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A Review and Classification of Ageing Models of Ageing Models for District Heating Pipelines

Deterministic, Probabilistic, and Data-Driven Approaches

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Abstract. District Heating (DH) systems have been an essential component of urban energy infrastructure for nearly a century, particularly in regions with severe winter climates, such as Northern Europe and the Baltic states. These networks reliably deliver thermal energy to residential, institutional, and industrial consumers. Like all infrastructure systems, the operational lifespan of DH pipelines is finite and is largely determined by material properties, operating conditions, and installation quality. To ensure long-term serviceability, investment planning, and effective asset management, it is critical to understand the ageing mechanisms of DH pipelines and to develop robust models for service life prediction and Remaining Useful Life (RUL) estimation. The European standard EN 253 provides quality assurance guidelines and minimum performance thresholds—typically specifying a 30-year minimum service life under defined operating conditions—for pre-insulated bonded pipe systems. While such standards offer valuable product-level benchmarks, they do not provide sufficient tools for predicting infrastructure-wide lifetime or RUL during operation. Existing literature classifies the ageing models as deterministic or probabilistic approaches, which they are respectively based on material science–based models, and on failure event statistics. These approaches are often described respectively as “Top-Down” (statistical) and “Bottom-Up” (material-based) methods. More recently, the emergence of machine learning and the increasing availability of operational and failure data have enabled the development of advanced data-driven models with improved predictive capabilities for both failure forecasting and remaining useful life estimation.

This paper presents a critical review and updated classification of ageing models for DH pipelines, organizing them into three main categories: deterministic, probabilistic, and data-driven approaches. The advantages and limitations of each class are discussed, with particular emphasis on their applicability to real-world DH network management and remaining useful life prediction. The proposed framework aims to support the development of integrated hybrid models that can better capture the complex, multifactorial ageing processes in DH systems and improve long-term infrastructure planning and maintenance strategies.

Keywords: District Heating, Ageing Models, Bonded Pipes, Service-Life, Remaining Useful Life

1. Introduction

District Heating (DH) networks represent long-lived, capital-intensive infrastructure systems whose reliability is central to urban energy security. Based on the Critical Entities Resilience

(CER) Directive (EU) 2022/2557 and its supplementing Commission Delegated Regulation (EU) 2023/2450 DH is a critical infrastructure and as many European DH systems approach or exceed their originally intended design life, the ability to predict pipe ageing and remaining useful life has become a critical concern for utilities, regulators, and policymakers. Ageing-related failures—such as leaks, insulation degradation, and corrosion-induced ruptures—can result in high economic costs, service interruptions, and safety risks. Although product standards such as EN 253 provide minimum performance requirements and qualification testing for pre-insulated bonded pipes (BP), they do not directly address the heterogeneous and evolving conditions encountered in real networks over decades of operation. Consequently, ageing models have been developed to support maintenance planning, risk assessment, and long-term investment strategies and in total improve the Asset Management (AM).

The Standard EN 253 contains various tests for each component of the BP as well as the entire pipe assembly but not necessarily the introduced tests are life-time prediction models but a quality assurance of the product that would remain in service for a certain period if operated under certain conditions. Most of these tests are focused on the physical entity of the product and they are experimental based. In another word, the approach is deterministic. Contrary, the system reliability engineering introduced another approach. Instead of going through the physical changes of the ageing phenomenon and understanding the degradation mechanisms, the engineers, grid operators, and experts look at the system as whole and investigate the failure data in different sectors of the grid. In system reliability approach, the datasets, system information and data statistics are translated to ageing information, and any distribution and survival function may be introduced to estimate the service life of the pipe and the ageing estimations.

1.1 Scope and Methodology of the Review

This review is grounded in the author’s research activities over the past five years, including the development and application of ageing models for DHpipelines within two collaborative research projects. Rather than aiming for an exhaustive bibliometric survey, the paper adopts a focused, expert-driven review methodology that emphasizes models with demonstrated relevance to real-world DH network operation.

The literature selection prioritizes peer-reviewed journal articles, conference proceedings, and technical reports that address ageing, degradation, failure prediction, or service-life modelling of DH pipes and closely related buried energy infrastructure. Particular attention is given to studies that:

- Explicitly link ageing mechanisms to operational, environmental, or material parameters;
- Have been validated using field data, laboratory experiments, or long-term monitoring;
- Are applicable at component, network, or asset-management levels.

The reviewed models are classified into deterministic, probabilistic, and data-driven categories, reflecting both methodological differences and their practical implications for DH utilities. Where relevant, insights from the author’s own modelling work are used to critically assess assumptions, data requirements, and transferability.

1.2 Limitations of the Review

The scope of this review is subject to several limitations. First, the emphasis on ageing models relevant to European DH systems may limit the generalizability of conclusions to regions with different climatic, regulatory, or operational contexts. Second, proprietary utility data and unpublished industrial studies—while often highly informative—are largely inaccessible and therefore underrepresented. Finally, rapidly evolving machine learning approaches may outpace the literature covered here; consequently, the discussion of data-driven methods focuses on conceptual maturity and applicability rather than completeness. These limitations are acknowledged to provide transparency and to delineate opportunities for future research.

2. Physical Ageing Mechanisms of District Heating Pipes

Understanding the dominant degradation mechanisms is a prerequisite for meaningful lifetime modelling. Major ratio of modern DH pipelines are BPs [1], which are composite systems typically consisting of a steel service pipe, polyurethane (PUR) foam insulation, and a high-density polyethylene (HDPE) casing. Each component is subject to distinct ageing processes, often interacting in complex ways. This section reviews the physical ageing mechanisms of DH pipes and systematically examines the principal modelling approaches proposed in the literature.

