Enhancing Knowledge Transfer and Reuse of Information Resources through a Specialised Metadata Catalog for Urban Digital Twins

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Keywords: Urban Digital Twins (UDT), Metadata Catalog, Interoperability, Knowledge Transfer.

Abstract

Smart city initiatives depend on robust data management to ensure the efficient use of digital resources. Managing data in these projects, especially during the development and operation of Urban Digital Twins (UDTs), is a complex task. While metadata catalogs provide a foundation for interoperability and data integration, their potential to enable knowledge transfer and reuse within and across municipalities in the UDT context has not yet been sufficiently explored. Through the formulation and empirical evaluation of four hypotheses on design principles for a specialised metadata catalog, this paper investigates how knowledge transfer and reuse in UDT environments can be supported by such a catalog. The study combines literature analysis with qualitative insights from two real-world case studies. The results confirm that a comprehensive metadata schema adapted to the components of UDTs, the use of FAIR-compliant open standards, multi-stakeholder access mechanisms, and knowledge graph representations of digital resources support the discoverability, reuse, and transfer of digital resources within and across organisations. The evaluation further reveals that usability and governance structures remain critical challenges that require future research.

1. Introduction

The concept of Digital Twins was originally developed in manufacturing and aerospace industries for real-time simulation and monitoring (Grieves and Vickers, 2017). It has been extended to urban contexts as Urban Digital Twins (UDTs) (Batty, 2018). Their implementation requires integrating heterogeneous data, tools, and services across domains and organisations, creating challenges for interoperability, scalability, and information management (Menon et al., 2023; Schubbe et al., 2023). The reuse of existing solutions and the transfer of knowledge across municipalities are therefore essential to reduce redundant effort and improve efficiency (Croket et al., 2025). Metadata catalogs are widely used for data discovery and interoperability in domains such as Spatial Data Infrastructures (SDI) and Open Data, but their role in supporting knowledge transfer and reuse of complex, multi-component solutions in UDT contexts remains underexplored. Existing approaches often lack mechanisms to represent semantic relationships between datasets, tools, and use cases, which are essential for understanding dependencies and facilitating transferability across urban contexts. This paper investigates how a specialised, semantically enriched metadata catalog can support knowledge transfer and reuse in UDT environments. Based on literature analysis and two real-world case studies, TwinBy[1] and SAVeNoW[2], it formulates and empirically evaluates design hypotheses for a metadata catalog grounded in FAIR principles (Boeckhout et al., 2018), and knowledge graph approaches has been developed and applied to real-world case studies.

2. Literature Review

UDTs represent digital models of cities that integrate static and dynamic data to support urban planning, infrastructure management, and decision-making (Abu-Matar, 2016; Batty, 2018). They combine heterogeneous data from multiple domains, such as IoT data, simulations, and static administrative sources, enabling the analysis of current conditions and the evaluation of future scenarios (Menon et al., 2023). Existing frameworks, such as the Smart City Charter (Günthner et al., 2017) and DIN SPEC 91607 (2024), highlight the importance of standardised infrastructures, data governance, and interoperability. Such frameworks aim to facilitate knowledge exchange and enable cities to reuse existing solutions and best practices when developing their UDTs (Croket et al., 2025). Catalog services play a central role in these infrastructures by enabling the discovery, access, and management of distributed data sources. Early approaches, such as the prototype of a Linked Open Data platform for Urban Information Modelling (Lopez et al., 2012), demonstrate the potential of semantic technologies in this context. Catalog services are widely applied in the Spatial Data Infrastructures (SDIs) and Open Data Platforms (ODPs). While SDIs are traditionally focused on geospatial datasets, ODPs provide access to a broader range of data types. However, both approaches offer limited support for representing semantic relationships between heterogeneous resources such as IoT devices, simulation results, analytical tools, and their integration into complex use cases (Knezevic et al., 2022). These limitations indicate the need for a specialised metadata catalog for UDTs, i.e., a catalog specifically designed to represent heterogeneous urban resources, their semantic dependencies, and their reuse within and across municipalities. Bucher et al. (2020) emphasise the need for catalog-based infrastructures to go beyond traditional SDIs by integrating semantic web technologies and governance models that facilitate knowledge sharing, interoperability, and sustainable metadata management principles. Besides SDIs and ODPs, the role of metadata for reusing data beyond its original context has been the subject of scientific studies in several domains, including research data management, environmental and life sciences, and reproducible computational research. FAIR-oriented approaches emphasise the need for comprehensive, semantically explicit, and interoperable metadata to support findability, accessibility, interoperability, and reusability (Beretta et al., 2021). Knowledge transfer in UDTs occurs both within and across municipalities, as solutions are adapted to

