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Data integration in asset management of municipal pipe networks in Sweden: Challenges, gaps, and potential drivers

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A R T I C L E I N F O

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A B S T R A C T

This study involved a survey of Swedish water utilities to evaluate their pipe-network data-collection objectives, usage, storage, and exchange routines. Factors impacting data integration (and the associated benefits) were also identified. Results showed that current data storage and exchange routines can be augmented to support commonly identified objectives and data utilisation needs, especially in larger water utilities. Levels of awareness of the opportunities for and benefits gained through asset management processes and data integration varied between utilities. Further research on the benefits of data integration in pipe network asset management is required to develop an evidence base on benefits accrued in practice, especially considering metadata, the diversity of legacy systems still in operation, costs and policy use.

1. Introduction

Municipal asset management (AM) systems are considered data-intensive (Alegre and Coelho, 2012). AM systems transform data into useful information, which allows utility managers to assess the gap between the status quo and the asset management objectives (Rokstad et al., 2016). Many water utilities face a challenge with their municipal AM data and systems being distributed and heterogeneous (Opar-a-Martins et al., 2015; Carriço et al., 2020). This challenge arises primarily from these systems' being mostly stand-alone with limited or no capability to share and exchange information with other systems. Such data and system configurations inadvertently foster a silo mentality which necessitates a reliance on intuition and tacit knowledge and results in complexities in decision-making within water utilities (Van Riel et al., 2014; Van Riel et al., 2017). Such decision-making complexities are especially the case in many Swedish water utilities where long-term planning is reported to be limited, and there are gaps in information sharing (Martenssoon and Rumman, 2019; Emilsson and Adrup, 2021). These challenges and associated complexities underscore the necessity of decision-making based on data-driven strategies (Hampapur et al., 2011). Despite frameworks and models for data-driven decision-making such as Eggimann et al. (2017), Amador-Jimenez and Mohammadi (2020), Kerwin and Adey (2020) and Meydani et al. (2022) as well as software solutions (e.g., ESRI, baseform, copperleaf, Oracle), barriers persist. Some of the most prominent are intrinsic challenges that prevent data integration and system interoperability. Implementing efficient municipal asset management systems requires addressing these challenges.

Efficiently integrating various function-specific and enterprise-wide systems for pipe network asset management (Vanier, 2014) is one of the most highlighted solutions for data integration. The fundamental question remains: can a unified approach to the interoperability of AM systems for pipe networks support better data management and information flow between various work processes? Several promising theoretical and practical solutions have previously been reported. These include using data warehouses, middleware (Carriço et al., 2020) and standard data models (Halfawy et al., 2006) such as a GIS database. Some difficulties in practically implementing such solutions include (1) the consequences of using commercial systems (Carriço et al., 2020), (2) Inconsistencies during the data collection (Rokstad, 2012) and (3) the identification of which AM systems need to be interoperable (Halfawy et al., 2003). When commercial systems are used, the question of who, in actuality, owns the data has been raised (Carriço et al., 2020). Commercial systems may also prevent water utilities from having full autonomy to use and analyse data according to their objectives. Generally, commercial systems have limitations and do not always match all the needs and goals of a utility. Uncertainties, biases and anomalies in the data collection phase, such as null, outlier, and incorrect values, need to

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be treated (identified, evaluated, and, if needed, corrected). In a pre-study including a focus group workshop, the findings suggested that not all pipe AM systems need to be interoperable. Therefore, AM data needs and strategic objectives for varying utility sizes, resource availability and data maturity levels should be understood to determine interoperability needs and desired levels.

Other challenges have been reported to affect interoperability (Parlikad and Jafari, 2016). These challenges include cybersecurity concerns and increased digitalization through the development of real-time data collection, such as IoT and intelligent sensors (Carriço and Ferreira, 2021). Furthermore, advanced analytics in areas such as building information modelling, artificial intelligence, machine learning, big data, and virtual and augmented reality further compound the challenges faced in achieving interoperability (Ahonen et al., 2019; International Water Association, 2022). Cloud storage services, 5G broadband technology, and blockchain technology are promising solutions for achieving interoperability (Arnell et al., 2023). These technologies offer scalability, multitenancy, elasticity, and on-demand access, which are crucial for future-proofing.

Moreover, they have the potential to increase data-driven IAM adoption. However, there are several challenges associated with using these technologies. For example, cost, data security, privacy concerns, and the complexity of IT infrastructure and processes are some of the most apparent issues (Ahonen et al., 2019). Addressing these challenges will be essential to ensure these solutions' successful implementation and adoption.

Okwori et al. (2021) contextualised objective-driven integrated asset management (OD-IAM) as the link between data quality and systems integration with specific objectives for managing pipe networks in water utilities. In this way, OD-IAM enables water utilities to effectively achieve their goals by using high-quality data and interoperable systems to support data-driven decision-making. This contextualisation needs further substantiation. Specifically, aspects linking system interoperability to OD-IAM still need to be empirically investigated and are considered part of the challenges of IAM implementation (Polenghi et al., 2021). Studies that can provide a guide to improve data integration and systems interoperability related to municipal or water utility pipe networks are also limited to supporting informed decision-making (Leal et al., 2019; Carriço et al., 2022).

This study aimed to contribute to the understanding of the impact of data integration on the application of data-driven approaches, the presence of data silos, and data management practices in the context of pipe network asset management (AM). The objectives were to evaluate the connections between data-collection objectives, data storage, and exchange routines and assess the key drivers, challenges, and benefits associated with data integration. This study also suggested improvement pathways to the challenges. The findings of this research contribute to developing a roadmap for policy and practical applications for digitalization and adopting data-driven strategies in pipe network management. In the context of this study, data integration refers to the capability or ability of different systems to exchange data in an automated manner (i.e., systems interoperability).

2. Methods

An online survey questionnaire was designed to get the perception of the Swedish municipalities and water utilities regarding the alignment of objectives to data integration needs and the challenges and benefits of data integration within municipal pipe networks. The questions were designed with input from focus group workshops and literature studies. The questionnaire comprised seven closed-ended questions with sub-questions and one open-ended question. The survey focused on the following.