2.1 Thermal and Mechanical Loading

DH energy providers use gliding temperature to supply the energy on the demand side [2]. According to [3] the operating temperature is 80°C when the outdoor temperature is 15°C and the supply temperature increases up to 130°C when the outdoor temperature is -10°C and lower. As the operational temperature is not fixed based on the outdoor temperature and heat demand on days and nights thermal cycling observed on the DH systems run with gliding temperature. Repeated thermal cycling due to varying supply and return temperatures induces expansion and contraction in the steel pipe, generating axial and radial stresses. Over long periods, these stresses may contribute to fatigue damage, joint failure, or debonding between pipe layers special at the interface of the steel pipe and PUR foam. The latter is probably the most decisive phenomena that determines the end of the service-life of a pipe based on the research of many scholars [4], [5], [6], [7], as the medium pipe can freely expand and contract and cause the damage at bends and T joints. Elevated operating temperatures also accelerate chemical degradation processes in PUR insulation foam and Arrhenius equation governs the degradation process. The long-term thermal performance of DH pipes is governed by the integrity of the PUR insulation. Thermal and thermal oxidation is a key mechanism that ages the PUR foam. This can be observed as gradient browning of the insulation layer, which is usually darker at the interface with medium pipe and brighter as move outward toward casing. The thermal and thermal oxidation leads to increased heat losses and mostly precedes structural failure. However, according to our investigations DH operators are less sensitive to thermal ageing than mechanical ageing of the PUR insulation layer. In another word, structural failure is the utmost concern of the grid operators.

2.2 Corrosion and Moisture Ingress

Corrosion of the steel pipe is recognized as a cause of DH pipe failures and that's why in some countries like Germany there are restricted regulations for the water quality in DH systems [8]. Moisture ingress from the HDPE casing layer of the pipe also like damaged or imperfect joints, compromises the insulation and increases heat losses and creates conditions favorable to corrosion. The rate of corrosion depends on soil properties, groundwater conditions, oxygen availability, and the effectiveness of cathodic protection systems [9], [10].

2.3 Installation and Manufacturing Defects

Defects introduced during manufacturing or installation—such as eccentric insulation, poor welding, or inadequate joint sealing—can significantly reduce service life. These factors introduce variability that is difficult to capture using purely deterministic approaches.

2.4 Unclassified Ageing Mechanisms

Beside the mentioned ageing mechanisms on previous subsections, there are debates among researchers and experts that other phenomena may play a role in ageing and degradation of the PUR foam and in general results lowering the service life of the pipe assembly. One of the mechanisms that are being discussed is blowing agent gas diffusion that leads to loss of thermal resistance of the foam and hydrolysis of the PUR foam which is a result of moisture ingress discussed before. As a BP structure is secured to moisture from outside with a HDPE layer and inside from a steel medium pipe and even in newer generations with an aluminum foil barrier, it is not plausible to have moisture inside the insulation layer. However, [11] argues that water vapor permeates the closed-cell foam insulation much more rapidly than blowing agent diffusion, which is about 2 to 3 times faster with calculation based on Graham's law for porous material and even 100 times faster based on Fick's law for Closed-Cell foams.

3. Ageing Models

Because of the multivariate nature of degradation mechanism of the PB, it is not straightforward to find a single method to calculate precisely the remaining useful life (RUL) and lifetime prediction. That could be the main reason EN 253 provides different tests methods for different components of BPs to ensure their service life for a minimum of 30 or 50 years based on certain conditions of operation. As the test methods provided in EN 253 is being used as benchmarks for PB service life, other stakeholders such as researchers, grid operators, and engineering companies focus on asset management (AM) try to find solutions for lifetime prediction to increase the system reliability. In 2017, a publication about "Asset Management of District Heating" summarized the ageing models in two groups as material based models and statistical based models [12] and argues that in both approaches the data quality is the buttle neck of the ageing models. However, in parallel the advancement of the machine learning (ML) technology from one side and data collection and implementation of sensory and IoT devices in DH, opened the field of data-driven models as a new approach to address the ageing and lifetime prediction for DH pipes generally at every level and pipe type of the DH system. Henceforth, in this paper it will be discussed the approaches and models under the classification of deterministic, probabilistic, and Data-Driven approaches (see Figure 1).

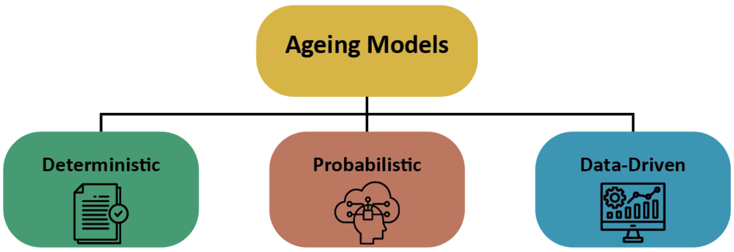

Figure 1. *Classification of ageing models for district heating pipes, grouped into deterministic, probabilistic, and data-driven approaches*

3.1 Deterministic Ageing Models

Deterministic models aim to describe pipe ageing using explicit physical or empirical relationships between operating conditions and degradation rates. These models typically assume known parameters and predictable behaviour. Physics-based deterministic models rely on material science principles, such as corrosion kinetics, thermal degradation laws, or creep and fatigue models. For example, temperature-dependent Arrhenius-type formulations have been used to estimate insulation ageing, while corrosion depth may be modelled as a function of exposure time and environmental factors. Such models offer interpretability and physical transparency but often require detailed input data that is rarely available at the network level. Empirical deterministic models are derived from laboratory testing or field observations and calibrated to specific pipe designs or operating regimes. While simpler to apply, their validity is often limited to conditions similar to those under which they were developed and tested. Extrapolation beyond the calibration range introduces significant uncertainty. The deterministic models are mostly covered in EN 253 [13] and EN 13941 [14], such as fatigue calculation, axial shear stress test, etc. However, for some tests and models literature provide more sophisticated and advanced models for the same problem solving (see Figure 2).