[1] https://www.stmd.bayern.de/themen/twinby/
[2] https://savenow.de/en/

different contexts, e.g., within different departments of the same city or across municipalities. Applications developed for specific use cases can be transferred to similar contexts or scaled from local to regional levels, supporting collaboration and knowledge exchange (Dembski et al., 2020; Schubbe et al., 2023). Metadata catalogs can support this process by documenting, linking, and organising digital resources and workflows, thereby enabling discovery, reuse, and interoperability across domains and stakeholders (Günthner et al., 2017; Lnenicka et al., 2024). As many municipalities face similar challenges, the ability to transfer digital solutions across use cases and sectors is increasingly important for reducing redundant effort, promoting collaboration, and fostering innovation. Their role in explicitly supporting knowledge transfer and reuse in UDTs remains insufficiently explored.

3. Research Questions, Methodology and Hypotheses

This study follows a qualitative research approach, combining a literature review with a thematic analysis of participant feedback from two real-world case studies. It addresses two main research questions: How should a metadata catalog be structured, designed and implemented to support municipalities in reusing existing solutions, reducing development effort, and transferring best practices within Urban Digital Twins? What role do FAIR principles and knowledge graphs play in enabling knowledge transfer and reuse in UDTs metadata catalogs?

Based on the literature review and our own experience from previous smart city data management projects, the following hypotheses were formulated and evaluated through a structured thematic analysis of participant feedback, as documented in Section 5:

H1: A metadata schema representing heterogeneous resources and their semantic relationships is required to enable the documentation, discovery, and reuse of complete UDT use cases and their dependencies. A comprehensive metadata schema is required to describe heterogeneous UDT resources, including datasets, geoobjects, devices, software, services, projects and use cases (Knezevic et al., 2022). In distributed environments, it should support structured representation and efficient discovery across stakeholders (Fox et al., 2024; Gil et al., 2024). It should represent both individual resources and complete use cases, including their components and dependencies (DIN, 2024), while enabling semantic relationships between resources (von Richthofen et al., 2022). This ensures consistent interpretation of datasets and facilitates discovery and advanced querying. The use of standard ontologies (e.g., OWL, RDF) enables explicit modelling of dependencies, forming knowledge graphs that support advanced querying and analysis. Knowledge graphs offer powerful analysis by linking different entities through defined relationships, as demonstrated by von Richthofen et al. (2022). By analysing these connections, municipalities can more easily identify which components have high reuse potential and may be worth prioritising for reuse. For example, graph-based centrality measures can be used to detect highly connected resources that are referenced across multiple datasets, services, and applications. Such resources can be interpreted as critical components within the UDT ecosystem, as they form the basis for multiple use cases and are therefore particularly relevant for reuse and maintenance (Knezevic et al., 2026). This also supports strategic planning, as highly connected resources may indicate critical data infrastructure that other cities can build upon or contribute to, helping stakeholders to understand relationships between datasets, tools, and applications, facilitating transfer and reuse across context. To support knowledge transfer and reuse, the schema should represent not only individual resources but also complete use cases, including their components and dependencies (DIN, 2024; Gil et al., 2024). The metadata schema should support rich textual descriptions and visual elements (e.g., images and diagrams) to improve understanding. Structured metadata enhances discoverability through efficient search and filtering (Fox et al., 2024).

H2: Standardised and interoperable metadata models and APIs facilitate cross-organisational knowledge transfer. Standardisation is essential for integrating heterogeneous UDT resources. Metadata should ensure that resources are Findable, Accessible, Interoperable, and Reusable (FAIR) by being structured, machine-readable, and consistently interpretable across systems and stakeholders. This requires shared vocabularies, standardised formats, and well-defined interfaces that support discovery, access, and metadata integration across organisational boundaries. The catalog should adopt open standards and APIs to enable discovery, interpretation, and reuse across systems and stakeholders (Kirstein et al., 2019). Compliance with open standards promotes interoperability and prevents vendor lock-in. Internationally recognised standards such as DCAT-AP[3] enable structured, machine-readable descriptions of datasets and improve interoperability between data catalogs. Open standards enable metadata harvesting across distributed catalogs, ensuring compatibility between systems and supporting bidirectional harvesting mechanisms. For example, if multiple cities maintain UDT catalogs based on a DCAT-AP-compatible schema, it becomes straightforward to establish aggregated catalogs at regional or state levels that harvest metadata from local sources. This allows centralised discovery of urban data resources and use cases, thereby facilitating knowledge sharing and reuse across municipalities. This approach does not transfer the information resources themselves (e.g., simulation models or applications), but provides structured metadata that enables stakeholders to discover, understand, and potentially adapt existing solutions. Standardised APIs enable integration with external applications and services, extending the usability of catalog data beyond the catalog platform itself.

H3: The catalog must support multi-tenancy, allowing direct multi stakeholder collaboration.

