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USE CASES FOR DIGITAL METHODS IN PROACTIVE MAINTENANCE OF SEWER INFRASTRUCTURE

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Abstract

Sewer infrastructure is vital for flood prevention, environmental protection, and public health. However, sewer systems are prone to deterioration, and traditional maintenance approaches remain largely manual, reactive, and based on inconsistent data, resulting in inefficiencies. Despite the long duration and importance of the operational phase, clear use cases for digital methods in sewer management remain scarce. This research addresses this issue by providing different use cases for digital methods, i.e. Building Information Modelling (BIM), in the operational phase of sewer infrastructure, and the requirements for its implementation in sewer maintenance. Following a literature review from previous research about the current state of digitalization and automation in proactive sewer maintenance, 20 guided expert interviews are conducted exploring the opportunities and challenges associated with digital methods and automation. These interviews resulted in potential use cases for optimizing proactive maintenance, which were subsequently validated during an expert workshop.

Key findings highlight varying levels of familiarity among stakeholders with digital tools. While AI is seen as crucial for future operations, robotics in sewer inspections remain controversial due to outdated network plans, making improved digital models with georeferencing essential. From the research results, specific use cases for the operational phase of sewer infrastructure are developed, addressing several challenges and offering a foundation for improved decision-making and efficiency in sewer maintenance.

Keywords: building information modeling (BIM), digital model, digital twin, sewer infrastructure, proactive maintenance.

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1. Introduction

Urban sewer systems form the backbone of modern civil infrastructure, playing a vital role in public health, environmental protection, and economic development [1]. Today, sewer systems are an integral part of global infrastructure and are closely interconnected with other infrastructure types, such as road networks. Consequently, damage to sewer systems can also affect different types of infrastructure, potentially leading to traffic congestion, environmental pollution or hazards to public health [2]. The management and maintenance of these complex networks face significant challenges due to their underground nature, aging components, and the vast amount of heterogeneous data associated with them.

In Germany, the wastewater infrastructure spans nearly 600,000 km and has an average age of 37 years [3]. According to DIN EN 805:2023-12, the design life of a wastewater pipe should account for a technical service life of 50 to 100 years, yet in major German cities, approximately 15% of the sewer system is over 100 years old [3]. Documentation practices are inconsistent: some utilities record the year the original pipe was installed, others note the date of the most recent rehabilitation, and for several network sections, no age information is available at all [3]. These data gaps complicate risk assessment and the strategic planning of renewal and maintenance measures.

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Constrained municipal budgets frequently force utilities to prioritize reactive maintenance over forward-looking investment, a tendency compounded by limited political commitment to finance innovative solutions [4]. This reactive posture further burdens an aging infrastructure stock, that urgently requires modernization to avert service failures. Climate change intensifies these pressures: more frequent flooding and extreme weather events increasingly exceed system design capacities, making adaptive strategies indispensable [5].

It is therefore evident that reliable monitoring approaches and proactive maintenance methods are essential to mitigate the risk of damage to sewer infrastructure. To date, however, only isolated approaches exist for the usage of digital methods in the maintenance of sewer systems – examples include automatic damage detection, creation of BIM models, or resilience forecast for critical infrastructure. In this context, a holistic approach based on digital twins of sewer systems and open data exchange formats for proactive maintenance management is being explored as a promising solution.

This research is being carried out as part of the KaSyTwin project, which addresses the need for efficient and resilient approaches to the management of sewer systems in Germany. It aims to establish a methodology for the semi-automated creation and use of digital twins, significantly improving data availability and operational resilience. The main project objectives and methodology have been published in a concept paper, which can be found in [6]. The aim of this work is to define potential use cases for digital methods in the operational phase of sewer infrastructure – including Building Information Modelling (BIM), methods for proactive maintenance, and digital twins – and to identify the main challenges and technical requirements for their practical implementation.