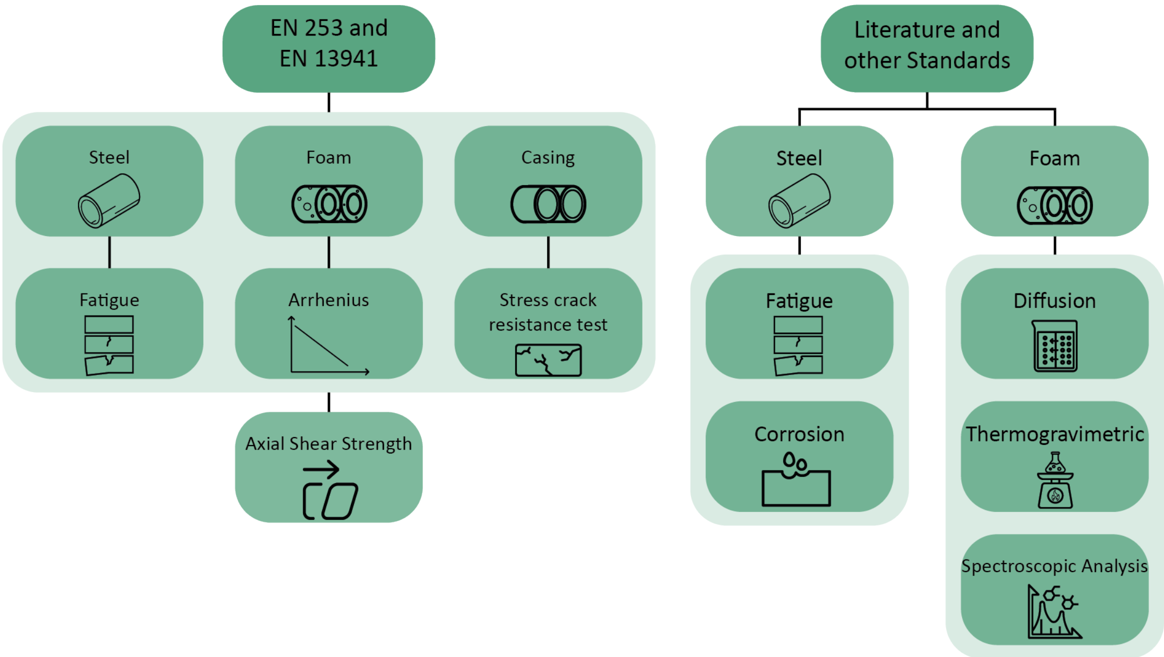

Figure 2. *Physics-based tests and models for quality assessment and lifetime prediction of district heating bonded pipes.*

Starting with the steel medium pipe, EN13941-1 offers Palmgren-Miner's rule for low-cycle fatigue in terms of the pseudo-elastic stress range. Fatigue is one of the well-studied phenomena discussed thoroughly by many scholars and researchers as well as the type of fatigue like stress-based or strain-based models and the governing form whether it is high-cycle, low-cycle or crack propagation [15], [16], [17], [18]. In 1999 a thorough study of fatigue analysis specifically in district heating pipes have been conducted by International Energy Agency Technology collaboration program on District Heating and Cooling (IEA-DHC) and there it has been fully discussed the origin of the SN curve given in EN13941-1, calculation methods and its limitations [19]. However, some aspects of fatigue analysis such as Measurement frequency (1 min, 1 h, 1 day, etc.), temperature bin size for rainflow counting (1 K, 5 K, 10 K, etc.) remain open since temperature variation profile depends strongly on climate, load profile, control strategy, and pipe system design. Because the nature of the mechanical force in DH systems is Thermal Stress, the mentioned fatigue aspects may be the more important aspects need further research compared to the issues like mean stress correction, strain-life models, or plasticity models (Neuber, Ramberg–Osgood). However, the track record of the PBs are showing a longer service life than expected -usually more than 50 years- which means the structure of the PBs are robust for DH operation, but to have a RUL and predictive maintenance (PdM) approach it is a necessity to fine tune a suitable fatigue model for DH networks.

As discussed before, the ageing of the PUR increases the heat losses of the system and also degrades mechanical properties and loss of adhesion special at the interface with medium pipe [20]. To evaluate the degradation at interface the accelerated ageing method is commonly used to ensure that the pipes last for a minimum of 30 years based on the axial shear strength test after the artificial ageing. However, there are discussions going on up to which temperature resembles the reality of in-field ageing. Annex A in EN253 shows an accelerated ageing up to 190°C for 2700 hours to be equivalent of a pipe which operated at 120°C for 30 years. However, [20], [21] argues that temperature above 170°C unleash other degradation mechanisms that not happening in real-world environments and it is suggested that not to accelerate age above 150°C. Consequently, the activation energy may vary based on the accelerated ageing temperature, type of pipe if the pipe has a diffusion barrier or not, or even the chamber is heated for further oxygen ingress through the outer casing or not. Therefore, the outcome usually is good enough for quality assurance but not precise for lifetime prediction based on the Arrhenius equation. To address this discrepancy other scholars and researchers try to quantify the ageing and oxidation level of the PUR with Fourier Transform Infrared Spectroscopy (FTIR) and Thermogravimetric Analysis (TGA) and.