Mechanisms including organisation-specific role-based access control and cross-organisational visibility are necessary to enable joint metadata maintenance and knowledge exchange across organisations. Multi-tenant architectures enable concurrent usage, identity management, and coordinated access across organisations (Mishra, 2023). By allowing stakeholders to directly maintain their own catalog entries through organisation-specific permissions, the catalog functions as a collaborative platform rather than a static metadata repository. Without such capabilities, metadata management is likely to remain fragmented, increasing administrative overhead and hindering collaboration and reuse across municipal and institutional boundaries. Isolated catalog spaces and separate user accounts can further lead to duplicated maintenance efforts, inconsistent metadata, and limited transparency regarding responsibilities and ownership. To promote transparency and collaboration, catalog entries from different organisations should be visible within the system, subject to appropriate access control, supporting data discovery, knowledge exchange, and joint projects. Users must be able to access multiple organisations through a single account while holding different

[3] https://interoperable-europe.ec.europa.eu/collection/semic-support-centre/solution/dcat-application-profile-data-portals-europe

https://doi.org/10.5194/isprs-annals-XII-4-W2-2026-97-2026 | © Author(s) 2026. CC BY 4.0 License.

roles in each organisation, reflecting distributed governance structures, particularly in smaller municipalities, and ensuring they can maintain only the catalog entries for which they are authorised. Providing such unified access reduces administrative overhead, simplifies user management, and enhances usability.

H4: Usable interaction mechanisms are necessary to enable users to consistently create, interpret, and link metadata entries within a UDT catalog. Usability is particularly important for municipalities with limited technical expertise. Even well-documented resources remain underutilised if users cannot easily find or understand them. As shown in usability studies of open government data portals, intuitive navigation, efficient search, and clear data presentation significantly improve user engagement and interaction (Molodtsov and Nikiforova, 2024). The catalog should provide an intuitive user interface with efficient navigation, search capabilities, and clear visualisations to support data exploration and understanding. This includes a visual classification of information resources - such as static datasets, software, online applications, and sensors - as well as a clear representation of the underlying knowledge graph structure. Collaboration mechanisms are essential for maintaining and improving catalog content: features such as user feedback, comments, and dataset evaluations support continuous improvement and facilitate knowledge exchange among stakeholders (Diaz and Breux, 2021). Notification mechanisms can further support user engagement by informing stakeholders about updates and new resources.

4. Catalog Prototype and Case Studies at the City and Cross-City Level

To evaluate the hypotheses formulated in Section 3 in practice, the Smart District Data Infrastructure (SDDI) catalog – an extension of the open-source software CKAN and a reference implementation of a specialised metadata catalog for UDT – is used in two real-world case studies. The conceptual foundations of the SDDI framework, including the extension of catalog services to manage heterogeneous urban resources and their relationships, have been described in detail by Knezevic et al. (2022). The SDDI catalog introduces a metadata model in which resources are represented as catalog entries and classified into nine categories: *Dataset, GeoObject, Device, Online Service, Online Application, Software, Method, Project,* and *DigitalTwin*. Each category represents a specific type of information resource, ranging from static datasets and physical objects to analytical methods and software components. The *DigitalTwin* category represents a collection of interconnected resources defined for a specific use case. This enables the catalog to describe not only individual resources but also their aggregations and dependencies, including the usage of persistent identifiers. The SDDI Catalog serves as a central component for managing distributed information resources in UDTs, enabling stakeholders to access, link, and exchange data across domains and organisations (Donaubauer et al., 2023; Knezevic et al., 2024). Its successful use also depends on clear processes, training, and supporting educational materials (e.g., through online learning materials such as the *CUT Academy*[4] or *Digital.Campus Bayern*[5,6] learning platform) and professional services provided by independent experts. The catalog enables the consistent integration and management of data originating from diverse stakeholders, sources, formats, and domains. Its metadata schema supports defining multiple UDTs by linking information resources across projects, municipalities, and applications. The schema defines three semantic relationship types (namely part of, depends on, links to) between catalog entries, that differ in their semantics. The catalog can be interpreted as a directed, typed graph, in which nodes represent catalog entries, and edges represent the semantic relationships between them. A detailed description of the resulting knowledge graph structure, including the logical properties of each relationship type and their implications for graph-based analysis, is provided in Knezevic et al. (2026). This allows the formulation of advanced queries and the analysis of dependencies and reuse relationships across datasets, tools, and applications (Knezevic et al., 2026). The hypotheses (Section 3) have been tested by using the SDDI catalog in two different real-world case studies: exemplified by the SaveNoW project (Section 4.1), we analyse the support of a specialised metadata catalog for reusing information resources at the city scale. The TwinBy project (Section 4.2) is used as an example for knowledge-transfer at the cross-city level.