2. Literature review

In a first step, a non-systematic literature review was carried out to analyze relevant German legislation and describe prevailing inspection and maintenance practices in Germany. Germany's regulatory framework for sewer inspection and maintenance comprises federal and state level guidelines. Together, these regulations provide a well-defined framework that prescribes inspection intervals, assessment methods, and documentation standards for municipalities. Operators are therefore legally required to inspect and maintain sewer infrastructure at regular intervals. Infrastructure and condition management is commonly carried out using a sewer cadaster, the *Kanalinformationssystem* (KIS), which integrates semantic and geometric data with geospatial information. While these systems provide a solid foundation for transitioning to 3D models and, consequently, to BIM for sewer infrastructure management, they have not yet led to its widespread adoption.

Following this, the current state of research on the implementation of digital methods for inspection, operation and maintenance of wastewater systems was examined through a systematic literature review (SLR). The databases Web of Science, Science Direct, and Scopus were searched using specific inclusion and exclusion criteria to identify relevant literature. The findings of the literature review focusing on the implementation of digital twins for sewer infrastructure can be found in [7].

The research revealed that sewer inspections are still carried out predominantly by manual methods [8]. The use of AI for the assessment of sewer systems remains limited. Main applications include data analysis tools for damage detection from inspection images, processing of laser scanning, and automatic creation of object-oriented BIM models with embedded georeferencing – implemented as digital twins. According to [9], numerous machine learning models are being explored to allow computers to automatically interpret data from traditional inspections. Automatic defect segmentation remains the least researched task compared to classification and object detection.

Various robotic platforms for automated inspection are discussed in the literature, ranging from micro air vehicles [10] to wheeled robots [11], each equipped with sensors for condition monitoring. For digital models of sewer infrastructure, Wang et al. [12] develop an integrated BIM-GIS information model that presents utility data in a unified way and can be used for sewer maintenance; schema mapping links the two data models so that they communicate effectively. Miyamoto [13] builds a GIS-based maintenance system that predicts concrete pipe corrosion from sensor-derived environmental data and plans interventions accordingly. Van Nguyen et al. [14] combine GIS, augmented reality and machine learning techniques in an application for managing and editing data via AR but note that the accuracy of the pipe geometry displayed is a limitation.

BIM is still uncommon for underground sewer pipes: existing research focuses mainly on information management [15]. Digital twins, unlike simpler digital models or digital shadows, enable real-time synchronization, allowing for an automated, bidirectional data exchange between physical and virtual systems [16] and offer numerous advantages for proactive maintenance in wastewater systems, particularly in the assessment of sewer infrastructure and damage prediction.

3. Research goals and objectives

As the initial research revealed, the use of digital methods in sewer maintenance is currently limited to isolated approaches that often lack a clear definition of their potential application areas in practice. Moreover, there is little guidance on how such methods can be practically implemented or adapted to the specific requirements and constraints of sewer infrastructure in Germany. This study therefore aims to provide concrete use cases for digital methods – focusing, though not exclusively, on Building Information Modelling (BIM) – in the operational phase of sewer infrastructure, identifying the technical requirements for their practical implementation, as well as the practical challenges and opportunities associated with their use.

In order to achieve this main goal, a set of research questions has been defined: (i) Describe the current state of inspection, maintenance, and data management methods which are currently employed in German sewer infrastructure, identifying their limitations and opportunities for improvement. (ii) Assess the digital maturity of different stakeholder groups involved in sewer management. (iii) Identify additional digital processes that could further enhance operational efficiency and reliability. (iv) Evaluate the main technical, data-related, and organizational requirements for the implementation of digital methods for the operation, inspection and maintenance of sewer infrastructure in the German context. (v) Consolidate the findings into a set of use cases digital methods for proactive sewer maintenance.

The results of this research are limited to the specific German regulatory framework. As such, the direct transferability of the findings to other national contexts may be limited. Secondly, although a wide range of stakeholders were consulted through interviews and workshops, the sample size was necessarily limited, which may affect the generality of certain findings. Finally, the technological focus is on BIM and digital twin approaches, which means that other potentially relevant technologies may not be considered in the same depth.