In FTIR, a chemical substance can be identified by passing infrared radiation through a sample. Specific functional groups absorb characteristic frequencies corresponding to their molecular vibrations. In polyurethane (PUR), functional groups such as urethane (C=O), benzene rings (C=C), and hydrogen bonds (N–H) are typically analyzed to identify degradation mechanisms including thermo-oxidative degradation, hydrolysis, post-curing, and chain scission [22], [23]. FTIR is widely used in various district heating (DH) laboratories and by researchers to monitor ageing processes and to support service-life predictions, as reported in [4], [20], [24]. However, investigations conducted by the author indicate that FTIR is not able to reliably identify degradation in PUR foams when the material becomes blackened. In such cases, the strong dark coloration suppresses the detectable absorption signals, particularly when the surface layer is black or nearly black. The author assumes that this effect is caused by a high degree of carbonization at the interface. Characteristic signals can be observed again only after performing a transversal cut approximately 1 mm toward the outer side of the pipe. This limitation makes it difficult to define a clear reference point for the end of the PUR service life. Nevertheless, an advantage of the Attenuated Total Reflection (ATR)-FTIR method is that it largely eliminates discrepancies related to variations in foam density. In addition to laboratory-based chemical characterization methods such as FTIR, field-based diagnostic approaches have also been developed. For instance, the PipeOpsy method, developed by RISE, combines the RISE Plug field test, which measures the adhesion (axial shear strength) between the service pipe and the insulation in operating pipelines, with laboratory analysis of extracted insulation samples using techniques such as FTIR. This integrated approach enables in-situ assessment of the degradation state of PUR insulation and the pipe–foam interface while allowing restoration of the insulation after testing, thereby minimizing permanent damage to the pipeline system [25].

Thermogravimetric analysis (TGA) is a widely used thermal analysis technique that measures the change in mass of a material as a function of temperature or time under a controlled atmosphere. By recording the mass variation during heating, TGA provides valuable information on thermal stability, degradation behavior, and reaction kinetics of materials. In addition, the resulting thermogravimetric and derivative thermogravimetric curves enable the identification of decomposition stages and the determination of kinetic parameters such as activation energy [26]. In recent years, the application of TGA has gained increasing attention for assessing the aging behavior of insulation materials used in DH pipes. Studies have explored the possibility of estimating the RUL of pre-insulated bonded pipe systems by analyzing changes in the activation energy of polyurethane foam at the steel–foam interface relative to that of an unaged reference foam. The relative difference in activation energy can then be expressed either as a percentage change or converted into an equivalent service life in years. Such an approach aims to provide a quantitative indicator of the degradation state of the insulation material and its expected residual lifetime [27]. Despite the promising potential of this method, a standardized experimental and analytical procedure has not yet been established. Issues related to the reproducibility of TGA measurements, sample preparation, heating protocols, and data interpretation remain insufficiently addressed. Consequently, further research is required to develop a robust and reproducible TGA-based methodology suitable for reliable RUL estimation of pre-insulated bonded pipes in district heating systems.

3.2 Probabilistic Ageing Models

Probabilistic models explicitly account for uncertainty by treating failures and degradation processes as stochastic phenomena. These approaches are particularly useful for system-level reliability assessment. Statistical models are often based on historical failure data and describe the probability of failure as a function of time, age, or explanatory variables. These models are frequently referred to as top-down approaches, as they infer ageing behaviour from observed outcomes rather than underlying mechanisms as illustrated in Figure 3.

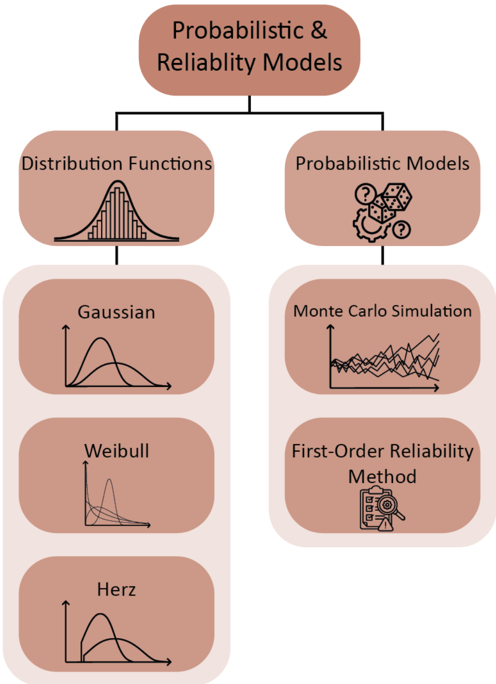

Figure 3. *Statistical models for evaluating the probability of failure in district heating networks.*