4.1 Reusing Information Resources at the City Scale Level – The SAVeNoW Project

SAVeNoW was a research project focused on developing and operating a Digital Twin for urban traffic, using the city of Ingolstadt in Germany as a case study. The project aimed to create a virtual simulation environment to analyse individual traffic situations, behaviours, and innovative mobility concepts, particularly assessing the impact of autonomous driving on safety, emissions, and efficiency. By combining simulation technologies with real-time data integration, the project enabled the evaluation of planning scenarios prior to physical implementation. One of the results of this project was the SAVeNoW SDDI Catalog[7], which demonstrates the use of a UDT metadata catalog for a large city in a research-oriented environment involving many stakeholders outside of the city administration, like car manufacturers and their partners. By the end of the project, the catalog contained 87 catalog entries (Table 3) contributed by 19 participating organisations. This catalog facilitated the efficient management of the projects Digital Twin for Ingolstadt and demonstrated the potential for reuse at a larger scale and in different urban contexts. The use case highlights the role of the catalog in supporting cities in addressing urban challenges, optimising resource use, and improving reaction time to urban events and environmental change. It enables access to pre-configured simulation scenarios for traffic flow, emergency response, and environmental impact assessment. Figure 1 shows a sub-graph of the knowledge graph, where nodes represent individual catalog entries, and arrows represent semantic relationships between them. The figure illustrates how the Online Service *Traffic data from Ingolstadt* (orange) is reused across multiple applications and processes. The catalog entry refers to a sensor service that gives access to real-time data on traffic densities in the roads and is linked to several online applications (grey) and a simulation method (red), demonstrating how the sensor service supports different analytical and operational components. It also shows the reuse of the sensor service by two subprojects (black), with the direction from the sensor service *Traffic data from Ingolstadt* to the subproject *Model Structuring and Architecture,* indicating that the data has been produced by this subproject, and the opposite direction from the subproject *Social participation and related research questions* to the

[4] https://www.connectedurbantwins.de/wissenstransfer/cut-akademie/
[5] https://www.digitalcampus.bayern/page/course/878
[6] https://www.digitalcampus.bayern/page/course/875
[7] https://catalog.savenow.de/

sensor service *Traffic data from Ingolstadt* indicating that it is being reused in this subproject.

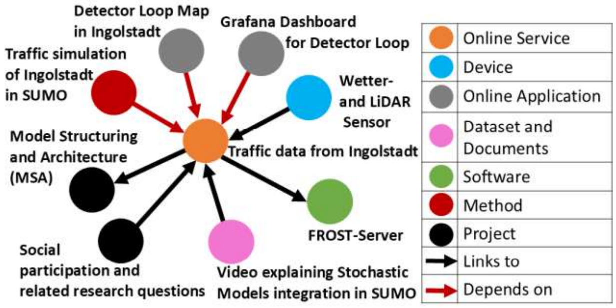

Figure 1: Sub-graph showing the reuse of the online service *Traffic data from Ingolstadt* across multiple online applications and subprojects, indicated by linked metadata catalog entries.

4.2 Knowledge-Transfer at the Cross-City Level – The TwinBy Project

The TwinBy project supported 17 municipalities in Bavaria, Germany, in developing UDT use cases from four domains: Energy and Environment, Health and Mobility, Small Municipalities (up to 10,000 citizens), and cross-domain. The project ran from April 2023 to March 2024 and resulted in the TwinBy SDDI Catalog, which included 432 catalog entries (Table 3) contributed by 25 organisations. The project demonstrates how a specialised UDT metadata catalog supports cross-city collaboration, particularly for smaller municipalities with limited financial and technical resources.

The catalog acted as a "Wikipedia for Smart City Use Cases", as it provided a centralised and structured repository in which use cases were documented, semantically described, and made accessible across municipalities, enabling users to explore and build upon existing solutions. Unlike open and unstructured platforms, the catalog is based on a structured metadata model that ensures consistent representation and interpretation of entries. To maintain data quality and avoid redundant or inconsistent entries, governance mechanisms were introduced, including clearly defined responsibilities, validation rules (e.g., mandatory metadata fields), versioning, and role-based access control. Smaller municipalities could reuse solutions developed by other cities, reducing the need for costly custom development. The central metadata catalog supported the discovery and structured organisation of distributed information resources, enabling the representation of all information resources and their relationships. Municipalities could explore existing use cases from other cities and adapt them to local contexts, rather than developing solutions from scratch. For example, if a neighbouring city has implemented a mobility management use case based on traffic and air quality data, municipalities do not directly replicate the solution. Instead, the catalog enables them to examine the underlying components, including datasets, software tools, sensors, and involved stakeholders, as well as the semantic relationships between them. These relationships describe how different resources depend on and interact with each other, for example, which datasets are used by a specific application, or which sensors provide input for certain analyses. This allowed municipalities to understand how the solution was realised, assess its transferability, and identify which elements could be adapted to their local context and which gaps, such as missing data sources or sensors, need to be addressed. This approach provided a structured basis for analysing existing solutions and identifying reusable components. The standardised metadata schema and semantic links supported data integration by enabling a structured representation of heterogeneous information resources and their relationships. Metadata standardisation also made catalog entries created by different municipalities comparable and facilitated mutual understanding of each other's digital resources. As part of the TwinBy project, the SDDI catalog was hosted centrally, which was necessary for many smaller municipalities, as they lacked the technical infrastructure and expertise required to operate and maintain their own catalog instances independently. Training materials such as videos, presentations, checklists, and templates were created to be reused by other municipalities, regions, and countries looking to implement similar initiatives.