4. Methodology

To complement the literature review with practical insights, expert interviews were designed to explore the topic "Opportunities and Challenges of Digitalization and Automation in Sewer Maintenance" with the goal of identifying the practical need for digital models of sewer infrastructure, digital methods for proactive maintenance and digital twins. A total of 20 guideline-based interviews were conducted with various stakeholders in the wastewater sector, including hydrologists, operators (municipalities), inspectors, rehabilitation experts, engineers and planners. The interviews were conducted using a semi-structured format, which allows respondents to shape their answers and emphasize topics while still being guided by a framework defined by the researcher. The questions were derived from the preliminary literature review to confirm existing findings and uncover additional aspects.

A total of 17 questions were developed and presented to the experts, grouped into four sequential thematic blocks, following the previously defined research questions in Section 3. An extensive list of the questions is provided in Appendix A. The interviews were evaluated through Mayring's qualitative content analysis, employing both frequency and contingency analyses. To keep the results clear, stakeholder groups were analyzed sequentially, and the key findings were then compared across groups.

Following the interviews and the insights of the literature research, the results were consolidated into potential use cases for digital methods for operation and maintenance sewer infrastructure. After further discussion with the project consortium during an expert workshop, 13 distinct use cases were chosen to be further developed within the research project.

5. Research & Results

Data management emerged as a key topic across all expert interviews, as evidenced by the high number of text segments assigned to this category. Within this domain, there was unanimous agreement among the experts that the ISYBAU and the DWA-M 150 formats (both XML-based standard exchange standards defined in the German legal framework) function effectively in the practice. Several different damage classification schemes are used to encode inspection results. These systems assign specific codes to types of damage in accordance with established guidelines, ensuring standardized documentation and interpretation across different stakeholders. It was frequently emphasized that these coding systems are largely similar.

It was also often noted that data exchange involves large volumes of information. Among engineering professionals, there was a clear belief that improved information management would lead to better data management. The identified use cases for digital methods in this area include (1) automatic actualization of the hydraulic model based on current conditions, (2) documentation and monitoring of structural changes and damage in the system over time within the model, and (3) context-specific information output from the model tailored to specific operational needs. A detailed description of all the identified use cases, including definition, opportunities, technical requirements, input data and expected output can be found in Appendix B.

The use and development of artificial intelligence (AI) was a focal point in all expert discussions. AI is particularly seen as having strong potential for future condition classification. However, inspectors were more critical than engineers and network operators, citing a lack of employee expertise in applying AI technologies. Nevertheless, AI offers the benefit of reducing employee workload by automating repetitive and physically demanding tasks. Consequently, a recommendation focusing on AI deployment and digital literacy is proposed to support the long-term integration of AI in condition assessment processes. Identified practical applications of AI in this field include (4) damage identification and localization using AI, (5) intelligent predictions for proactive maintenance based on historic and sensor data, and (6) AI-supported tender preparation for construction and maintenance.

Another main topic during the interviews was the use of digital models of the sewer system. All expert interviews also emphasized the importance of digital Geographic Information Systems (GIS). These models are intended both for collision and synergy planning as well as for data exchange between stakeholders. Therefore, it must be ensured that the digital models are complete and reflect the current state of the sewer network. When creating comprehensive sewer network plans, the integration of BIM and GIS should be considered. In addition to digital models, the topic of digital twins was also addressed. Digital twins were initially viewed critically, particularly by network operators and inspectors. A digital twin representing the entire sewer network was deemed not to offer a favorable cost-benefit ratio. Instead, the experts suggested beginning with digital twins for special structures as a first step in implementation. Identified use cases for digital methods in this area include (7) scenario simulation using the digital twin to support investment decisions, (8) monetary valuation of sewer infrastructure and projection of asset development for investment accounting, (9) semi-automated network operation based on real-time digital sensor data, (10) comparison of surface runoff and sewer flow to detect overloads or incorrect discharges and (11) specific model derivation from the digital twin for various applications.