Distribution functions used in reliability analysis are described in several statistical handbooks (e.g [28], [29]). In DH network asset management, the Gaussian, Weibull, and Herz distributions are among the most commonly applied. While Gaussian and Weibull models are widely used in system engineering and reliability analysis, the Herz distribution [30] is more specialized and is primarily applied to model the ageing behavior of water and DH pipelines. These statistical approaches are often implemented through reliability frameworks such as Weibull-based models, proportional hazards models, and Bayesian updating. Survival analysis techniques enable the estimation of hazard rates and RUL while accounting for censored data, such as pipes that have not yet failed. Model performance can be further improved by incorporating covariates such as pipe diameter, installation year, soil conditions, and temperature regime [31]. An example application is presented in [32], where a network-wide risk analysis was conducted using GIS data (pipe location, diameter, age, and technology) combined with a maintenance database containing all recorded leakages since 1998. Survival curves were derived for the pipe population to estimate failure probabilities over time, identifying pipe age as the dominant factor influencing system reliability, with different degradation rates across pipe technologies. The resulting survival functions were used to assign a risk index to each pipe segment, representing its relative failure likelihood. These risk indices were subsequently integrated into a maintenance optimization model that evaluates long-term strategies based on the Net Present Value (NPV) of network operation, enabling the comparison of preventive and corrective maintenance while accounting for repair costs, reinvestment costs, and operational losses. This approach demonstrates how survival-based reliability modelling can support data-driven maintenance planning and long-term asset management in DH networks [32]. More examples of utilizing the survival-based models could be found in [33], [34].

Additionally, other probabilistic models such as Monte-Carlo Simulation and First-Order Reliability method is used for market prediction as well as failure prediction in DH system [35], [36], [37].

3.3 Data-Driven and Machine Learning Approaches

The increasing digitalization of DH systems and improved data collection have enabled the application of data-driven modelling techniques. Machine learning approaches, including a wide range of established regressor/classification models such as random forests, support vector machines, as well as deep learning architectures and neural networks, are growing rapidly for pipe failure prediction and degradation states. These models can capture nonlinear relationships and complex interactions among multiple variables without explicit assumptions about physical processes. As illustrated in Figure 4, statistical trend analysis may also be considered a data-driven modeling approach. However, it is difficult to clearly distinguish it from other subcategories, such as pattern recognition and hybrid models, as these approaches often overlap or incorporate statistical trend analysis as an input component or as an integral part of the model. Among these models, pattern recognition models such as acoustic signal monitoring and thermography is commonly use for detecting anomalies in DH networks. The are different types of implementations in acoustic signal monitoring depending on the application. For example, [38] provide a framework for quality and condition assessment of the district heating valves. In another study, researchers collected signals from the pipe using accelerometers and acoustic emission sensors to classify the abnormal pipe conditions [39]. Multiple studies shown the advantages of the Thermography methods for the systems that are not or very limited equipped with leak detection systems. The common practice is infrared imageing and Airborne Thermography to detect leakages [40], [41]. However, the guide lines should be considered such as wind speed, surface dampness, relative humidity, etc. for better results [42].

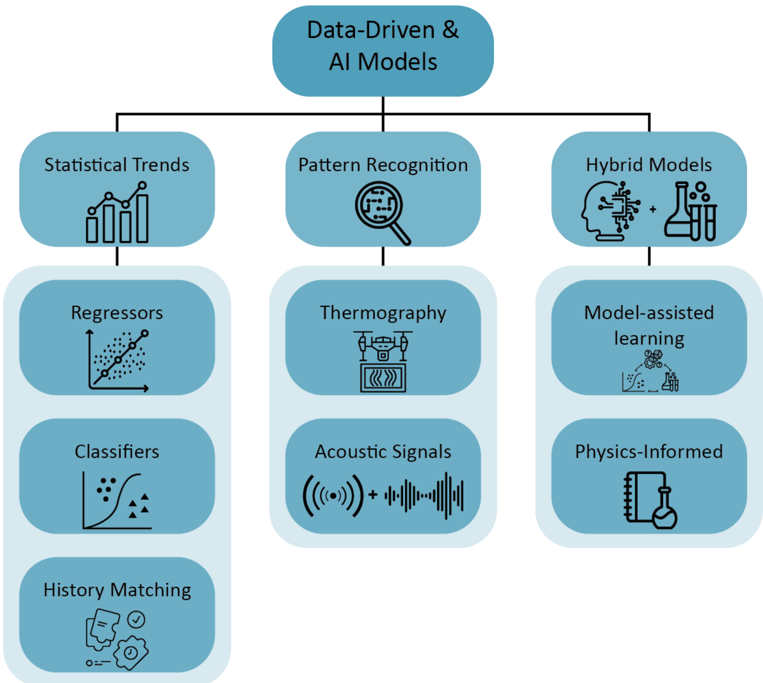

Figure 4. *Data-driven approaches for failure detection and prediction in district heating networks.*

Recent research has increasingly explored hybrid approaches that combine data-driven methods with physical knowledge to improve model generalizability, robustness, and interpretability. In parallel, purely data-driven models have been developed to predict failures of PBs in DH networks based on historical operational and failure data, as demonstrated in [31]. In the present project, the author investigates a model-assisted learning approach, in which laboratory measurements and physically based lifetime predictions of PBs are used to support the training of predictive models. Such approaches represent a form of hybrid modelling, where data-driven techniques are complemented by domain knowledge describing degradation processes. With the rapid progress of artificial intelligence (AI), it is expected that more advanced physics-informed machine learning models will increasingly be applied to lifetime prediction and the estimation of RUL. These models integrate known degradation mechanisms, governing laws, or boundary conditions into the learning process, thereby constraining predictions and improving their physical consistency and reliability.

4. Comparative Assessment of Ageing Models

A comparative analysis of deterministic, probabilistic, and data-driven approaches highlights trade-offs between interpretability, data requirements, uncertainty representation, and applicability. Deterministic models excel in physical insight, probabilistic models in risk quantification, and data-driven models in predictive performance. No single approach adequately captures all relevant aspects of DH pipe ageing. Major aspects of deterministic, probabilistic and data-driven approach is briefed in **Table 1**.