Figure 2 illustrates how a centrally maintained *3D building model – LoD2* (purple) dataset provided by the state mapping agency has been reused and referenced by multiple municipalities and UDT applications (pink). This dataset acts as a central resource within the network and is linked to several Digital Twin use cases and online applications across different cities. The organisations associated with each resource are written in blue. The arrows and their direction represent different types of semantic relationships. By explicitly representing these dependencies and links, the knowledge graph enables stakeholders to identify central resources, understand their role within different use cases, and assess their reuse potential across municipalities (Knezevic et al., 2026). For example, the dependency between the UDTs of several municipalities in the *Statewide 3D building models - LoD2* dataset indicates that this dataset has been validated as useful across multiple contexts. New municipalities developing similar UDTs can treat such widely referenced datasets as trusted, community-validated resources.

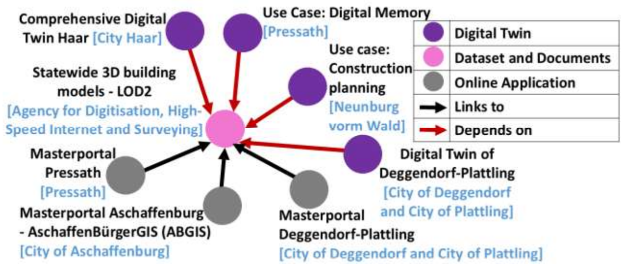

Figure 2: Shared use of a centrally maintained 3D building model (3D building models – CityGML LoD2) by multiple cities and applications.

5. Hypothesis Evaluation

5.1 Evaluation Methodology

Building on the catalog prototype and case studies presented in Section 4, this section evaluates the hypotheses defined in Section 3 based on qualitative user feedback and catalog content analysis. Given the relatively small number of participants and the applied, context-specific nature of the case studies, the evaluation relies on qualitative methods rather than statistical analysis. However, this approach aligns with the exploratory character of the study, which aims to derive and assess design principles for a specialised UDT metadata catalog in real-world settings rather than to statistically accept or falsify hypotheses. The participants' feedback was categorised into strengths and limitations of the SDDI catalog and is presented in Section 5.2. Additionally, the contents of the catalog instances were analysed qualitatively and using graph-theoretic measures to assess how the metadata schema was applied in practice, identify reusable components and common dependencies, and evaluate the quality and completeness of the resulting catalog entries (Section 5.3). The hypotheses were then evaluated based on the combined findings from user feedback and catalog analysis (Section 5.4). In the TwinBy project, feedback was collected iteratively through partner discussions and two online user workshops involving 32 participants who actively used the catalog. An interactive collaboration platform (Conceptboard) was used to gather observations, suggestions, and concerns, allowing participants to contribute and vote on key issues. The vote counts in Tables 1 and 2 reflect the votes received by posts in each theme, indicating relative importance rather than statistical significance. Participants were asked to post their observations, suggestions, and concerns directly on the shared board and to vote on the contributions of other participants. Feedback was inductively grouped into thematic categories. This format enabled participants to highlight the most relevant aspects of the catalog while ensuring that different perspectives were captured. The discussions focused on the practical applicability of the catalog, possible use cases, and requirements for further development. The sessions among project partner leads provided insights into the implementation of UDT use cases and the supporting SDDI processes. In the SAVeNoW project, due to its smaller scale and different project structure, feedback was collected qualitatively through individual discussions with participating project partners. These discussions focused on the practical use of the catalog within the project, including its role in managing data, linking resources, and supporting the implementation of the developed solutions. While no formal voting or structured aggregation of feedback was conducted, the insights obtained provided valuable qualitative evidence and were consistent with the findings from the TwinBy project, particularly regarding usability, governance requirements, and the need for clear guidance and training.

