, monthly patterns, pipe type, material, diameter class, and failure mechanism.

If some variables are missing, the corresponding records should not be automatically removed from the dataset. In the OFCA method, incomplete records may still be used for those parts of the analysis for which the required information is available. For example, a record without a clear failure mechanism may still be used in the annual failure count, while a record without a nominal diameter may be excluded only from the diameter-based analysis. This approach preserves as much operational information as possible and avoids unnecessary reduction in the dataset. This variable-specific inclusion rule was used to reduce complete-case deletion bias and to ensure that each analysis was based only on records containing the information required for that specific classification.

Unclear or ambiguous records should be classified conservatively. If the material, diameter, or failure mechanism cannot be reliably identified, the record should be assigned to an 'unknown', 'mixed', or 'unclear' category. This approach is preferable to forced classification because it preserves as much operational information as possible while making data-quality limitations visible in the final assessment.

## 2.6. Failure Classification and Temporal Analysis

Failures were classified according to pipe type, material, nominal diameter, and failure mechanism. These criteria were selected because they are commonly available in utility records and directly relevant to operational interpretation. The classification makes it possible to move beyond the total number of failures and to identify which parts of the network, which materials, and which mechanisms dominate the failure structure.

Pipe type was used to distinguish failures occurring in different functional parts of the network. Water connections, distribution pipes, and main pipes differ in hydraulic function, operational importance, and potential consequences of failure. Failures of water connections may dominate numerically, whereas failures of main pipes may be less frequent but more important for system operation.

Failures were also classified by material. This classification is important because different materials are associated with different degradation processes. Metallic pipes may be more strongly related to corrosion and joint deterioration, while plastic pipes may be associated with leakage at connections, cracking, or mechanical damage. Material categories were harmonized according to the rules described in Section 2.4.

Nominal diameters were used both to assign pipe function and to support the interpretation of failures by pipe size. In the basic OFCA, the diameter-based pipe function classification may be sufficient. If a more detailed analysis is required, the operator may introduce additional diameter classes, provided that the adopted thresholds are stated explicitly and applied consistently across the dataset.

Failure mechanisms were derived from original cause descriptions. The adopted mechanism categories included corrosion, leakage or loss of tightness, leaking joint or socket, fracture, cracking, mechanical damage, fittings or appurtenance-related failure, and other or unclear causes. Records referring to corrosion were assigned to the corrosion category. Records describing loss of tightness were assigned to leakage or loss of tightness. Records referring to leaking joints or sockets were classified as joint-related failures. Fracture and cracking were treated separately because they may indicate different physical failure processes. Ambiguous descriptions were classified conservatively.

For each classification dimension, including pipe type, material group, diameter class, and failure mechanism, the number of recorded failures and their percentage share were calculated. The denominator used for each analysis corresponded to the number of records with valid information for the given classification dimension, including records assigned to

“unknown”, “mixed”, or “unclear” categories where applicable. The percentage share of failures in category  $i$  was calculated according to Equation (1):

$$S_i = \frac{N_i}{N_{total}} \cdot 100\%, \quad (1)$$

where

$S_i$  is the share of failures in category  $i$ , expressed as a percentage;

$N_i$  is the number of failures in category  $i$ ;

$N_{total}$  is the total number of failures in the analyzed dataset;

$i$  denotes the analyzed category, such as pipe type, material, diameter class, or failure mechanism.

The resulting shares describe the structure of recorded failures in the analyzed dataset. They should not be interpreted as length-normalized failure intensities or as category-specific repair-cost contributions. In particular, a high share of failures in a given material, diameter class, or pipe function may reflect the exposure of that category in the network rather than a higher failure rate per kilometer. Similarly, because repair costs were available only as aggregated annual expenditures, the categorical failure structure was used to contextualize repair cost trends, not to allocate costs to specific materials, diameters or failure mechanisms.

The same calculation principle was applied to all categorical failure analyses. This ensured that failure structures obtained for different technical categories were comparable and could be interpreted jointly with repair cost indicators.

Temporal failure analysis was conducted after the classification stage. The annual number of failures was calculated for each year within the failure observation period, while monthly data were used, when available, to identify potential seasonal patterns. The annual failure count was treated as the basic operational indicator in the OFCA method, but it was not interpreted in isolation. It was used as the reference variable for comparison with total annual repair costs and the average repair cost per failure. The percentage share of failures in each month or year was calculated using the same formula as for other categorical analyses.

## 2.7. Cost Indicators and Trend Analysis

Cost analysis is performed for the period in which annual failure counts and annual repair costs are both available. This period is denoted as  $T_c$ . The base year is denoted as  $y_0$  and should be selected as the first year in  $T_c$  for which both failure and cost data are complete and internally consistent. This rule ensures that all relative changes and indexed values are calculated from a comparable starting point.

For each year  $y$  within  $T_c$ , two input variables are required: the number of recorded failures and the total annual repair cost. In the case study application, repair costs were recorded by the utility in Polish złoty (PLN). To improve international readability, the corresponding values were additionally expressed in euros (EUR). The EUR values were calculated using the official average EUR/PLN exchange rate published by the National Bank of Poland for the reference year adopted for currency conversion. For comparative purposes, PLN values were converted into EUR using a fixed reference exchange rate for 2024. This conversion was used only to improve international readability and did not affect the indexed trend analysis (1 EUR = 4.2730 PLN).