Regarding the use of autonomous robots for optical inspection, there was a consensus that such systems require complete and up-to-date sewer network plans for navigation. It must also be ensured that robots can move through the sewer without prior cleaning, or that a cleaning process is carried out beforehand. (12) Semi-automated inspection with robotic platforms has been identified as the main use case in this field, reducing personnel dependency and inspection time.

The visualization of the above-ground environment around sewer access points was particularly emphasized by sewer inspection professionals. A lack of consideration for above-ground infrastructure often hinders the execution of inspection tasks. For instance, insufficient maneuvering space for inspection vehicles or the construction of other structures over critical nodes in the sewer infrastructure often leads to complications. (13) Visualization of the surroundings of manholes and structures for inspection was identified as a use case focusing on this topic.

6. Outlook

The analysis of the current state of inspection, maintenance, and data management practices in German sewer infrastructure has revealed a heterogeneous landscape. Municipalities usually follow the existing regulations for inspection intervals, assessment methods, and documentation standards. Moreover, standardized data exchange formats have proven to be effective in practice. The quality and consistency of inventory data varies strongly between municipalities. The increased use of digital tools offers potential for the semi-automation of inspection and documentation processes, which could significantly reduce manual workload and improve data consistency.

Key findings from the interviews highlight the varying levels of familiarity among stakeholders with digital tools such as BIM, digital twins, and AI. Engineers tend to be more informed than sewer inspectors in all these areas, indicating a clear need for education and training. Digital tools – such as AI-based damage detection, real-time system monitoring, and data-driven maintenance planning – offer promising ways to increase the efficiency and resilience of sewer networks. While AI is seen as crucial for the future of operations and maintenance of sewer systems, the use of robotics for inspection remains controversial due to outdated network plans – making improved digital models with geo-referencing essential. In addition, defining the appropriate level of information for different applications in sewer operations and maintenance is considered critical.

Based on the findings of the interviews and further validation through consultation with the project consortium, 13 specific use cases for digital methods for operation and maintenance sewer infrastructure have been developed. The defined use cases can be outlined in four groups: Data Management, Artificial Intelligence, Digital Models and Digital Twins, Autonomous Inspection, and Infrastructure Visualization. For each of the use cases, the opportunities, requirements, input data and expected output have been identified and can be found in Appendix B.

However, due to constraints such as technical feasibility, implementation challenges, and the size and complexity of existing sewer networks, not all use cases can be implemented within the available timeframe of the research project. Therefore, a strategic selection of focus areas and a detailed validation of the identified required inputs and expected outputs for implementation is required. To support this process, a follow-up survey will be conducted, building on the results of earlier qualitative interviews, to prioritize the use cases based on their practical relevance. Feasibility of implementation and alignment with available project resources will also be considered.

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Appendix A. Interview Questions

Block 1: Current state of practice and methods used in sewer maintenance

Q1: Do you use the damage classification scheme of the DIN standard (DIN EN 13508-2) and/or the DWA standard (DWA-M 149-3) to classify defects in sewer pipes? What advantages and disadvantages do you see in both coding systems?

Q2: Which procedure do you use for condition assessment and evaluation of sewer pipes?

Q3: How do different stakeholders typically collaborate and communicate about data management (exchange, volume, format)?

Q4: Where do you see challenges in the current operation and maintenance of sewer infrastructure regarding the following aspects?

- Data management (exchange, volume, format)
- Information management (Which information is contained in the data?)
- Proactive action based on predictions (How/when/where could which failures occur?)

Q5: What works well in your organization in the areas of data management, data exchange, and information management related to sewer maintenance?

Block 2: Status of digitalization among stakeholder groups

Q6: Is your company already using BIM or other digital methods in certain areas? If so, how are they being used?