5.2 User Feedback

One of the main findings was that municipalities required significant support in the early project phase, particularly in understanding the objectives of the project, defining realistic use cases, and assessing the available data resources. Project partners also emphasised the importance of clearly communicating the added value of SDDI and UDT approaches to municipal decision-makers in order to ensure continued engagement and support. Participants highlighted several strengths of the SDDI Catalog, particularly its ability to support knowledge sharing, improve the discoverability of use cases, and facilitate collaboration across organisations (Table 1). Several of the most frequently mentioned strengths directly relate to knowledge transfer and reuse of digital resources, including the catalog's role as a shared knowledge base reducing time-consuming information searches (3), its explicit support for knowledge transfer in UDT development (5), the inspiration provided through documented use cases and templates (6), and the replicability of solutions across municipalities (7). At the same time, challenges were identified, particularly regarding stakeholder engagement, governance responsibilities, usability, and interoperability between systems (Table 2). Several of these challenges directly affect the catalog's ability to support knowledge transfer and reuse, including coordination difficulties between different data catalogs and infrastructures (2), unclear responsibilities for maintaining catalog entries (5), and difficulties in creating and linking metadata entries (7). For example, participants reported that choosing the appropriate type and direction of semantic relationships between entries proved challenging without prior training, resulting in inconsistent knowledge graph structures that limited cross-organisational interpretability. Furthermore, participants frequently reported that effectively managing metadata for a huge number of sensors, including their type, location, accuracy, ownership, update frequency, and operational status, is technically and organisationally challenging. Sensor observations are typically provided through heterogeneous sensor services and platforms (e.g., IoT platforms or Sensor Observation Services), which differ in data models, interfaces, and update mechanisms. Sensors are often managed by different departments or third parties, and their configurations may change frequently due to maintenance, relocation, or upgrades. For UDTs, accurate sensor metadata is critical to ensure that simulations, analyses, and decision-support tools are based on reliable inputs. Due to the scope of the projects and the importance of sensor data, sensors were primarily registered as individual entries within the catalog. While this allows detailed metadata representation, it becomes difficult to manage large numbers of sensors. Furthermore, since each sensor is represented by an individual node in the knowledge graph, the resulting graph grows rapidly in size and complexity, making it difficult for users to navigate and extract meaningful insights, which ultimately hinders knowledge transfer. To address this, further research has explored approaches for grouping sensors and representing them as aggregated entities (Limnardy, 2025). Similar observations were also made in the SAVeNoW project. Although feedback was collected primarily through qualitative discussions, the results aligned closely with the TwinBy insights, especially regarding the need for clear guidance, practical examples, and improved communication of benefits.

Table 1: Strengths Identified by Participants.

	Observation	Votes
1.	Central repository for Smart City use cases (incl. descriptions and contacts).	8
2.	Centralised collection of information for UDT use cases.	7
3.	Shared knowledge base reducing time-consuming information searches.	7
4.	Improved collaboration and knowledge exchange across organisations.	5
5.	Support for knowledge transfer in UDT development.	5
6.	Inspiration through documented use cases and templates.	4
7.	Replicability of “one-for-all” solutions across municipalities.	3
8.	Central storage of datasets, sensors, and tools.	3
9.	Open-source implementation with harvesting capabilities.	2

Table 2: Limitations and Challenges Identified by Participants.

	Observation	Votes
1.	Handling duplicate entries when documenting similar sensor deployments.	5
2.	Coordination challenges between different data catalogs and infrastructures.	4
3.	Need to involve colleagues and supervisors in the adoption process.	3
4.	Maintenance effort required for large numbers of catalog entries.	2
5.	Unclear responsibilities for maintaining catalog entries.	2
6.	Long-term governance and operation of the catalog service.	2
7.	Difficulty creating and linking metadata entries.	1
8.	Limited usability without training.	1

5.3 Catalog Content Analysis

Table 3 shows the distribution of catalog entries across the nine metadata categories for the TwinBy and SAVeNoW projects. The distribution indicates that users applied the metadata schema to represent heterogeneous digital resources. In both cases, entries are predominantly related to the category *Datasets and Documents*, indicating a focus on documenting data resources. The absence of *Digital Twin* entries in the SAVeNoW catalog can be explained by the project structure, where the overall system corresponds to a single, integrated Digital Twin rather than multiple distinct instances. In the TwinBy project, 26 entries were registered in the category *Project* and 26 as *Digital Twin*, reflecting multiple use cases across municipalities. In contrast, the SAVeNoW catalog represents a more centralised structure, where a single top-level entry in the category *Project* represents the overall system. The five subprojects are also registered as entries in the same category but are linked to the main project via *part of* relationships directed from the subprojects to the parent entry.