I. Identification of the data collection objectives for the maintenance and management of pipe networks.
II. The respondents' perceptions about data utilisation routines for long-term maintenance and management of the pipe networks.
III. The respondents' perceptions about data storage and exchange routines for the pipe networks' operations, maintenance, renewal and strategic planning.
IV. Perceptions about technical, organisational and meta-data-related factors reported as impactful to data integration.
V. Perceptions on perceived benefits of data integration.

The questionnaire was created using the Survey Monkey web-based tool (2022). It was sent out in May 2022 and was open until August 2022. It was distributed to technical professionals in the 290 municipalities working with the pipe networks. The survey was initially delivered to the central registrar at the municipality or water utility, which was asked to forward the questionnaire to the technical personnel with adequate knowledge of pipe network maintenance and management. This group comprised water and wastewater engineers and individuals in managerial roles, such as chief executives, unit managers, operational managers, unit heads, investigation and planning engineers, project engineers, and operations engineers. Refer to supplementary material I for the developed survey questions.

2.1. Survey questionnaire design

The methodology used to develop the questionnaire was based on (Jebb et al., 2021). The methodology entails a systematic approach to developing questions that utilize the Likert scale to measure respondents' perceptions on a particular subject. This systematic approach consisted of choosing relevant questions based on research objectives and existing literature. A pilot test assessed these items for clarity and relevance. Feedback from the pilot test lead to refinements. Subsequently, the questionnaire underwent validation to confirm its structure and consistency. The finalized survey was then distributed to the intended audience.

Ethical standards, including participant privacy and informed consent, were maintained throughout this process. Fig. 1 specifies what these systematic steps entailed that are particular to this present study.

As part of the piloting process, the questionnaire was refined and fine-tuned in two rounds to enhance understandability. This approach leveraged the tacit knowledge of a municipality's retired head of water services. Their experience was valuable in improving the questionnaire and ensuring it was clear and understandable.

2.2. Response rate statistics

Sixty-five respondents participated in the survey and represented 92 of the 290 Swedish municipalities since some water utilities provide water services for several municipalities (an approximately 32% response rate). The percentage distribution of respondents by role consisted of 35% water and wastewater engineers, 37% had managerial positions, e.g. chief executive, unit manager, operational manager, or unit head, 15% were investigation and planning engineers, and 12% were project engineers, or operation engineers and others. The percentage distribution of respondents according to utility type and size, i.e., the number of inhabitants served by the pipe network within the municipalities or utilities, is presented in Table 1.

2.3. Statistical analysis

The survey results are presented using diverged stacked and stacked bar charts showing the percentage distribution of responses, indicating the frequencies of responses that are in agreement or disagreement, and identifying outliers. The method used for creating diverged stacked bar charts is based on Heiberger and Robbins (2014).

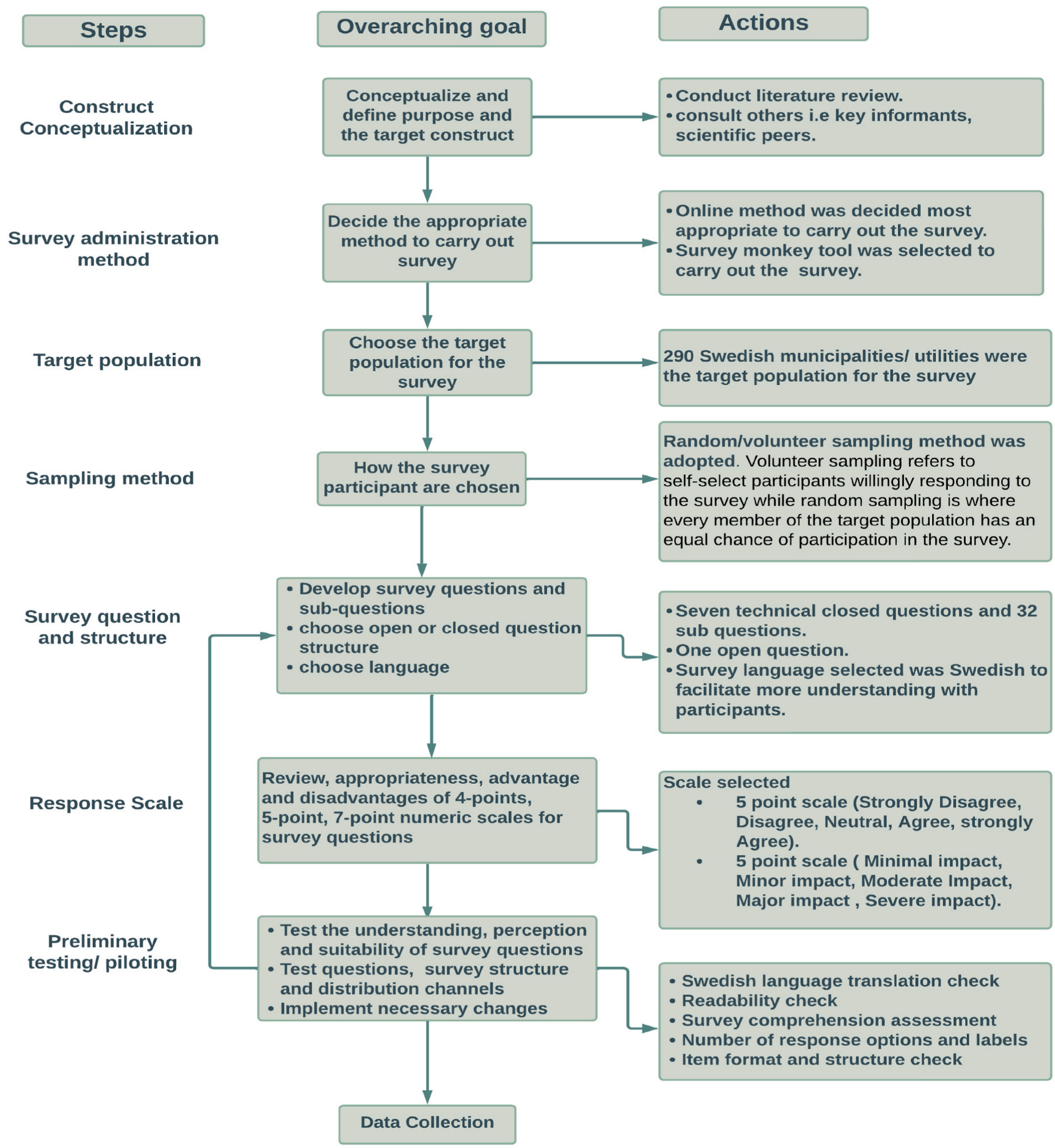

Fig. 1. Flowchart showing methodology and steps in developing the questionnaire based on (Jebb et al., 2021).