The number of failures in year  $y$  is denoted as  $N_y$ , while the total annual repair cost in year  $y$  is denoted as  $TC_y$ . On this basis, the average repair cost per failure, relative changes, and indexed values are calculated. The cost and trend indicators used in the OFCA method are summarized in Table 5.

**Table 5.** Cost and trend indicators used in the OFCA method.

| Indicator                                          | Equation                                                           | Interpretation                                                                      |
|----------------------------------------------------|--------------------------------------------------------------------|-------------------------------------------------------------------------------------|
| Average repair cost per failure                    | $ARCF_y = \frac{TC_y}{N_y}$                                        | Average annual repair cost assigned to one recorded failure in year y.              |
| Relative change in failure count                   | $\Delta N_y = \frac{N_y - N_{y0}}{N_{y0}} \cdot 100\%$             | Percentage change in the number of failures relative to the base year.              |
| Relative change in total repair cost               | $\Delta TC_y = \frac{TC_y - TC_{y0}}{TC_{y0}} \cdot 100\%$         | Percentage change in total annual repair cost relative to the base year.            |
| Relative change in average repair cost per failure | $\Delta ARCF_y = \frac{ARCF_y - ARCF_{y0}}{ARCF_{y0}} \cdot 100\%$ | Percentage change in the average repair cost per failure relative to the base year. |
| Failure number index                               | $I^{N_y} = \frac{N_y}{N_{y0}} \cdot 100$                           | Indexed number of failures, with the base year equal to 100.                        |
| Total repair cost index                            | $I^{TC_y} = \frac{TC_y}{TC_{y0}} \cdot 100$                        | Indexed total annual repair cost, with the base year equal to 100.                  |
| Average repair cost per failure index              | $I^{ARCF_y} = \frac{ARCF_y}{ARCF_{y0}} \cdot 100$                  | Indexed average repair cost per failure, with the base year equal to 100.           |

In addition to nominal repair cost indicators, an inflation-adjusted sensitivity analysis was performed. Reported annual repair costs were converted into constant 2024 PLN using annual consumer price inflation data for Poland from the World Bank World Development Indicators database, based on International Monetary Fund International Financial Statistics. The analysis was used to assess whether the observed increase in repair cost indicators was driven only by general price inflation or whether the divergence between failure frequency and repair cost pressure remained visible after price-level correction.

In Table 5,  $y$  denotes an analyzed year within TC, while  $y_0$  denotes the base year.  $N_y$  is the number of recorded failures in year  $y$ ,  $TC_y$  is the total annual repair cost in year  $y$ , and  $ARCF_y$  is the average repair cost per recorded failure in year  $y$ . The corresponding values for the base year are denoted as  $N_{y0}$ ,  $TC_{y0}$ , and  $ARCF_{y0}$ .

The  $ARCF_y$  indicator should not be interpreted as the cost of a specific individual failure. It is an annual average calculated from aggregated cost data. Its purpose is to describe how the average economic burden associated with one recorded failure changes over time.

The relative change indicators show whether failure frequency, total repair cost, and average repair cost per failure increased or decreased compared with the base year. Positive values indicate an increase, while negative values indicate a decrease. Indexed values make it possible to compare variables expressed in different units on a common scale, because the base year is assigned a value of 100 for all three indicators.

The interpretation of OFCA results is based on the joint assessment of annual failure frequency, reported total repair costs, and the average repair cost per recorded failure. The most relevant diagnostic situation occurs when the number of recorded failures decreases while total repair expenditures or  $ARCF_y$  increase. Such divergence indicates that failure frequency alone does not adequately represent the repair cost pressure associated with network operation. However, when costs are analyzed in nominal terms, the observed increase in repair expenditures should be interpreted as the combined effect of repair complexity, changes in the structure of failures, site conditions, and market-related price changes, including labor, materials, equipment, and surface restoration costs.

### 3. Results

#### 3.1. Scope of the Case Study and Characteristics of the Analyzed Network

The proposed OFCA method was applied to an anonymized municipal water distribution network. In the analyzed case study, the failure observation period,  $T_f$ , covered the years 2015–2025, while the repair cost analysis period,  $T_c$ , covered the years 2016–2024. The year 2016 was adopted as the base year  $y_0$  for the cost trend analysis, because it was the first year for which both the annual number of failures and total annual repair costs were available in a complete and comparable form. Data from 2026 were not included in the analysis because they represented an incomplete year of observation.

The analyzed network was first characterized according to the technical classification rules defined in the OFCA method. Consequently, 2015 was used only for the technical failure occurrence analysis, while all repair cost indicators were calculated for 2016–2024. Figure 1 presents the location of research object. Location-specific information was removed to preserve the confidentiality of the data provider. The figure is intended to illustrate the general network layout only and does not represent a scale-based spatial analysis.



**Figure 1.** Anonymized schematic representation of the analyzed municipal water distribution network used as the research object in the OFCA application.