In both cases, the catalogs contain detailed documentation of UDT use cases, including their components and dependencies. This allows stakeholders to analyse existing solutions, identify reusable elements, and adapt them to their local context rather than developing solutions from scratch. Participants consistently reported that the structured representation of resources reduced the effort required for identifying relevant datasets and use cases, particularly during the initial discovery phase. Relations defined between datasets or services across multiple use cases could be identified as common components, illustrating practical instances of reuse. Since most users had no prior experience with the catalog and required training, defining appropriate types and directions of semantic relationships proved challenging. After training, users showed an improved understanding of semantic linking, resulting in more consistent connections between entries. This process required additional review and correction of incorrectly defined relationships in consultation with the municipalities.

At the beginning of both projects, catalog maintenance was often perceived as an administrative task rather than a strategic activity. This was reflected in incomplete entries, where essential information such as detailed descriptions and semantic relationships to other resources was often missing. This lack of semantic relationships can also be identified through graph-based analysis. For example, the detection of isolated nodes indicates missing relationships and gaps in metadata linking and the detection of important resources using graph centrality measures (Knezevic et al., 2026). Overall, the catalog entries covered a wide spectrum, ranging from well-structured entries with complete metadata and appropriately defined relationships to incomplete entries with missing descriptions or links. While the introduction of mandatory metadata fields improved data quality and consistency, certain aspects, such as the quality and level of detail in descriptions, remained dependent on individual users. The naming of catalog entries plays an important role in enabling discovery and interpretation, particularly in cross-city contexts. In several cases, entries were assigned generic titles such as "*Sensor at parking garage*", which do not provide sufficient contextual information about their location or relevance. While such information may be available through metadata fields such as geolocation, it is not immediately visible during browsing or search. This limits the ability of users from other municipalities to assess whether a resource is relevant for their own context. More descriptive and context-specific titles improve the interpretability of entries and support more efficient discovery and reuse across different organisations and application contexts. A catalog entry can be considered poor and not suitable for knowledge transfer if it contains incomplete, inconsistent, or outdated metadata, lacks clear descriptions of the underlying data, or omits essential information such as data provenance, licensing conditions, or dependencies on other resources. Well-documented entries reduce uncertainty and lower the effort required for reuse, thereby increasing the overall adoption of the catalog.

Considering these metadata quality aspects, in the SAVeNoW project, around 80% of catalog entries are suitable for knowledge transfer, whereas in the TwinBy project this proportion is approximately 60%. Entries were considered suitable for knowledge transfer if they contained sufficiently complete metadata, i.e., a clear and descriptive documentation that could be understood by stakeholders outside the originating organisation, information that enabled the resource to be interpreted and assessed in contexts beyond its original use case, licensing information, and correctly applied semantic links to related resources. This assessment was conducted by the authors based on the catalog content available at the end of each project. This difference can be primarily attributed to the project structure and stakeholder composition. SAVeNoW was conducted in a more controlled, research-oriented environment with a limited number of experienced partners, which facilitated consistent metadata creation, better understanding of the catalog model, and closer coordination among contributors. In contrast, the TwinBy project involved a larger number of municipalities with varying levels of technical expertise and prior experience with metadata catalogs. The higher number of contributors and decentralised data management in TwinBy increased the complexity of governance and quality assurance processes. This led to greater variability in how catalog entries were created and maintained. These observations highlight the importance of training, governance structures, and user guidance in ensuring high-quality metadata in distributed UDT environments. The clearly defined metadata structures, open standards, and the catalog provides a structured basis for documenting and exploring UDT use cases across different contexts. In the TwinBy project, metadata harvesting was implemented to aggregate into a higher-level catalog. Entries with appropriate licensing were successfully harvested into the central Bavarian open data portal. This portal serves as a centralised platform for publishing and discovering datasets and metadata from across Bavaria. Harvesting metadata from distributed sources enables cross-city visibility of information resources and supports the exploration of use cases beyond local project boundaries.

Table 3: Distribution of Catalog Entries Across Metadata Categories in the TwinBy and SAVeNoW Projects.

Main Category	TwinBy	SAVeNoW
Dataset and Documents	157	49
GeoObject	33	0
Device/Item	58	3
Online Service	34	2
Online Application	34	9
Software	34	16
Method	30	2
Project	26	6
Digital Twin	26	0

5.4 Evaluation of Hypotheses

To systematically assess the contribution of a specialised UDT catalog to knowledge transfer and reuse in UDT contexts, the hypotheses defined in Section 3 are evaluated based on qualitative feedback and the analysis of the catalog entries and knowledge graphs from the two case studies. Table 4 summarises the results of the hypotheses evaluation.

Table 4: Evaluation result and Evidence from Case Studies.