2.3.1. *Principal component analysis and multiple correspondence analysis*

Principal Component Analysis (PCA) is an exploratory multivariate analysis for reducing the dimensionality of datasets and increasing interpretability while reducing information loss (Husson et al., 2022). PCA summarises the variation in data, identities, relationships, and associations between variables capable of explaining the variation in relatively large datasets. A detailed explanation of the PCA methodology can be found in Shaffer (2002) and Husson et al. (2022). In this study, two PCAs were performed to identify associations and correlations which can provide additional insights from the survey responses. The first PCA was carried out between surveyed objectives for data collection, data utilisation routines, data storage and exchange routines, and variables for utility type and size. The second PCA was carried out between surveyed technical, organisational and metadata factors that affect data integration and systems interoperability and responses for data storage and exchange routines. The various associations and correlations identified by the PCA were further explored by carrying out multiple correspondence analyses with questionnaire responses for individual sub-questions. For example, responses to questions A and B can be analysed to evaluate if respondents who" strongly agreed" with A also "strongly disagreed" with B or vice versa. Multiple correspondence analyses can generally be understood as a type of PCA for categorical data, where the geometric definition of PCA is considered rather than its statistical definition. A detailed description of multiple correspondence analysis methodology can be found in Greenacre and Pardo (2007). Results from the PCA and multiple correspondence analyses are presented via asymmetric biplots in supplementary data II.

2.3.2. *Word count analysis*

Responses to the open question regarding the perceived benefits of increased systems interoperability in asset management and decision-making for pipe networks were analysed by the count of adjectives used to qualify various potential benefits of systems interoperability. In this study, the words were manually counted to identify repeated

Table 1
Descriptive information of survey respondents
Swedish Association of Local Authorities and Regions, 2017 and Svenskt Vatten (2022).

Survey respondents based on water utility type (percentage of total respondents)	
Municipality: *The municipality water department is responsible for the management of water and sewerage services and operations*	34 (53%)
Water Utility *- The water services are managed by a municipal water company or other municipal association to manage water and sewerage services and operations. The utility can be a pure water or sewerage company*	29 (45%)
Other, i.e., organisational structures that do not fall into any of the categories described above or maybe *water and sewerage companies jointly owned by several municipalities, or Several municipalities form a joint municipal association*	1 (2%)
Survey respondents based on the number of habitants connected to the pipe networks within the municipality (percentage of total respondents)	
More than 200,000 *-municipalities with a population of at least 200,000 inhabitants with at least 200,000 inhabitants in the largest urban area*	3 (5%)
50,000–200,000- *Medium-sized towns – municipalities with a population of at least 50,000 inhabitants with at least 50,000 inhabitants in the largest urban area.*	19 (30%)
15,000–50 000 *- municipalities with a population of at least 15,000 inhabitants in the largest urban area*	34 (38%)
Fewer than 15,000 *- municipalities with a population of fewer than 15,000 inhabitants in the largest urban area,*	18 (28%)

adjectives. Commonly used words without contextual meaning were excluded, for example, words like “as” and “was”. Furthermore, findings were sorted from high-frequency to low-frequency words (Rouder et al., 2021).

3. Results

3.1. Assessment of collection, usage, storage, and exchange routines of data to support asset management

The respondents’ perceptions regarding objectives for data collection, data utilisation, data storage and exchange routines between systems for management of the pipe networks are presented in Fig. 2.

The reported objectives for data collection typically represented some of the common strategic, tactical, and operational objectives for asset management of pipe networks (Fig. 2a). The objectives that were observed to be more common among respondents (60–80% of respondents) compared to others included analysis of operational disturbances (A1), renewal planning (A2), maintenance planning (A3), and planning for network expansion (A4). Risk and impact assessment (A5), analysis of network capacity (A6), and reporting purposes (A7) were considered objectives by approximately 50% of respondents. Only 35% and 6% of respondents agreed that the estimation of project costs (A8) and geotechnical assessments/soil investigations (A9) were objectives for data collection. Additionally approximately 60 % of the respondents indicated that data was utilised for strategic and tactical decision-making and managed by several diverse systems and databases (Fig. 2b, B1–B2).

Survey responses were indicative that current data storage and exchange routines were inadequate to support data utilisation by multiple systems or AM models simultaneously. Evidence to support this can be seen in responses from the data storage routines investigated, where only 36% of respondents indicated that data was stored in a manner that it could be used by several systems and databases (Fig. 2c, C1). Additionally, 73% of respondents indicated a lack or uncertainty in the availability of policy that specifies how data should be stored or managed so it can be used by multiple systems (Fig. 2, C2). Responses about data exchange routines (Fig. 2b, B3) showed that 44% of respondents reported that data was managed using manual routines, 56% that systems/databases did not exchange data with automatic routines and 30% were uncertain (Fig. 2b, B7). Fig. 2d also showed that slightly more than a third of respondents had neutral perceptions of how data is exchanged, while 20%–34% responded that data was exchanged manually between systems. An excerpt from respondents that further supports these findings is presented below.

> “Much data is currently collected in VA-banken*. We have a functioning connection for data exchange between VA-banken and the billing system, which contains records for all services and water consumption (charged) for all properties for which the municipality provides water services. A connection between VA-banken and other systems/databases (finance, hydraulic models, water samples analyses, customer complaints databases) are still lacking.”

*VA-banken is a software for managing water and sewerage network information. It lets users record pipeline data, report issues, prioritize tasks, and evaluate network status.