Q7: Are you already using fully or partially autonomous robots for inspection in parts of the sewer system? If so, how are post-processing, evaluation and sorting handled?

Q8: Is there already a digital model of any part of the sewer infrastructure in place?

- Geographic Information System (GIS) localization for future maintenance activities
- Comparison with other underground infrastructure networks

Q9: Are you familiar with the differences between digital models, digital shadows, and digital twins?

Block 3: Digital processes for workflow optimization in sewer management

Q10: What maintenance processes do you think could be optimized by implementing digital models? Which information is required for that?

Q11: Do you think the use of digital shadows or digital twins for sewer maintenance will be useful as digitization continues?

Q12.1: Does your organization use the following practices to provide information within the Building Information Modeling (BIM) process?

- Level of Information Need (LOIN)
- Level of Development (LOD)

Q12.2: What is your assessment of the potential benefits of these practices in terms of the following aspects?

- Definition of information needs and information provision
- Information exchange

Q13: Is artificial intelligence (AI) already being used in your organization? Can you describe the use cases? How does AI impact data and information management?

Block 4: Requirements needed for implementing digital solutions

Q14: Is employee knowledge about digital twins and digitization a bigger challenge than technical hurdles?

Q15: Do you see challenges and needs related to existing hardware?

- Age of the equipment
- Cost of new purchases
- Integration of technology into the working environment

Q16: Are there challenges and needs related to software applications?

- Missing or unaffordable licenses (e.g., GIS, BIM, Hykas, etc.)
- Lack of user skills
- Data systems and data exchange platforms

Q17.1: How do you assess the opportunities for further digitalization of the sewer infrastructure in terms of the following technologies?

- Use of fully autonomous robots
- Data evaluation using AI

Q17.2: Where is there a need for optimization? In which areas is digitalization already progressing well?

Appendix B. Identified use cases for digital models in sewer maintenance.

Use Case 1: Automatic actualization of the hydraulic model based on current conditions

Definition:	Automatic actualization of the hydraulic model based on current conditions (environmental parameters relating to soil, sealing, etc.) by integrating inventory data from various sources.
Opportunities:	Reduction of information loss due to late entry of changes in the network or manual transfer
Requirements:	Data availability; Automated data collection and integration; Relevance filtering for simulation impacts
Input Data:	Environmental parameters; Damage information**;** Current (outdated) hydraulic model; Structural and operational changes (i.e. new construction)
Output:	Updated hydraulic model

Use Case 2: Documentation and monitoring of structural changes and damage in the system over time

Definition:	Information on structural changes and damage in the sewer network is stored in a digital model for monitoring purposes and semantically assigned to the respective sections of the sewer system. Damage is visually represented within the model.
Opportunities:	Easier tracking; Monitoring of the damage over time; Visual clarity
Requirements:	Regular and comprehensive inspections; Standardized data collection; Use of a central data environment; Clear definition of the information requirements before the inspection
Input Data:	Coding system for damage classification; Video and image material from inspections; Digital model (BIM/GIS)
Output:	Semantically enriched model including damage information; Monitoring of damage development during time

Use Case 3: Context-specific information output

Definition:	Derivation and output of application-specific filtered models from the digital twin.
Opportunities:	Improved communication; Data load reduction; Data privacy improvement
Requirements:	Defined information needs; Data filtering logic; Standardization of output formats.
Input Data:	Required Level of Information for each application; Digital model
Output:	Filtered information package

Use Case 4: Damage identification and localization using AI

Definition:	Damage is identified and localized by AI from the data collected during inspection and documented in the model
Opportunities:	Accurate, objective, and efficient damage classification
Requirements:	Data quality; Model training sufficiency
Input Data:	Inspection Data
Output:	Damage Classification

Use Case 5: Intelligent predictions for proactive maintenance based on historic and sensor data

Definition:	Forecasts based on real-time and historical data to enable proactive maintenance