The total length of the network, including water connections, was 1053.152 km. The largest part of the system was represented by distribution pipes, with a length of 558.910 km, corresponding to 53.07% of the total network length. Water connections accounted for 346.730 km, representing 32.92% of the system. Main pipes accounted for 129.420 km, corresponding to 12.29% of the total length. Ambiguous or mixed sections represented

10.082 km, while sections without a clearly defined nominal diameter represented 8.009 km. These two categories together accounted for less than 2% of the total network length, and therefore did not substantially affect the interpretation of the general network structure. Table 6 presents the functional structure of the analyzed network according to the adopted diameter-based classification.

**Table 6.** Functional structure of the analyzed water distribution network.

| Pipe Function               | Diameter Range         | Length [km] | Share [%] |
|-----------------------------|------------------------|-------------|-----------|
| Water connections           | DN 20–DN 63            | 346.730     | 32.92     |
| Distribution pipes          | DN 65–DN 200           | 558.910     | 53.07     |
| Main pipes                  | DN 250–DN 1200         | 129.420     | 12.29     |
| Ambiguous or mixed sections | Not clearly assignable | 10.082      | 0.96      |
| Sections without defined DN | Missing DN information | 8.009       | 0.76      |
| Total                       | -                      | 1053.152    | 100.00    |

The material structure of the analyzed network was also heterogeneous. PE pipes represented the largest share of the system, with a total length of 503.445 km. Steel pipes accounted for 217.929 km, while PVC pipes represented 197.379 km. Cast iron pipes accounted for 118.155 km. Other materials, ductile cast iron, and asbestos cement occurred in considerably smaller shares. The coexistence of older metallic pipes and more recent plastic materials is important for the interpretation of failure mechanisms, because different material groups are associated with different degradation processes and repair conditions.

The network structure shows that the analyzed system is dominated by distribution pipes and water connections, which together represent more than 85% of the total length. At the same time, the system contains a substantial share of steel and cast iron pipes, which are particularly relevant from the perspective of corrosion-related failures and long-term rehabilitation planning. The technical heterogeneity of the network provides a suitable basis for applying the OFCA method, because it allows failure occurrence and repair cost dynamics to be interpreted in relation to pipe function, material, and diameter.

### 3.2. Failure Occurrence in the Water Network

In the analyzed case study, 2015–2025 was used as the failure observation period, Tf. The annual number of recorded failures is presented in Figure 2.

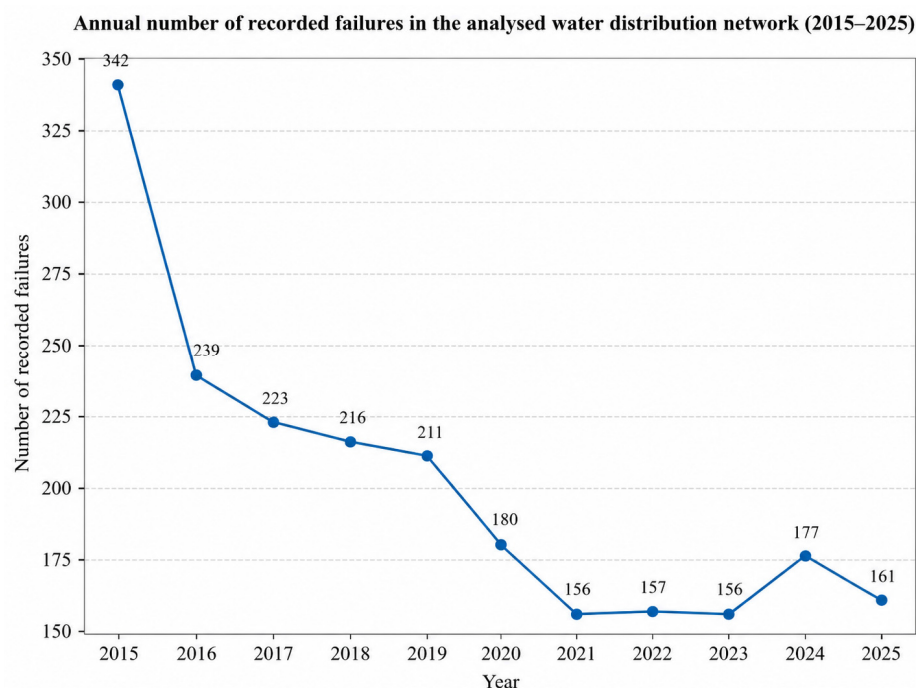
The annual number of failures decreased substantially over the period analyzed. The highest number of recorded failures occurred in 2015, when 342 failures were registered. From 2016 onwards, the annual number of failures remained below 240 events. The lowest values were recorded in 2021 and 2023, with 156 failures in each year. A moderate increase was observed in 2024, when the number of failures rose to 177, followed by a decrease to 161 failures in 2025.

Between 2015 and 2025, the number of recorded failures decreased from 342 to 161, corresponding to a reduction of 52.9%. This result indicates a substantial descriptive decline in recorded failure occurrence over the observation period. However, the annual pattern was not strictly monotonic, and 2015 should be interpreted as part of the broader failure observation period rather than as the base year for cost assessment. For this reason, the subsequent cost-related analysis was based on the common period 2016–2024.

The observed reduction in recorded failures should be interpreted descriptively rather than as evidence of a single identified intervention. The available dataset did not include a complete year-by-year record of rehabilitation works, operational changes, or changes in failure reporting practice. Therefore, the decrease in failures may reflect a combination

of network renewal, operational improvements, changes in exposed assets, climatic or hydraulic variability, and reporting practices.