The quote also emphasizes using VA-banken as a central repository for collecting and storing data but lacks a connection to other critical systems or data. This situation is hypothesized to be common in municipalities and utilities in managing pipe network data, as noted by previous studies such as Halfawy et al. (2002) and Emilsson et al. (2021).

However, one respondent pointed out that prioritization is necessary when resources are limited, especially when it comes to connecting databases and systems to facilitate data exchange and conduct more advanced analyses:

> “It is important to decide how data should be managed. Establishing a link between systems so data can be exchanged is often expensive and requires maintenance. However, it may be cost-effective to link databases if possible.”

The quoted statement also emphasizes that the perceived costs associated with setting up and maintaining data exchange connections between systems can pose a challenge to establishing effective data exchange routines. This perception of cost extends to the person-hours required to enhance system interoperability and the availability of requisite expertise. It is crucial to align strategic asset management objectives with decisions about which systems to link to overcome this challenge (Okwori et al., 2021). Specifically, one approach is to base decisions about data exchange on the objectives for managing pipe networks, as this can provide a valid justification for determining which systems should be interconnected.

Defining the AM objectives for pipe networks includes having measurable criteria, metrics and targets related to various objectives (Grigg, 2003). For utilities to efficiently define and accomplish their objectives, data related to pipe networks and associated analytical systems are required. The responses in Fig. 2 show that the most common objectives for collecting data are analysis of operational disturbances, renewal, and maintenance planning. These objectives typically require data from multiple sources (Grigg, 2003). The survey findings also indicated that a significant proportion of respondents (67%) agreed that collected data is used to make strategic and tactical decisions related to pipe networks. This observation underscores the essential function that data plays in guiding decision-making related to the management of pipe networks.

3.2. Linking utility size, objectives, and data management routines: results from principal component and multiple correspondence analyses

Principal component analysis (PCA) and multiple correspondence analysis were used to examine the linkages between utility size, utility type, data collection objectives (A1-A9), data utilisation routines (B1–B7), storage routines (C1–C2), and exchange routines (D1-D3). The following sections present associations highlighted by the results, illustrated in Supplementary Data II, Figs. 1–5, and account for approximately 44% of the variance in the responses.

The analysis revealed that respondents from larger utilities serving

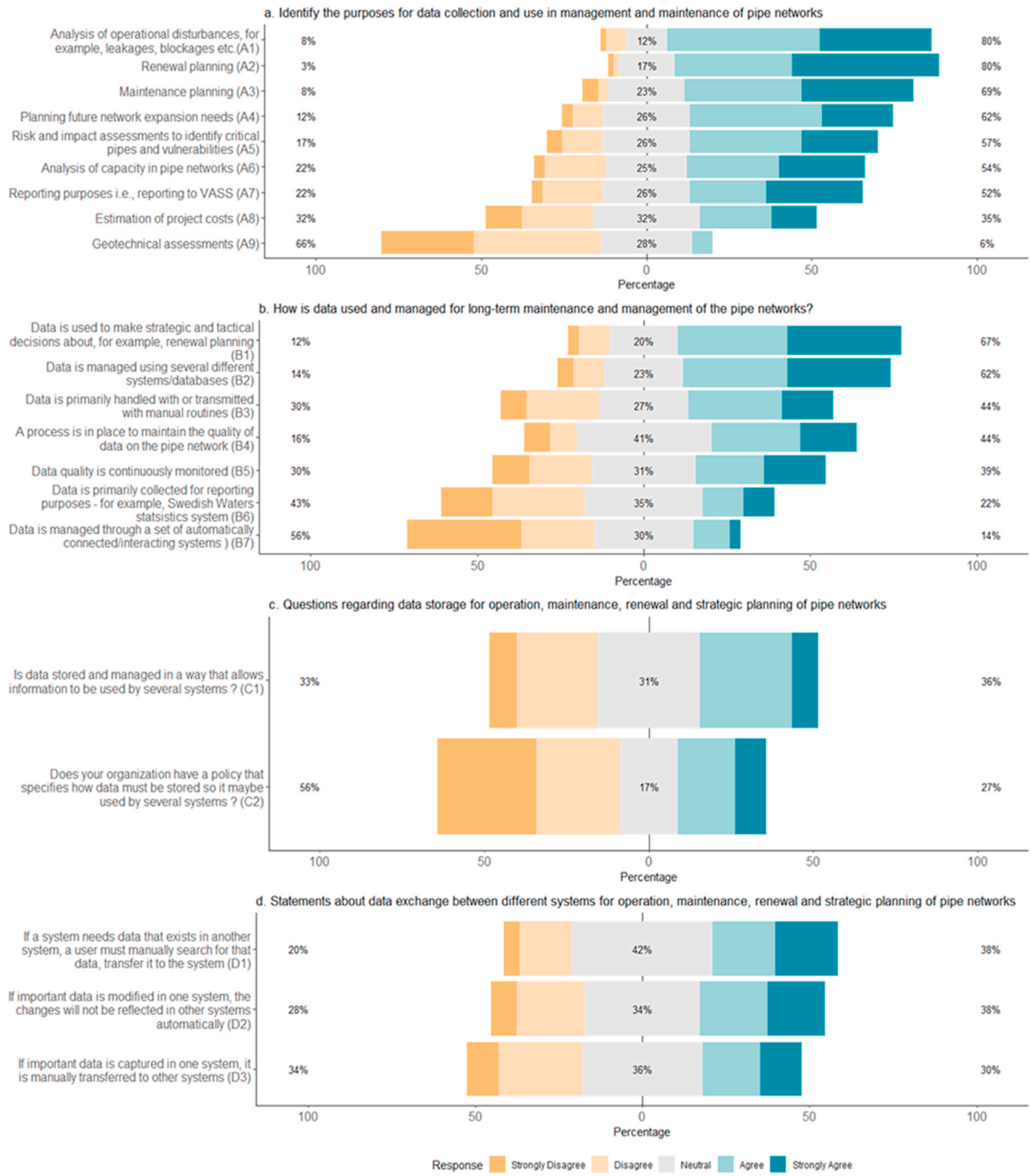

Fig. 2. Respondents' perception regarding data collection objectives(a), its utilisation (b), storage(c), and exchange (d) routines between systems for management and maintenance of the pipe networks.

more inhabitants were likelier to agree that objectives such as analysing operational disturbances, renewal and maintenance planning (A1-A3), and utilizing data for strategic and tactical decision-making (B1) were important. They also exhibited a positive correlation between these critical objectives and data usage for strategic and tactical decision-making. Conversely, smaller utilities, serving fewer inhabitants, were more likely to agree that data was manually queried between systems (D1) and manually updated between systems (D2). One respondent from a smaller utility provided insights highlighting the challenges smaller utilities face in digitalization and data integration. This respondent emphasized that smaller utilities are still in the process of digitalization and rely primarily on hardcopy maps, which suggests a predominant reliance on tacit knowledge and experience for decision-making and management within the pipe networks.