Table 1. *Comparison of Ageing Model Categories for District Heating Pipes*

Aspect	Deterministic	Probabilistic	Data-driven
Core Principle	Physics-based or empirical formulations using fixed parameters	Statistical modeling of failure processes using probability distributions	Machine learning or statistical learning from historical data
Strengths	High interpretability; suitable for component-level analysis and design optimization	Explicit uncertainty quantification; suitable for asset management and risk-based decisions	High predictive accuracy; captures complex nonlinear relationships
Limitations	Limited uncertainty representation; sensitive to incomplete material and boundary data	Strong dependence on failure data quality; susceptible to reporting bias	Black-box nature; strong data dependency; limited extrapolation capability
Data Requirements	Material properties, geometry, operating and environmental conditions	Failure records, inspection data, maintenance history	Large, high-quality operational, environmental, and failure datasets
Uncertainty Handling	Limited; conservative assumptions and safety factors	Explicit stochastic representation using probability distributions	Implicit; learned from data but often difficult to interpret
Typical Applications	Design optimization, lifetime estimation, sensitivity analysis	Risk assessment, reliability analysis, maintenance planning	Failure prediction, condition monitoring, predictive maintenance

Deterministic models are well suited for component-level analysis and design optimization. However, they struggle to represent the inherent uncertainty and heterogeneity of large DH networks, particularly when data on boundary conditions and material properties are incomplete. Probabilistic models are attractive for asset management due to their ability to quantify risk and uncertainty. However, their accuracy depends heavily on the availability and quality of failure records, which may be inconsistent or biased by historical maintenance practices. Data-driven models often demonstrate superior predictive accuracy when large, high-quality datasets are available. Nevertheless, their black-box nature, data dependency, and limited extrapolation capability remain significant challenges for practical implementation.

5. Conclusions

This review has presented a structured overview of ageing mechanisms and modelling approaches for DH pipelines. By critically assessing deterministic, probabilistic, and data-driven models, the paper highlights both the progress achieved and the remaining gaps. Advancing ageing prediction will require interdisciplinary approaches, improved data integration, and closer alignment between standards, research, and operational practice. The ageing of DH pipes is inherently multi-factorial, resulting from complex interactions between material degradation, operational loads, and environmental influences. Traditional lifetime prediction approaches, such as accelerated thermal ageing tests, often fail to capture the nuanced deterioration of pre-insulated pipes under real service conditions. Accelerated methods may overestimate or underestimate remaining life due to differing mechanistic pathways in natural ageing, particularly in polymeric insulation and steel interfaces. These limitations highlight the need for integrated modelling frameworks that combine insights from material science, statistical inference, and machine learning. Material-based models provide a mechanistic understanding of local degradation processes, such as adhesion loss, foam degradation, and thermal conductivity changes, while statistical reliability models quantify probabilistic failure trends across heterogeneous pipe populations. Machine learning methods complement these approaches by capturing complex nonlinear relationships between operational conditions and observed deterioration, enabling predictive maintenance, vulnerability ranking, and optimized reinvestment strategies. Recent research demonstrates that hybrid models incorporating historical operational data, sensor measurements, and material ageing parameters significantly improve the accuracy of remaining useful life predictions. Furthermore, integrating these predictive models into sustainable asset management strategies allows operators to balance cost-effectiveness, reliability, and environmental impact. Moving forward, research should focus on developing unified modelling paradigms that combine physical deterioration models with data-driven approaches, enabling scenario-based planning, informed decision-making under uncertainty, and resilient management of ageing DH infrastructure in line with sustainability objectives.

Author contributions

Pakdad Langroudi: Conceptualization, Investigation, Methodology, Writing – original draft, Validation. **Ingo Weidlich:** Writing – review & editing. **Stefan Hay:** Writing – review & editing.

Competing interests

The authors declare that they have no competing interests.

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References

[1] P. Langroudi, „Predictive maintenance: Ageing and lifetime modeling of pre-insulated district heating pipes“, PhD Thesis, HafenCity Universität Hamburg (HCU), 2025.
[2] P. P. Langroudi, „An Analysis of the most Frequent Operational“.
[3] A. Paar und AGFW, Der Energieeffizienzverband für Wärme, Kälte und KWK, Hrsg., *Transformationsstrategien von fossiler zentraler Fernwärmeversorgung zu Netzen mit höheren Anteilen erneuerbarer Energien: Endbericht*. in Forschung und Entwicklung / AGFW, no. 24. Frankfurt am Main: AGFW-Projektges, 2013.
[4] A. Vega, N. Yarahmadi, und I. Jakubowicz, „Determining the useful life of district heating pipes: Correlation between natural and accelerated ageing“, *Polymer Degradation and Stability*, Bd. 175, S. 109117, Mai 2020, doi: 10.1016/j.polymdegradstab.2020.109117.