For the cost-related part of the OFCA, the common period with both failure and repair cost data covered 2016–2024. Within this period, the number of failures decreased from 239 in 2016 to 177 in 2024, corresponding to a reduction of 25.9%. This operational trend provides the reference background for the subsequent comparison with total repair expenditures and the average repair cost per failure.



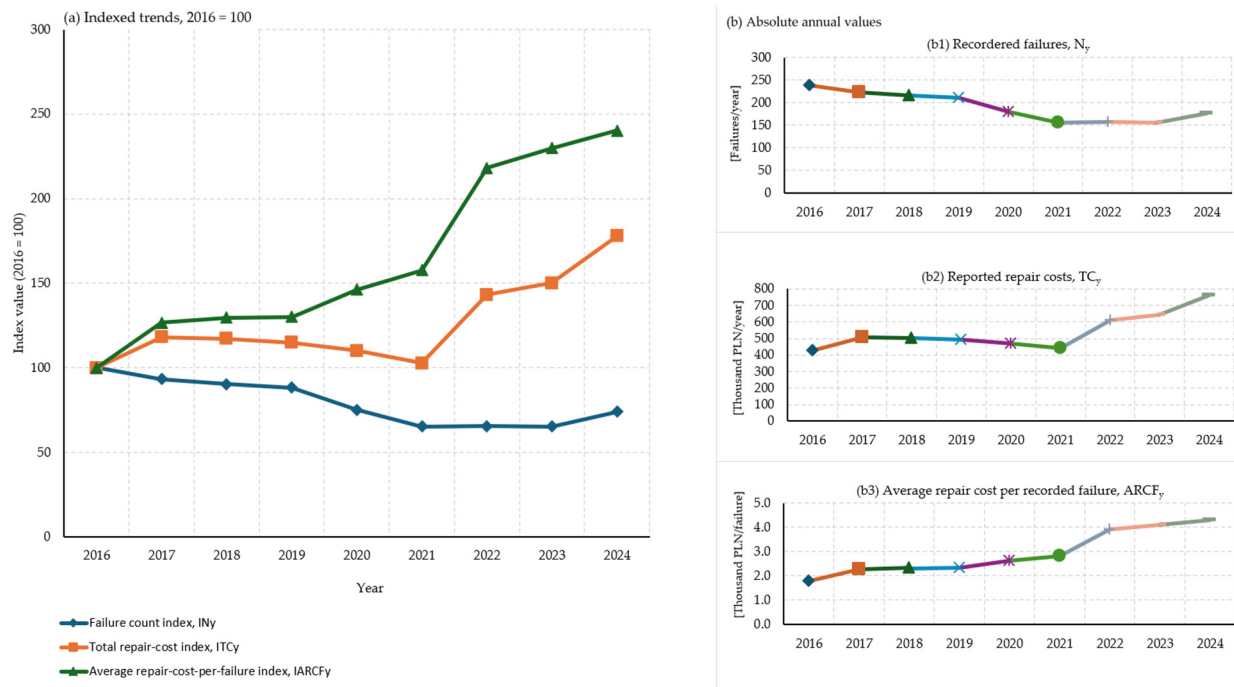
**Figure 2.** Number of recorded failures in the analyzed water distribution network, 2015–2025.

### 3.3. Repair Cost Dynamics and Average Repair Cost per Failure

The next stage of the OFCA involved linking annual failure counts with annual repair expenditures. In the analyzed case study, the repair cost analysis period,  $T_c$ , covered the years 2016–2024. This period was selected because, for these years, both the annual number of recorded failures and the total annual repair costs were available in a complete and comparable form. The year 2016 was adopted as the base year  $y_0$  for the indexed trend analysis.

The base year was selected on the basis of data completeness and comparability. The year 2016 was the first year in the common analysis period for which both the annual number of recorded failures and total annual repair costs were available in a complete and internally consistent form. It was not selected because it represented an extreme or particularly favorable year, but because it provided the first reliable common reference point for indexed comparison. According to the source data, 239 failures were recorded in 2016, and the total annual repair cost amounted to 428,000 PLN. The base-year average repair cost per failure was therefore 1790.80 PLN/failure. Consequently, the reference values used for the indexed analysis were  $N_{y_0} = 239$  failures,  $TC_{y_0} = 428,000$  PLN/year, and  $ARCF_{y_0} = 1790.80$  PLN/failure. All indexed values were calculated relative to these base-year values, with 2016 equal to 100.

Therefore, the notation “2016 = 100” used in Figure 3 indicates the base year of the indexed comparison and does not refer to an absolute value.



**Figure 3.** Comparison of operational and repair cost trends in the analyzed water distribution network, 2016–2024: (a) indexed trends in recorded failure occurrence, reported nominal annual repair costs, and average repair cost per recorded failure, with 2016 = 100; (b) corresponding absolute annual values of recorded failures, total annual repair costs, and average repair cost per recorded failure. Absolute values are also reported in Table 7.