Opportunities:	Reduced downtimes of the network; Improved efficiency; Supported maintenance strategy
Requirements:	Sensor integration; Historical data, Deterioration models; Data quality; Long-term monitoring.
Input Data:	Digital model; Sensor data; Historical data; Deterioration model
Output:	Forecasts and recommended maintenance strategy

Use Case 6: AI-Supported tender preparation for construction and maintenance

Definition:	AI identifies action needs for construction and maintenance and supports automated tender creation
Opportunities:	Reduced manual workload and faster procurement
Requirements:	Trained AI; Legal framework for automation; Human oversight; Approval processes; Legal compliance
Input Data:	Inspection data; Digital model
Output:	Draft of tender documents

Use Case 7: Planning scenario simulation and variant comparison to support investment decisions

Definition:	A digital model can be used to simulate scenarios and compare investment alternatives
Opportunities:	Improved investment decisions; Risk reduction
Requirements:	Up-to-date digital model of the network; Sufficient computational power; Simulation software
Input Data:	Illustration and/or description of the different planning scenarios; Construction costs
Output:	Effects of different variants on the network; Investment roadmap

Use Case 8: Asset Value Estimation for Investment Accounting

Definition:	Digital models can be used to estimate the asset value of the sewer system for municipalities and forecast the asset's development. The asset value of the sewer system is constantly revalued and projected into the future based on the monetary information stored in the model and the damage situation.
Opportunities:	Precise valuation and support for municipal asset management
Requirements:	Digital twin or digital shadow; Damage records; Valuation standards; Depreciation modeling
Input Data:	Digital model; Financial data; Damage assessment; Interest rates; Depreciation values
Output:	Current asset value of the sewer network

Use Case 9: Semi-automated network operation based on real-time sensor data

Definition:	Network elements are controlled in real time using data from sensors of the digital twin. Network control is only partially automated, with recommendations for action based on AI, but with humans as the executing body.
Opportunities:	Optimize the existing potential of the network without physical expansion
Requirements:	Real-time sensors; controllable actuators; accurate model; trained operator

Input Data:	Real-time flow data from sensors; Current hydraulic measurement data; Digital model of the network
Output:	Instructions for the control elements; Recommended actions for operators

Use Case 10: Comparison of surface runoff and sewer flow to detect overloads or incorrect discharges

Definition:	Sensors in the sewer network and runoff data can be used to compare discharges and identify the cause in the event of a faulty discharge.
Opportunities:	Identification of overloads or incorrect discharges.
Requirements:	Real-time sensors; Accuracy of surface runoff estimation, Synchronization of datasets.
Input Data:	Flow rate measurements (sewers); Surface runoff data
Output:	Location and probable cause of incorrect discharge

Use Case 11: Specific model derivation from the digital twin for various applications

Definition:	Derive application-specific models from the digital twin.
Opportunities:	Avoids redundant modeling; Improved consistency between models
Requirements:	Suitable digital model or digital twin; LOIN definition for each application; Conversion tools
Input Data:	Required Level of Information**;** Digital model
Output:	Derived model with reduced information

Use Case 12: Semi-automated inspection with robotic platforms

Definition:	Semi-automated inspection with robotics
Opportunities:	Faster inspections; Less expertise needed
Requirements:	Robotic platform for inspection; AI processing capabilities; Navigation in confined spaces, Data interpretation accuracy
Input Data:	Pipe geometry
Output:	Damage identification and location

Use Case 13: Visualization of the surroundings of manholes and structures for inspection

Definition:	Georeferenced photos and laser scan models of the area around manholes and entrances to structures (storm water retention basins, etc.) are stored in the model to help contractors and inspectors identify access points to manholes.
Opportunities:	Improved planning of access points; improved traffic safety
Requirements:	Photographic documentation; Georeferencing tools; Consistency in data collection
Input Data:	Photos; Laser scan point clouds; Georeferencing; Street view data
Output:	Visual representation of manholes and their surroundings for inspection

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