[5] G. Banushi *u. a.*, „Durability of District Heating Pipelines Exposed to Thermal Aging and Cyclic Operational Loads“, *J. Pipeline Syst. Eng. Pract.*, Bd. 12, Nr. 1, S. 04020067, Feb. 2021, doi: 10.1061/(ASCE)PS.1949-1204.0000521.
[6] H. Kim, J. Kim, H.-Y. Lee, und J. Yoon, „Shear strength distribution of district heating pipe under accelerated aging condition with respect to PU foam density“, *Polymer Testing*, Bd. 110, S. 107567, Juni 2022, doi: 10.1016/j.polymertesting.2022.107567.
[7] S. Naseem, H. Below, und A. Leuteritz, „Accelerated aging of industrial polyurethane (PU) pipes under pressurized conditions and thermogravimetric analysis (TGA)“, gehalten auf der PROCEEDINGS OF THE 38TH INTERNATIONAL CONFERENCE OF THE POLYMER PROCESSING SOCIETY (PPS-38), St. Gallen, Switzerland, 2024, S. 050003. doi: 10.1063/5.0204659.
[8] *Requirements for circulation water in industrial and district heating systems and recommendations for their operation*, Arbeitsblatt FW 510, Frankfurt am Main., Juli 2022. [Online]. Verfügbar unter: https://www.agfw-regelwerk.de/component/5
[9] Y.-S. Kim und J.-G. Kim, „Corrosion Behavior of Pipeline Carbon Steel under Different Iron Oxide Deposits in the District Heating System“, *Metals*, Bd. 7, Nr. 5, S. 182, Mai 2017, doi: 10.3390/met7050182.
[10] L. R. Hilbert, L. V. Nielsen, und A. Andersen, *Corrosion Rate Monitoring In District Heating Systems*, Bd. All Days. in NACE CORROSION, vol. All Days. 2005.
[11] J. Murphy, „Long-term Aging of Closed-Celled Foam Insulation“, *Cellular Polymers*, Bd. 29, Nr. 5, S. 313–326, Sep. 2010, doi: 10.1177/026248931002900504.
[12] I. Weidlich und G. K. Schuchardt (neé Bestrzynski), „New Approach for Asset Management in District Heating (DH) Networks“, *Energy Procedia*, Bd. 113, S. 22–27, Mai 2017, doi: 10.1016/j.egypro.2017.04.007.
[13] EN 253, „Preinsulated Bonded Pipe Systems for Underground Hot Water Networks - Pipe Assembly of Steel Service Pipes, Polyurethane Thermal Insulation and Outer Casing of High Density Polyethylene“, European Committee for Standardization (CEN), Brussels, Belgium, Standard EN 253, 2024.
[14] EN 13941, „District heating pipes – Design and installation of thermal insulated bonded single and twin pipe systems for directly buried hot water networks“, European Committee for Standardization (CEN), Brussels, Belgium, Standard EN 13941, 2024.
[15] A. Fatemi und L. Yang, „Cumulative fatigue damage and life prediction theories: a survey of the state of the art for homogeneous materials“, *International Journal of Fatigue*, Bd. 20, Nr. 1, S. 9–34, Jan. 1998, doi: 10.1016/S0142-1123(97)00081-9.
[16] M. H. Sabour, „Fatigue“, in *Encyclopedia of Tribology*, Q. J. Wang und Y.-W. Chung, Hrsg., Boston, MA: Springer US, 2013, S. 1026–1032. doi: 10.1007/978-0-387-92897-5_1176.
[17] N. E. Dowling, „Mean stress effects in strain–life fatigue“, *Fatigue Fract Eng Mat Struct*, Bd. 32, Nr. 12, S. 1004–1019, Dez. 2009, doi: 10.1111/j.1460-2695.2009.01404.x.
[18] N. E. Dowling, „NOTCHED MEMBER FATIGUE LIFE PREDICTIONS COMBINING CRACK INITIATION AND PROPAGATION“, *Fat Frac Eng Mat Struct*, Bd. 2, Nr. 2, S. 129–138, Sep. 1979, doi: 10.1111/j.1460-2695.1979.tb01349.x.
[19] R. Christensen und Internationale Energieagentur, Hrsg., *Fatigue analysis of district heating systems*. in IEA district heating, no. 1999,T4. Sittard: Netherlands Agency for Energy and the Environment, 1999.
[20] N. Yarahmadi, A. Vega, und I. Jakubowicz, „Accelerated ageing and degradation characteristics of rigid polyurethane foam“, *Polymer Degradation and Stability*, Bd. 138, S. 192–200, Apr. 2017, doi: 10.1016/j.polymdegradstab.2017.03.012.
[21] A. Vega, N. Yarahmadi, und I. Jakubowicz, „Optimal conditions for accelerated thermal ageing of district heating pipes“, *Energy Procedia*, Bd. 149, S. 79–83, Sep. 2018, doi: 10.1016/j.egypro.2018.08.171.
[22] L. Doyle und I. Weidlich, „Effects of thermal and mechanical cyclic loads on polyurethane pre-insulated pipes“, *Fatigue Fract Eng Mat Struct*, Bd. 44, Nr. 1, S. 156–168, Jan. 2021, doi: 10.1111/ffe.13347.
[23] S. França De Sá, J. L. Ferreira, I. Pombo Cardoso, R. Macedo, und A. M. Ramos, „Shedding new light on polyurethane degradation: Assessing foams condition in design