**Table 7.** Annual failure occurrence and repair cost indicators for the analyzed water distribution network, 2016–2024.

| Year | $N_y$<br>[Failures/Year] | $TC_y$<br>[PLN/Year] | $TC_y$<br>[EUR/Year] | $ARCF_y$<br>[PLN/Failure] | $ARCF_y$<br>[EUR/Failure] | $I^{N_y}$ | $I^{TC_y}$ | $I^{ARCF_y}$ |
|------|--------------------------|----------------------|----------------------|---------------------------|---------------------------|-----------|------------|--------------|
| 2016 | 239                      | 428,000              | 100,164              | 1790.80                   | 419.10                    | 100.0     | 100.0      | 100.0        |
| 2017 | 223                      | 506,000              | 118,418              | 2269.06                   | 531.08                    | 93.3      | 118.2      | 126.7        |
| 2018 | 216                      | 501,800              | 117,435              | 2323.15                   | 543.70                    | 90.4      | 117.2      | 129.7        |
| 2019 | 211                      | 491,800              | 115,095              | 2330.81                   | 545.46                    | 88.3      | 114.9      | 130.2        |
| 2020 | 180                      | 471,200              | 110,274              | 2617.78                   | 612.64                    | 75.3      | 110.1      | 146.2        |
| 2021 | 156                      | 440,300              | 103,044              | 2822.44                   | 660.67                    | 65.3      | 102.9      | 157.6        |
| 2022 | 157                      | 613,200              | 143,552              | 3905.73                   | 913.95                    | 65.7      | 143.3      | 218.1        |
| 2023 | 156                      | 642,200              | 150,340              | 4116.67                   | 963.44                    | 65.3      | 150.0      | 229.9        |
| 2024 | 177                      | 761,540              | 178,223              | 4302.49                   | 1006.43                   | 74.1      | 177.9      | 240.3        |

Notes: Repair costs were originally recorded in PLN. EUR equivalents are provided for international readability and were calculated using a fixed reference exchange rate of 1 EUR = 4.2730 PLN. All primary calculations and indexed trends in this table are based on the original nominal PLN values. Annual repair costs were analyzed according to the accounting year in which they were reported by the utility and should therefore be interpreted as annual financial aggregates rather than event-matched costs assigned to individual failures recorded in the same calendar year. The influence of general price-level changes was assessed separately through the inflation-adjusted sensitivity analysis reported below.

Table 7 presents the annual number of failures, total annual repair cost, average repair cost per recorded failure, and indexed values calculated according to the OFCA method. The variables  $N_y$  and  $TC_y$  were taken directly from the source data provided by the utility, whereas  $ARCF_y$  and the indexed indicators were calculated as part of the analysis.

The results show a clear divergence between the operational and economic trends. Between 2016 and 2024, the number of recorded failures decreased from 239 to 177, corresponding to a reduction of 25.9%. Over the same period, total annual repair costs increased from 428,000 PLN, approximately 100,164 EUR, to 761,540 PLN, approximately 178,223 EUR, representing an increase of 77.9%. The average repair cost per recorded failure increased from 1790.80 PLN/failure, approximately 419.10 EUR/failure, in 2016 to 4302.49 PLN/failure, approximately 1006.43 EUR/failure, in 2024, corresponding to an increase of approximately 140.3%.

To account for general price-level changes, the reported annual repair costs were additionally recalculated in constant 2024 PLN. After inflation adjustment, the total annual repair cost increased from approximately 651,000 PLN in 2016 to 761,540 PLN in 2024, corresponding to an increase of about 17%. Over the same period, the inflation-adjusted average repair cost per recorded failure increased from approximately 2724 PLN/failure to 4302 PLN/failure, corresponding to an increase of about 58%. This indicates that general price inflation explained a substantial part of the nominal increase in repair expenditures, but did not fully eliminate the divergence between decreasing failure frequency and increasing repair cost pressure.

This divergence represents the key result of the OFCA application. The decrease in the number of recorded failures did not translate into a decrease in reported annual repair expenditure. By 2024, the failure count index had decreased to 74.1, whereas the total repair cost index had increased to 177.9 and the average repair-cost-per-failure index had increased to 240.3. This means that, compared with the 2016 base year, the number of recorded failures was lower, while reported nominal repair expenditures were almost 1.8 times higher and the annual aggregate repair cost per recorded failure was approximately 2.4 times higher. These results should be interpreted as evidence of increasing repair cost pressure at the utility level, not as event-level repair cost estimates.

The most pronounced increase in repair cost indicators occurred after 2021. In 2021, the total repair cost index was still close to the base-year level, while the average repair-cost-per-failure index had already increased to 157.6. In 2022, both cost indicators increased sharply, although the number of failures remained almost unchanged compared with 2021. This indicates that reported repair cost pressure became increasingly important in the overall assessment of network operation.

The results demonstrate the practical value of the OFCA method. If the assessment were based only on the number of failures, the analyzed network could be interpreted as showing improved or stabilized operational performance. However, the simultaneous increase in total repair expenditures and average repair cost per failure indicates growing economic pressure. This confirms the need to combine failure records with repair cost indicators when evaluating water distribution network performance and planning maintenance, rehabilitation, or replacement activities.

### 3.4. Technical Context of Recorded Failures

The technical classification of recorded failures provided additional context for the interpretation of the OFCA results. The classification was performed for 1715 recorded failures from the common failure and cost analysis period (2016–2024). In the analyzed failure dataset, metallic pipes dominated the recorded events. Cast iron, galvanized steel, and steel together accounted for 73.6% of classified failures. This indicates that a substantial part of the failure records was associated with pipe materials that may be affected by corrosion, aging, and joint deterioration.