Additionally, the respondent noted that most strategies and developments within AM for pipe networks are geared toward larger utilities, leaving smaller utilities lacking insight into AM and digitalization. Smaller utilities face different Asset Management (AM) and data integration challenges compared to larger utilities, and understanding how smaller utilities can cope and move forward may be more critical. Another view is that utilities with vast scale and complexity require more sophisticated software solutions than utilities with limited budgets and simpler needs, which may find more value in straightforward, simple, more cost-effective solutions (International Water Association, 2022).

The analysis revealed no definitive patterns regarding data storage and exchange routines relative to utility type. However, it was observed that water utilities were less likely to have a clear policy regarding data management for use by multiple systems (C1) and were also less likely to manage data in a way that can be used by multiple systems (C2). Conversely, municipalities tended to agree more that data was manually queried between systems (D1) and manually updated between systems (D2).

3.3. Technical, organisational, and metadata-related factors affecting data integration in managing pipe networks

Survey responses related to various investigated technical, organisational, and metadata-related factors that may affect data integration in the context of managing pipe networks are presented in Fig. 3.

Regarding technical factors surveyed, data privacy and cybersecurity concerns (T3) and the diversity of data sources (T2) were considered to have the most adverse impact on data integration. The effect of commercial legacy systems usage was, on the other hand, considered the least impactful factor on data integration (T1). Based on additional comments from respondents, the cost of data integration between the systems and their associated maintenance and IT infrastructure (e.g., size of servers and administration) was also highlighted.

Limited human resources (O3) and problems related to limited access, permissions (O2), and authorisation (O5) to various systems for data management were considered most adversely impactful to data integration from an organisational perspective. Respondents considered the lack of policy (O4) and cost of data integration solutions (O1) to have a lesser impact on data integration. Challenges such as O1 –O5 can result in deficiencies in the data structure and composition, leading to inadequate prioritization, limited long-term maintenance planning, and a lack of objectives for data management. This observation was further supported by the comments from a respondent, which are presented below:

> "There is poor strategic management regarding prioritisation and long-term maintenance planning, including limited maintenance. Regarding data management, there are ambitions, but no goals set or responsible persons."

The results from the survey indicated a varied understanding of metadata and its significance in data integration among the respondents. Specifically, between 25% and 30% of the respondents expressed uncertainty about the role of metadata. Additionally, 20%–25% indicated that their perception was that metadata played a minimal or minor role in data integration, as shown in Fig. 3M. This disparity could suggest that either metadata is not deemed crucial by these respondents or there is a general lack of awareness regarding its importance in data integration.

3.4. Associations between data storage, exchange routines, and factors affecting data integration

The Cross-sectional analysis between surveyed data storage, exchange routines, and factors that may impact data integration provides insights into the challenges faced by managing pipe networks. The PCA and multiple correspondence analyses were conducted on various factors surveyed. Figs. 6–9 in Supplementary Data II provide biplots that illustrate the results of these analyses. Although the PCA analysis only