Hypothesis	Evaluation result, Evidence from Case Studies and relation to FAIR principles
H1: Comprehensive Metadata Schema	Supported. **User feedback:** Joint representation and linking of datasets, applications, sensors, and use cases enabled identification and understanding of complete solutions and use cases. Participants highlighted the catalog as a shared knowledge base reducing time-consuming searches (***F**AIR*), a source of inspiration through documented use cases, and a tool supporting knowledge transfer in UDT development (*FAI**R***). Structured representation was reported to reduce discovery effort (***F**AIR*). **Content analysis:** The use of all nine metadata categories confirms that the metadata schema adequately reflects the diversity of resource types relevant to real-world UDT use cases. The knowledge graph allowed for the identification of shared dependencies between municipalities (e.g., LoD2 building models), demonstrating the potential for reuse and knowledge transfer *(FAI**R**)*. Incomplete entries remain a challenge.
H2: Metadata Standardisation, Interoperability, and Compliance with Open Standards	Supported. **User feedback:** Participants reported that the standardised metadata structure promoted mutual understanding across organisations, as entries created by one organisation could be consistently interpreted by others *(FA**I**R)*. Coordination challenges between different catalog infrastructures were identified as a limitation. **Content analysis:** Entries with appropriate licensing were successfully harvested into the central Bavarian open data portal, demonstrating cross-system interoperability. The use of DCAT enabled machine-readable, consistently structured metadata across organisations *(FA**IR**)*.
H3: Collaboration realized by multi-tenancy catalog	Supported. **User feedback:** Multiple organisations share and manage their own metadata in the catalog *(F**A**IR)*. **Content analysis:** In TwinBy, 25 organisations contributed 432 entries; in SAVeNoW, 19 organisations contributed 87 entries. Cross-organisational visibility was enabled through the shared catalog instance *(F**A**IR)*. Inconsistent entries across organisations indicate that governance structures need further development.
H4: User Accessibility, Usability, and Collaboration.	Partially supported. **User feedback:** Users highlight usability as a key factor that is not yet fully addressed by the current catalog implementation. However, the findings also show that beyond technical usability, onboarding support and governance structures are equally critical for ensuring consistent metadata quality and effective knowledge transfer. **Content analysis:** Weak catalog entries hinder knowledge transfer and resource reuse *(FAI**R**)*. Quality is subject to varying levels of expertise and governance maturity.

6. Conclusions and Future Work

This paper investigates how a specialised, semantically enriched metadata catalog can support knowledge transfer and reuse in UDT environments. Two research questions guided the study: (1) how a metadata catalog should be structured and implemented to enable municipalities to reuse existing solutions and transfer best practices across contexts, and (2) what role FAIR data principles and knowledge graph approaches play in enabling this. To address these questions, four hypotheses were formulated and evaluated through qualitative user feedback and catalog content analysis from two real-world case studies. The need for these specific design principles of the SDDI-based catalog was previously motivated through a conceptual comparison against existing SDI and ODP catalogs (Knezevic et al., 2022; Moshrefzadeh, 2025), which lack adequate support for semantic relationships, heterogeneous resource types, and individual object-level registration. However, a controlled empirical comparison against alternative catalog designs was outside the scope of this study. Therefore, the study does not provide empirical evidence that these principles outperform alternative catalog designs. The results confirm that a specialised metadata schema, a knowledge graph representation of digital resources, and multi-stakeholder access mechanisms are principles for a UDT metadata catalog that support knowledge transfer and reuse (RQ 1). All four hypotheses were supported or partially supported by the empirical evidence. Furthermore, the findings demonstrate that FAIR data principles and knowledge graph approaches play an essential role in supporting knowledge transfer and reuse in UDT contexts (RQ 2). Compliance with open standards and FAIR-oriented metadata structures enabled cross-organisational interoperability, consistent interpretation of entries, and successful metadata harvesting across system boundaries. Knowledge graph representations of catalog entries enabled the identification of shared dependencies, reusable components, and highly connected resources, supporting strategic planning and knowledge transfer both within and across municipalities. At the same time, the evaluation also revealed important challenges in governance processes and user support mechanisms, as well as limitations of the current catalog implementation, mainly regarding usability. These challenges and limitations highlight the need for further research on methods for supporting users in creating, maintaining, and validating metadata. The observed differences in metadata quality further indicate the need for research on defining and assessing what constitutes a high-quality catalog entry for knowledge transfer. These aspects are being explored in ongoing research, including the Twin4Clim project, which investigates approaches for advancing UDT infrastructures in climate-related applications. Potential approaches will include guided interfaces for different user groups, validation mechanisms, and semi-automated assistance, for example through AI-based methods to support metadata search, creation, and quality assessment.

Acknowledgements

This work was supported by the Bavarian State Ministry for Digital Affairs (TwinBy), the Federal Ministry of the Interior and Community (Connected Urban Twins, in cooperation with the City of Munich), the Federal Ministry for Digital and Transport (SAVeNoW), and the EU INTERREG programme (Twin4Clim).

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