Failure mechanisms were concentrated in a limited number of categories. Corrosion-related failures accounted for 46.5% of classified events, while leakage or loss of tightness

accounted for 40.0%. Together, these two categories represented 86.5% of the classified failure records. This pattern suggests that material degradation and loss of tightness were the dominant recorded failure mechanisms in the analyzed dataset. However, this interpretation should be understood as a classification of reported failure descriptions rather than as a direct physical diagnosis of each failure event.

Failures were mainly concentrated in smaller diameter classes.  $DN \leq 50$  accounted for 38.7% of failures, while  $DN 51\text{--}100$  accounted for 28.6%. Together, pipes up to  $DN 100$  represented 67.3% of recorded failures. Failures in pipes with  $DN > 400$  were rare and represented only 1.0% of events. However, such failures may have higher operational relevance because large-diameter pipes often perform transmission or strategic distribution functions.

These results should be interpreted as failure counts and shares, not as length-normalized failure intensities. Therefore, they do not directly indicate which material or diameter class has the highest failure rate per kilometer. They also do not indicate category-specific repair-cost contributions, because repair costs were available only as aggregated annual expenditures. Nevertheless, the results provide important technical background for the OFCA by showing which material groups, failure mechanisms, and diameter classes dominated the recorded failure structure. Table 8 presents the technical structure of recorded failures in the common failure-cost analysis period 2016–2024. The classification dimensions are presented separately for material group, failure mechanism, and diameter class. They were not cross-classified by pipe function, because the objective of the basic OFCA application was to provide a utility-level diagnostic assessment rather than an exposure-normalized asset-group model.

**Table 8.** Technical structure of recorded failures in the common analysis period 2016–2024.

| Classification/Dimension | Category                     | N<br>[Number] | Share [%] | Methodological Interpretation                                                               |
|--------------------------|------------------------------|---------------|-----------|---------------------------------------------------------------------------------------------|
| Material group           | Cast iron                    | 567           | 33.1      | Failure share in the classified dataset; not a length-normalized failure intensity.         |
| Material group           | Galvanized steel             | 360           | 21.0      |                                                                                             |
| Material group           | Steel                        | 335           | 19.5      |                                                                                             |
| Material group           | PE                           | 286           | 16.7      |                                                                                             |
| Material group           | PVC                          | 148           | 8.6       |                                                                                             |
| Material group           | Asbestos cement              | 19            | 1.1       | Based on recorded descriptions/classification, not direct physical diagnosis of each event. |
| Failure mechanism        | Corrosion-related failures   | 797           | 46.5      |                                                                                             |
| Failure mechanism        | Leakage or loss of tightness | 686           | 40.0      |                                                                                             |
| Failure mechanism        | Fracture                     | 150           | 8.7       |                                                                                             |
| Failure mechanism        | Cracking                     | 82            | 4.8       | Failure share; not normalized by pipe length or number of assets.                           |
| Diameter class           | $DN \leq 50$                 | 663           | 38.7      |                                                                                             |
| Diameter class           | $DN 51\text{--}100$          | 490           | 28.6      |                                                                                             |
| Diameter class           | $DN 101\text{--}200$         | 284           | 16.6      |                                                                                             |
| Diameter class           | $DN 201\text{--}400$         | 261           | 15.2      | Rare events may still have high operational consequences.                                   |
| Diameter class           | $DN > 400$                   | 17            | 1.0       |                                                                                             |

Notes: Percentages were calculated for  $N = 1715$  recorded failures in the common failure-cost analysis period 2016–2024. The classification dimensions are presented separately for material group, failure mechanism, and diameter class. They are not cross-classified and should not be interpreted as length-normalized failure intensities or category-specific repair-cost contributions. Metallic pipes, including cast iron, galvanized steel, and steel, accounted for 1262 failures, corresponding to 73.6%. Corrosion-related failures and leakage or loss of tightness together accounted for 1483 failures, corresponding to 86.5%. Failures in pipes up to  $DN 100$  accounted for 1153 failures, corresponding to 67.3%.

## 4. Discussion

### 4.1. Divergence Between Failure Frequency and Repair Cost Burden

The results of the OFCA application demonstrate that failure frequency and repair cost burden may evolve in different directions. In the analyzed network, the number of recorded failures decreased during the observation period, while total annual repair expenditure and the average repair cost per failure increased substantially during the repair-cost analysis period. This is the central finding of the study, because it shows that the annual number of failures, although useful, is not sufficient to describe the actual operational and economic burden of a water distribution network.

The inflation-adjusted analysis confirms that the interpretation of the OFCA should not rely only on nominal repair costs. While part of the increase in reported repair expenditures was associated with general price-level changes, the increase in average repair cost per recorded failure remained visible after conversion to constant 2024 PLN. Therefore, the observed divergence should be interpreted as a combined effect of price-level changes and other possible factors, such as changes in labor and material costs, repair complexity, excavation and surface restoration requirements, or site-specific repair conditions.