objects“, *Polymer Degradation and Stability*, Bd. 144, S. 354–365, Okt. 2017, doi: 10.1016/j.polymdegradstab.2017.08.028.
[24] A. Vega, N. Yarahmadi, und I. Jakubowicz, „Cyclic axial loads and thermal ageing of district heating pipes“, *Energy Reports*, Bd. 7, S. 105–109, Okt. 2021, doi: 10.1016/j.egyr.2021.09.033.
[25] I. Jakubowicz, J. H. Sällström, A. Vega, und N. Yarahmadi, „LIFETIME PREDICTIONS AND STATUS ASSESSMENTS OF DISTRICT HEATING PIPELINES“, 2022. [Online]. Verfügbar unter: https://energiforsk.se/media/31455/liftetime-predictions-and-status-assessments-energiforskrapport-2022-872.pdf
[26] Y. Ha und J. Jeon, „Thermogravimetric analysis and pyrolysis characterization of expanded–polystyrene and polyurethane–foam insulation materials“, *Case Studies in Thermal Engineering*, Bd. 54, S. 104002, Feb. 2024, doi: 10.1016/j.csite.2024.104002.
[27] S. Hay, A. Leuteritz, und M. Morgenthum, „Remaining service life of preinsulated bonded pipes—A key element of transformation strategies and future district heating systems in Germany“, *Energy Reports*, Bd. 7, S. 440–448, Okt. 2021, doi: 10.1016/j.egyr.2021.08.084.
[28] K. Krishnamoorthy, *Handbook of statistical distributions with applications*. in Statistics, a series of textbooks & monographs, no. 188. Boca Raton: Chapman & Hall/CRC, 2006. doi: 10.1201/9781420011371.
[29] C. Walck, „Hand-book on STATISTICAL DISTRIBUTIONS for experimentalists“, 2007. [Online]. Verfügbar unter: https://www.stat.rice.edu/~dobelman/textfiles/DistributionsHandbook.pdf
[30] R. Herz, „Developing Rehab Strategies For Drinking Water Networks“, Fraunhofer-Informationszentrum Raum und Bau IRB, 2002. [Online]. Verfügbar unter: https://www.irbnet.de/daten/iconda/CIB9342.pdf
[31] S. Hay *u. a.*, *EnEff:Wärme - Entwicklung von neuen und verbesserten Instandhaltungsstrategien für kleine und große Wärmeverteilnetze durch Kombination statistischer Alterungsmodelle mit materialbasierten Nutzungsdauermodellen: Instandhaltung-FW*. in Forschung und Entwicklung / AGFW, Der Energieeffizienzverband für Wärme, Kälte und KWK, no. Heft 63. Frankfurt am Main: AGFW, Projektgesellschaft für Rationalisierung, Information und Standardisierung mbH, 2022.
[32] M. Pozzi *u. a.*, „District heating network maintenance planning optimization“, *Energy Reports*, Bd. 7, S. 184–192, Okt. 2021, doi: 10.1016/j.egyr.2021.08.156.
[33] L. Mortensen und H. Shaker, „Data-Driven Reliability Prediction for District Heating Networks“, *Smart Cities*, Bd. 7, Nr. 4, S. 1706–1722, Juli 2024, doi: 10.3390/smartcities7040067.
[34] T. Vilbrad Rishøj Jensen, M. Tahavori, H. Reza Shaker, und H. Mirshekali, „Predicting Pipe Failures: A Machine Learning Approach to Asset Management in District Heating“, *IEEE Access*, Bd. 13, S. 168893–168902, 2025, doi: 10.1109/ACCESS.2025.3612096.
[35] M. Valinčius, I. Žutautaitė, G. Dundulis, S. Rimkevičius, R. Janulionis, und R. Bakas, „Integrated assessment of failure probability of the district heating network“, *Reliability Engineering & System Safety*, Bd. 133, S. 314–322, Jan. 2015, doi: 10.1016/j.ress.2014.09.022.
[36] I. Dimoulkas und M. Amelin, „Monte Carlo simulation of district heating system short-term operation in electricity markets“, *energetika*, Bd. 63, Nr. 3, Nov. 2017, doi: 10.6001/energetika.v63i3.3560.
[37] N. Marx, R. Blakcori, T. Forster, K. Maggauer, und S. Ralf-Roman, „Risk assessment in district heating: Evaluating the economic risks of inter-regional heat transfer networks with regards to uncertainties of energy prices and waste heat availability using Monte Carlo simulations“, *Smart Energy*, Bd. 12, S. 100119, Nov. 2023, doi: 10.1016/j.segy.2023.100119.
[38] P. Potočnik, B. Olmos, L. Vodopivec, E. Susič, und E. Govekar, „Condition classification of heating systems valves based on acoustic features and machine learning“, *Applied Acoustics*, Bd. 174, S. 107736, März 2021, doi: 10.1016/j.apacoust.2020.107736.

[39] H. Wook Ji, H. Lee, und I. Hwang, „Supervised learning-based classification of acoustic emission and vibration signal for identifying condition change of district heating system“, *Measurement*, Bd. 220, S. 113388, Okt. 2023, doi: 10.1016/j.measurement.2023.113388.

[40] O. Friman, P. Follo, J. Ahlberg, und S. Sjokvist, „Methods for Large-Scale Monitoring of District Heating Systems Using Airborne Thermography“, *IEEE Trans. Geosci. Remote Sensing*, Bd. 52, Nr. 8, S. 5175–5182, Aug. 2014, doi: 10.1109/TGRS.2013.2287238.

[41] Y. Zhong *u. a.*, „Pipeline leakage detection for district heating systems using multisource data in mid- and high-latitude regions“, *ISPRS Journal of Photogrammetry and Remote Sensing*, Bd. 151, S. 207–222, Mai 2019, doi: 10.1016/j.isprsjprs.2019.02.021.

[42] S.-A. Ljungberg, „Thermography For District Heating Network Applications: Operational Advantages And Limitations“, gehalten auf der 1988 Technical Symposium on Optics, Electro-Optics, and Sensors, R. D. Lucier, Hrsg., Orlando, FL, United States, Jan. 1988, S. 70. doi: 10.1117/12.968487.