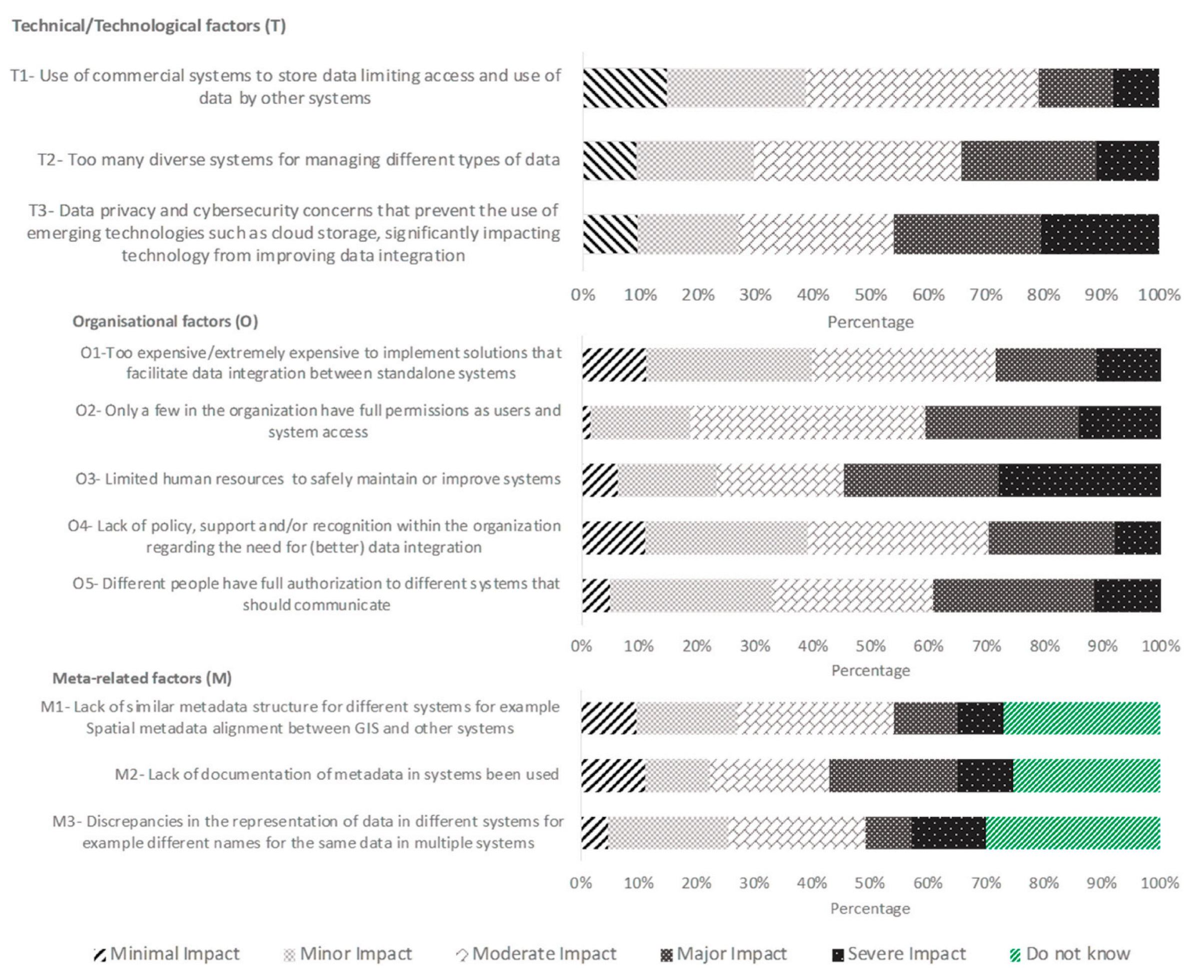

Fig. 3. Respondents' perceptions regarding technical (T), organisational (O), and metadata-related (M) factors that impact data interoperability relative to the set objectives.

accounted for approximately 36% of the variance in the responses, the multiple correspondence analyses allowed for deeper associations to be identified. Therefore, the multiple correspondence analyses analysis provided a more detailed understanding of the factors that impact data integration.

One notable finding was that the lack of metadata documentation and system unification could be linked to increased manual routines for data exchange. Respondents who reported that data was manually queried (D1), updated (D2), or transferred (D3) between systems also tended to report that the lack of metadata documentation (M2), lack of similar metadata structure (M1), and discrepancies in data representation (M3) adversely affect data integration The correlation between the variables/correlation coefficient was estimated at 0.5; see Supplementary Material II, Fig. 10.

The evaluated technical factors affecting data integration, such as diversity and the commercial nature of systems used, are also hypothesized to be drivers impacting organisational factors. For instance, respondents reported that factors such as limited authorisation to different systems (O5), limited human resources (O3), and cost (O1) had adverse impacts on data integration and also tended to answer that the use of too many diverse commercial legacy systems had an impact, and vice versa. The degree of association between variables was estimated at 0.5; see Supplementary Material II, Fig. 11. Using standardized data models, such as standardized datasets and a unified system schema, could address organisational challenges associated with data integration. This approach includes improving data and system accessibility and overcoming human resource limitations (Halfaway et al., 2006).

Approximately 70% of respondents considered data privacy and cybersecurity concerns (T3) related to cloud storage solutions to have a moderate to severe adverse impact on data integration. These respondents also agreed that there was a lack of policy regarding how data should be managed to support usage by multiple systems (C1) and that the data was not managed in a way that supported multi-systems utilisation (C2). The degree of association between variables was estimated at 0.6; see Supplementary Material II, Fig. 12. This finding suggests that respondents considered that cloud storage could improve data integration. However, data privacy and cybersecurity challenges need to be sufficiently addressed. Similar sentiments have also been given by Arnell et al. (2023).

3.5. Perceived benefits of data integration for pipe network AM

The responses to the open-ended question regarding the perceived benefits of data integration revealed several advantages for managing pipe networks. These benefits include improved data management, prioritized strategic planning, enhanced renewal efforts, more data-informed decisions, and efficient operations management. A word count analysis of the adjectives used to quantify these advantages included adjectives such as “better”, “improved”, and “increased” used 16 times. Similarly, terms such as “time-saving”, “quick”, and “access” were mentioned 15 times. Descriptive words such as “correct”, “accurate”, and “updated information” also appeared ten times.

Meanwhile, adjectives like “efficient”, “easier”, “safer”, and “advanced” were cited fewer than eight times. While the overall sentiments about the benefits of data integration were positive, the percentage of respondents who responded to the open question accounted for only 25% of respondents. This finding supports the argument that the benefits of data integration need to be substantiated more practically in the day-to-day operations of water utilities.

To further emphasise the advantages and benefits of data integration, one respondent indicated:

> “It would give a better overall picture of the entire system as a whole and enable more advanced analyses. Better efficiency and collaboration between different departments. Higher quality of the data.”

Another respondent emphasized that increased data integration can lead to

> “Better and more efficient decision-making. More effective operational support.”

The role of data integration as a mechanism to enable co-infra coordination or multi-infrastructure coordinated maintenance was also highlighted. Additionally, merging data from various systems can improve the database’s precision and dependability, making it better suited for decision-making (Carriço and Ferreira, 2021). Another respondent indicated that data integration will lead to the following:

> “Faster and more fact-based decisions regarding water and sewer network renewal and expansion. Lower environmental impact (prevent sewer overflows, infiltration, and inflow) and fewer operational disruptions. Better (more accurate) early cost estimates for renewal and network expansion projects.”

While the perceived benefits of data integration for asset management in pipe networks reported were generally positive, the notion that the benefits have not been adequately identified or quantified has been highlighted by a respondent, which indicates that:

> “The benefits and costs of integrating different IT systems (and maintaining this integration) have not been adequately identified.”

4. Discussion

4.1. Relevance of data integration in asset management and digitalization for municipal pipe networks

Whilst evidence on the benefits of integrating data to enhance the efficiencies of objective-driven asset management of pipe networks is growing in the literature (e.g. Okwori et al., 2021), municipalities and water utilities face ongoing challenges in implementing integrated data and synchronized systems for structured analytics and decision-making (Fileto, 2001; Carriço et al., 2020; Emilsson et al., 2021). The results of this study supported these findings, indicating that whilst the potential benefits of data integration are recognised, more evidence on the types and magnitudes of benefits accrued in practice is required to facilitate the adoption of data integration practices in the day-to-day operations of water utilities. To better substantiate these benefits, one approach is to focus on improving integration, i.e., interoperability between systems between different datasets, leading to identifying and quantifying synergies, such as those accrued by the combination of outputs of hydraulic models, SCADA systems, and IoT devices. By leveraging these synergies, it is possible to achieve better performance and hydraulic efficiency for pipe networks (Hampapur et al., 2011).