If the analysis had been based only on the number of failures, the network could have been interpreted as showing improved or stabilized operational performance. Between 2016 and 2024, the number of recorded failures decreased by 25.9%. However, during the same period, total annual repair costs increased by 77.9%, and the average repair cost per recorded failure increased by approximately 140.3%. This divergence indicates that fewer failures did not result in lower repair expenditure. On the contrary, the cost of managing failures became increasingly important in the overall assessment of network operation.

This finding has direct implications for utility-level performance assessment and maintenance planning. The number of recorded failures remains an important operational indicator, but it should not be interpreted as a sufficient measure of maintenance pressure or repair-cost consequences. A reduction in failure frequency may coexist with increasing reported repair expenditure when the remaining failures are more complex, occur in more difficult or operationally important pipe sections, require more demanding excavation and surface restoration works, or take place under changing market conditions affecting labor, materials, equipment, and transport costs. In the present study, repair costs were analyzed as nominal annual expenditures and were not assigned to individual failure events. Although an inflation-adjusted sensitivity analysis was added to account for general price-level changes, the results should still be interpreted as utility-level repair cost pressure rather than as a full economic assessment of individual failures.

The indexed comparison used in this study provides a simple way to reveal this divergence. By expressing the number of failures, total repair cost, and average repair cost per failure on a common scale, the OFCA method makes it possible to compare operational and economic trends directly. This is particularly useful for water utilities, because the method can be applied using routinely collected annual data and does not require complete cost information for every individual failure event.

### 4.2. Technical Interpretation and Asset Management Implications

The technical structure of recorded failures provides additional context for interpreting the observed repair cost dynamics. The analyzed failure records were dominated by metallic pipes, especially cast iron, galvanized steel, and steel. These material groups together accounted for a large share of classified failures. At the same time, corrosion and leakage or loss of tightness were the dominant failure mechanisms. This pattern is consistent with the expected behavior of aging metallic infrastructure, where corrosion processes, joint deterioration, and progressive loss of tightness may contribute significantly

to operational failures. Pipe age, especially for metallic and cast iron pipes, is an important explanatory factor in failure analysis; however, complete and consistent age-by-material records were not available for the analyzed dataset. In addition, the dataset did not include detailed soil conditions, pressure transients, local environmental exposure, or pipe-level failure history. Therefore, the mechanisms reported in this study should be interpreted as recorded failure categories rather than direct physical diagnoses of each event. A more detailed mechanism-oriented analysis would require additional environmental, hydraulic, age-related, and pipe-level historical data. The concentration of recorded failures in smaller diameter classes may be explained by the greater number and cumulative exposure of water connections and smaller distribution pipes, their higher density of joints, fittings, and service connections, local installation conditions, and susceptibility to local ground works. Therefore, the high share of failures in  $DN \leq 100$  should not be interpreted as higher intrinsic failure intensity without normalization by pipe length or number of assets. This interpretation is consistent with failure modeling, deterioration, and rehabilitation studies, which emphasize that categorical failure shares should be assessed together with asset exposure, pipe characteristics, and network structure [5,6,9,16,17].

These technical distinctions are important for asset management, but the results should be interpreted as preliminary diagnostic evidence rather than as a direct prioritization of pipe groups for renewal. The OFCA results show that failure records should not be evaluated only by frequency, because annual repair cost indicators may follow a different trajectory from the number of recorded failures. However, in the present study, repair costs were available only as aggregated annual expenditures and were not assigned to specific pipe materials, diameter classes, or pipe functions. Therefore, the technical classification of failures should be understood as contextual information that helps identify asset groups requiring further diagnostic attention, rather than as evidence that these groups generate the highest repair burden or operational risk. More detailed prioritization would require length-normalized failure intensity, event-level cost allocation, and spatial analysis [16–22].

#### *4.3. Transferability, Limitations, and Further Development of the OFCA Method*

The main methodological contribution of this study is the formalization and application of the OFCA method as a minimum-data, utility-level procedure for linking recorded failure occurrence with reported annual repair cost indicators. The method is not intended to replace detailed failure prediction models, life-cycle cost analyses, or rehabilitation optimization tools. Rather, it addresses a common practical situation in which water utilities maintain operational failure records and financial data, but these datasets are not integrated at the level of individual failure events.

The transferability of OFCA is based on its limited data requirements. In its basic form, the method requires annual failure counts, basic technical attributes of recorded failures, such as pipe type or nominal diameter, material and failure cause, and reported total annual repair costs. These data are sufficient to calculate annual failure trends, average repair cost per recorded failure, and indexed repair cost indicators. This makes the method suitable for preliminary diagnostic assessment, periodic reporting, budgeting support, and the identification of divergence between operational and repair cost trends.

In its basic form, OFCA should be understood as a preliminary screening tool rather than an asset-level predictive model. It does not directly identify individual assets likely to fail or quantify failure probability, failure consequences, consumer interruption, water loss, hydraulic criticality, or replacement benefit; these applications would require event-level, spatial, and hydraulic data. However, OFCA can help practitioners identify when simple failure counting is insufficient and where more detailed asset-level diagnostics should be initiated.

Although the empirical application was based on one anonymized municipal water distribution network, the transferable contribution of the study lies in the OFCA procedure rather than in the specific numerical values obtained for the analyzed system.

The available dataset did not include repair costs assigned to specific repair types or individual failure events. Therefore, it was not possible to compare the cost of the same repair type across individual years. The inflation-adjusted analysis was performed at the annual aggregate level and should not be interpreted as a repair-type-specific cost comparison. Future applications should decompose repair costs into labor, materials, equipment, transport, excavation, surface restoration, and administrative components to explain why similar failure counts or similar failure types may generate different repair expenditures.

At the same time, the present application has several methodological limitations. First, repair costs were available only as aggregated annual expenditure and were not assigned to individual failure events. Therefore, the study does not quantify repair costs for specific pipe materials, diameter classes, pipe functions, failure mechanisms, or locations. The average repair cost per recorded failure should be interpreted as an annual aggregate proxy of repair cost pressure, not as an event-level economic indicator. Second, although an inflation-adjusted sensitivity analysis was performed, the available dataset did not include cost-component decomposition. Therefore, the adjusted results cannot distinguish between the effects of labor, materials, equipment, transport, excavation, surface restoration, or administrative costs. Consequently, observed cost increases may reflect a combination of repair complexity, changes in failure structure, site conditions, and market-related price changes. Third, exact failure locations were not reported in order to protect the confidentiality of the data provider and prevent identification of specific problematic streets or pipe sections.

A further limitation is that the present article does not use length-normalized failure or cost indicators as main results. Network length and technical inventory data were used to characterize the system and support interpretation, but the calculation of failure intensity per kilometer and repair cost intensity per kilometer was not the focus of this study. This decision was intentional, because the present paper develops the basic OFCA layer based on annual failure and repair cost dynamics. A natural extension of the method is the development of length-normalized indicators, including failure intensity and repair cost intensity.

In future applications, OFCA may be extended by calculating failure intensity as the number of failures per kilometer of pipe per year and by combining this indicator with the average repair cost per recorded failure. Such an extension would allow the development of a Repair Cost Intensity indicator expressed in monetary units per kilometer per year. This would provide a stronger basis for comparing pipe materials, diameter classes, and functional pipe groups while accounting for the length of the exposed infrastructure. In this way, the present study provides the methodological foundation for more advanced asset management analyses, including length-normalized cost ranking, spatial risk mapping, event-level cost allocation, and rehabilitation prioritization [17–22,25–30].

## 5. Conclusions

This study proposed and applied the Operational Failure-Cost Assessment (OFCA) method as a minimum-data procedure for linking water distribution network failure records with reported annual repair cost indicators. The method was designed for utility datasets in which operational and financial records are available, but repair costs are not assigned to individual failure events. In its basic form, OFCA uses annual failure counts, selected technical attributes of recorded failures, and reported total annual repair expenditure to support cost-informed interpretation of network operation.

The application of the OFCA method to an anonymized municipal water distribution network showed that failure frequency alone is not sufficient to describe maintenance pressure at the utility level. During the common analysis period 2016–2024, the number of recorded failures decreased by 25.9%, whereas reported nominal annual repair costs increased by 77.9% and the average repair cost per recorded failure increased by approximately 140.3%. This divergence demonstrates that a decreasing number of recorded failures does not necessarily imply decreasing repair cost pressure.

The inflation-adjusted sensitivity analysis showed that general price-level changes explained a substantial part of the nominal cost increase. However, the divergence remained visible after conversion to constant 2024 PLN, with total annual repair costs increasing by approximately 17% and the average repair cost per recorded failure increasing by approximately 58%. Therefore, the main conclusion should be interpreted as evidence of increasing repair cost pressure after accounting for inflation, although the magnitude of the increase was lower than in nominal terms.

The indexed comparison of failure occurrence, total repair costs, and the average repair cost per recorded failure provided a simple and transparent way to identify divergence between operational and repair cost trends. Such information can support maintenance budgeting, diagnostic planning, and preliminary screening of rehabilitation or replacement needs. However, the average repair cost per recorded failure should be interpreted as an annual aggregate indicator, not as the cost of an individual failure event.

The technical classification of failures showed that the recorded events were strongly associated with metallic pipes, corrosion and leakage-related mechanisms, and smaller diameter classes. These findings provide useful technical context for interpreting repair cost dynamics, although they should be understood as failure counts and shares rather than length-normalized failure intensities or category-specific repair-cost contributions.

The proposed OFCA method can be implemented as a basic spreadsheet-based diagnostic tool and further developed into more advanced asset management applications. Future research should extend the method by incorporating length-normalized failure intensity, repair cost intensity, event-level cost allocation, spatial analysis, and rehabilitation prioritization. In particular, the development of repair-cost intensity indicators expressed in monetary units per kilometer per year would allow more robust comparisons of pipe materials, diameter classes, and functional pipe groups.

The proposed OFCA structure may also support water utilities in improving routine failure and repair-cost data collection. By distinguishing minimum, recommended, and extended data levels, the method provides a practical template for preparing utility datasets for future operational and cost-informed assessments.

In this broader context, OFCA can be understood as an infrastructure-oriented complement to hazard-, exposure-, or consumer-oriented decision-support approaches in water supply management. By linking failure occurrence with repair cost dynamics, the method supports cost-informed asset management as one of the operational prerequisites for maintaining reliable and safe water supply.

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made publicly available because they contain sensitive operational information, including failure records and network-related details. Aggregated data supporting the findings are presented in the manuscript. Further inquiries may be directed to the corresponding author, subject to permission from the data provider.

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