These synergies could also improve proactive asset management (Carriço et al., 2020), collaboration, and multi-utility coordination (Vanier, 2014; Daulat et al., 2022). Despite attempts to leverage such data synergies, data suggests that water utilities and municipalities are yet to fully realise the potential benefits in practice with a combination of site-specific, organisational and operational factors identified. For example, data integration requirements of water utilities vary greatly, necessitating more modular solutions tailored to specific objectives, as evidenced by the range of responses to questions related to data storage and exchange routines. Further, approximately 60% of organisational reliance on legacy and commercial systems hinders effective data integration. For example, one respondent highlights a commercial system’s inability to adequately address the needs of managing the pipe networks effectively.

> “The same system is used throughout the organisation. However, our system is best suited for fibre and electricity.”

In addition, responses indicated that the trade-off between perceived costs (including person-hours) and the potential benefits of data integration requires further research at both strategic and operational levels of asset management within water utilities where perspectives on where an appropriate balance should fall.

4.2. Perceived challenges of data integration for asset management of pipe networks in the Swedish context

This study identified perceived challenges and drivers to achieving data integration for effective asset management in pipe networks from practitioner perspectives. The challenges can be categorized into two groups: direct (respondent lead) and indirect (emerged from data analysis).

The first category relates to limited resources, limitations due to the diversity and use of commercial legacy systems (Carriço and Ferreira 2021), concerns about data privacy and cybersecurity (Ahonen et al., 2019) and semantic, syntactic, and schematic heterogeneities inferred from the inconsistency of data storage routines and data exchange routines. Whilst these challenges have been identified by previous studies and options for their mitigation suggested, e.g. Halfawy et al. (2002), Beck et al. (2007, 2008), Panetto et al. (2016), and more recently, Fossatti et al. (2020), the fact that such challenges exits indicate the proposed solutions are not feasible in practice, or a reluctance to implement change at an organisational level (i.e., institutional inertia).

The indirect challenges involved data collection objectives considered common by respondents such as analysing operational disturbances, renewal planning, maintenance, network expansion, and risk assessments. These objectives may require high levels of data integration from varied sources, as emphasized by Grigg (2003), Rokstad et al. (2016), and van Riel et al. (2014). However, differences in data storage and exchange responses suggest a potential misalignment between these objectives and current storage and exchange practices. The multiple correspondence analysis (supplementary material II, Figs. 2–4) also suggests that smaller utilities (serving relatively lower population densities and associated support infrastructure) often use manual data exchange, further impacting the ease with which data sets can be integrated. Further indirect challenges observed regarding gaps are discussed in the following section.

4.3. The gap between theory and practice

The survey results evidence the gap between the theoretical concepts of data integration, as outlined in literature, and the lack of evidence supporting the realisation of these benefits in practice. Specific areas include.

4.3.1. Data quality

Studies by e.g. Jwan Khisro (2020) and Daraio et al. (2022) emphasized that data quality is critical for enhanced interoperability. However, the results of the present survey showed mixed responses related to data quality maintenance practices. Specifically, whilst 44% of respondents reported that their organisation has a process to maintain data quality, 41% responded neutrally, with 16% identifying that their organisation did not currently have a process to maintenance data-quality. Similarly, 39% of respondents agreed that data quality in their organisation is continuously monitored, 31 % had neutral opinions, and 30% disagreed. The range of approaches to data-quality management identified here highlights inconsistencies in data quality assurance practices within and between organisations, with impacts on the potential for data integration and the type and magnitude of benefits accrued.

4.3.2. Meta-data documentation, structure, and representation

The survey indicated a gap in understanding the impact of metadata-related factors on data integration at the structure and exchange levels for Swedish water utilities. Specifically, at least 30% of respondents did not understand how the lack of metadata documentation and the similarity of its structure between systems and representation could impact data integration. Twenty-five percent of the respondents also acknowledged that metadata had minimal or moderate impacts on data integration. This finding suggests that about 70% of the respondents either did not recognize the importance of metadata-related factors or considered it to have a minimal impact. However, previous studies such as Halfawy et al. (2003), Beck et al. (2007, 2008), Halfawy (2008), and Carriço et al. (2022) have emphasized the significance of semantic and syntactic heterogeneities in metadata documentation, structure, and representation that affect data integration.

4.3.3. Diversity and use of commercial legacy systems

The survey findings indicated that most respondents did not view commercial legacy systems hindering data storage and exchange. However, previous research have suggested otherwise (Fileto, 2001; Carriço and Ferreira, 2023). Such systems often have “lock-in effects”, inhibiting data use across different platforms. Water utilities often use multiple systems that are not mutually compatible. This incompatibility complicates data integration, which is accentuated by technological gaps between old and new systems (Iqbal et al., 2003; Muketha and Ondimu, 2012). Furthermore, these legacy systems may reduce a utility’s data autonomy, limiting its operational effectiveness (Carriço and Ferreira, 2023).

4.3.4. Data integration policy

The survey findings suggested that the prevalence of manual data routines may be associated with a lack of policy. Evidence of this can be observed, with results indicating that 56% of respondents reported an absence of policy within their organisations regarding data storage for utilisation by multiple systems. The multiple correspondence analysis (supplementary material II, Fig. 5) also showed a high degree of association among respondents that indicated policy for data usage by multiple systems was absent, and more manual routines were used for data exchange (coefficient of association of 0.6). Policy is considered a driver of organisational decision-making in utilities (Almeida et al., 2022).

4.3.5. Lack of human resources

Approximately 80% of respondents considered limited human resources to maintain or improve systems to have a moderate to severe impact on data integration. This finding aligns with Emilsson et al.’s (2021) report on asset management in Swedish water organisations. However, it may not be universal, as only a few studies, such as Carriço et al. (2022), have reported similar in Portuguese water utilities.

4.3.6. Cost of data integration solutions

The cost associated with establishing and maintaining data integration can be considered from different standpoints: the availability of competence, i.e., technological skills necessary for integration tasks and time allocation, which depend on economic and financial circumstances. Notably, the survey findings indicated a considerable level of consciousness regarding competency but not as much for time allocation. These costs can be considered one of the major barriers to data integration (Ahonen et al., 2019).

4.4. Implications for stakeholders, practice, and plausible pathways forward

The perceived challenges to data integration highlighted in the preceding section may pose several implications for various stakeholders, i.e., water utilities, regulators, software developers and researchers. Below, some of the more apparent implications are presented.

Potential inconsistencies in data storage and exchange routines and perceived associated misalignments that may arise from such routines may result in adverse effects such as data silos and data fragmentation Halfawy (2008). Hence, there is a need for a process that aligns data integration needs with the strategic objectives of asset management in pipe networks. The methodology proposed by Noshahri et al. (2021), which categorises data needs based on sewer inspection methods, offers an illustrative example of such a process. Furthermore, as Arnell et al. (2021) emphasized, such a process is crucial, given the varying digitisation needs across different utilities.

The need for standardisation and open architecture frameworks and solutions, such as using middleware or Application Programming Interface (APIs), has been consistently highlighted in previous studies as solutions to data integration and interoperability issues. Examples of these studies and frameworks include Halfawy et al. (2006), Vemulapally and Sinha (2009), Angkasuwansiri and Sinha (2018), Hernández et al. (2020), Jin et al. (2021) and Webber et al. (2022). However, the discrepancy between theory and practice regarding metadata documentation, representation, and structure poses significant challenges to using and adopting such frameworks and solutions to achieve more synchronized data and systems. Another plausible reason for the slow adoption of such standardised protocols or frameworks could be the lack of a coherent policy regarding how data can be stored so it can be used by multiple systems, which is also highlighted in this study.

The diversity of commercial legacy systems in water utilities may lead to "lock-in effects," limiting data access and use for asset management of pipe networks. This challenge has been highlighted by researchers like Kasunic and Anderson (2004) and Carriço et al. (2020), who state that modern technologies offer potential solutions. Cloud storage can centralize data, blockchain can ensure consistency, and 5G can reduce latency (Mathew, 2008; Carriço and Ferreira, 2021; Ugarelli, 2021; Haddara et al., 2021). However, concerns about data privacy appear to hinder the adoption of these solutions, as noted by Ahonen et al. (2019), and a potential walkaround to these concerns has been proposed by (Arnell et al., 2023), some of which include Information classification and clear data ownership.

Implications of poor data quality for data integration and interoperability of systems may intensify semantic heterogeneities like unit mismatches, spatial reference variances, and scale discrepancies (Beck et al., 2007). For example, unreliable data can skew analyses, leading to costly maintenance errors. It can also misguide resource allocation, causing disproportionate maintenance efforts. Additionally, integrating diverse data sources becomes challenging. Hence, a more profound comprehension of data quality, maintenance, and implications for data integration and system interoperability is essential.

4.5. *Comparative contextualisation of survey findings and limitations*

The survey findings provided valuable insights into the challenges of data integration for asset management in pipe networks as perceived by practitioners. Whilst the response rate of approximately 32% indicates that the survey covered a broad range of responses, further research is needed. For example, the identified challenges associated with the absence of policies for data storage, facilitating its use across various systems is a consistent finding in Swedish-based studies and reports such as Syssner and Jonsson (2020), Arnell et al. (2021), Emilsson and Adrup (2021), Arnell et al. (2023) and Bennich et al. (2023). In contrast, we identified challenges related to metadata, the diversity and lock-in effects of commercial legacy systems, effects of data quality, and concerns over data privacy and cybersecurity (especially in cloud storage) that have been widely reported in more international contexts. Examples include Vemulapally and Sinha (2009), Opara-Martins et al. (2015), Panetto et al. (2016), Carlo et al. (2011), Garramone et al. (2020), Jin et al. (2021), Carriço and Ferreira (2023) and International Water Association (2022) This study provides a detailed picture of current practices in Swedish water utilities. However, future research could address developments through a longitudinal study, which may involve replicating the survey in Sweden and other countries after a set period to trace the evolution of practices.

5. Conclusion

The main finding of this study was that data storage and exchange routines were perceived to be inadequate to support the expected levels of data integration needed for commonly identified data collection objectives. This misalignment gives rise to data silos and fragmented data structures, which in turn negatively impact asset management within pipe networks. The degree of this misalignment can differ depending on the size of the utility and its digital maturity level.

The study also identified several perceived data integration challenges in the context of pipe network asset management in Sweden. Previous research has also highlighted these challenges, suggesting persistence and indicating that current solutions might be impractical or not widely adopted. The identified challenges also shed light on the reasons for this reluctance. These challenges and potential pathways include the need to practically substantiate the benefits of data integration in the pipe-network asset-management context, which was also highlighted in the survey results. Discrepancies in perception between theory and practice can be considered one of the plausible reasons for the lack of substantiation. There are several areas where such discrepancies were observed to be more prominent, such as metadata documentation, structure, representation, commercial legacy systems, cost of data integration and a lack of policy guiding how multiple systems should use data. The heterogeneity and lock-in effects of commercial legacy systems and data privacy and cybersecurity concerns were also emphasized. It is hypothesized that mitigating challenges associated with the lock-in effects and data privacy will positively influence identified organisational factors that affect data integration, such as inadequate resources and restricted system access.

The identified challenges provide a roadmap for stakeholders to enhance data synergies for more objective-driven management of pipe networks.

CRediT authorship contribution statement

E. Okwori: Writing - review & editing, Writing - original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **M. Viklander:** Writing - review & editing, Visualization, Supervision, Methodology, Data curation, Conceptualization. **A. Hedström:** Writing - review & editing, Writing - original draft, Visualization, Supervision, Resources, Project administration, Funding acquisition, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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