SDDI - Minimal Ecosystem for the Establishment of Urban Digital Twins

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Abstract: Urban Digital Twins (UDT) promise to improve city planning by providing a comprehensive and up-to-date digital representation of the real city. However, cities are complex systems involving diverse stakeholders with different interests and knowledge of various aspects of physical urban elements. Therefore, integrating, managing, and visualizing information from distributed sources is a common challenge in UDT development. Typically, UDT are implemented as distributed systems of systems that serve various applications by using diverse digital resources (sensor measurements, point clouds, virtual 3D city models and further geospatial data, spreadsheets, simulation results) across stakeholders. An essential and robust management system is needed to manage digital representations of physical urban objects in a distributed UDT. In response to these requirements, the Smart District Data Infrastructure (SDDI), a framework for use case-driven data management and data integration in smart cities, has been developed. Initially, the SDDI concept was developed and applied mainly to districts of large European cities.
This paper addresses how SDDI can technically be implemented in smaller municipalities with their limited financial and human resources. In particular, we define a minimal ecosystem aiming at enabling smaller municipalities to implement beneficiary applications based on a distributed UDT. Furthermore, we discuss the role of the two SDDI core components, the SDDI catalogue and Virtual District Model (VDM), within the minimal ecosystem. Using the SDDI catalogue as an example, we describe how cloud-optimized open-source software can achieve a low entry barrier for deploying and operating an SDDI core component.
As a proof of concept, we present use cases from 17 smaller Bavarian municipalities and discuss the deployment and application of the minimal ecosystem for a specific UDT use case.

1 Introduction

Urban Digital Twins (UDT) promise to improve city planning by providing a comprehensive and up-to-date digital representation of the real city. As complex systems, cities involve many stakeholders, each with different interests and knowledge of different aspects of urban infrastructure. Therefore, the integration of information, its management, and visualization from distributed sources is a common challenge in many smart city projects, especially in projects aimed at developing UDTs (SCHUBBE et al. 2023). UDTs are distributed systems consisting of different subsystems that serve various applications. These applications rely on a variety of digital resources, such as sensor measurements, point clouds, virtual 3D city models and further geospatial data, spreadsheets, and simulation results, from different stakeholders (KOLBE 2009). To digitize and maintain a digital representation of physical urban objects and manage a UDT effectively, it becomes essential to establish a robust management system that handles the

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interconnections among the digital resources of diverse organizations and urban institutions within a distributed framework that spans the lifespan of these objects (KNEZEVIC et al. 2022).
This paper aims to highlight the role of two SDDI core components – the SDDI catalogue and Virtual District Model (VDM) as a minimal ecosystem for UDTs. It describes how cloud-optimized open-source software can achieve a low entry barrier for deploying and operating SDDI core components. The practical implementation will be discussed through experiences gained in real cities, specifically within 17 smaller Bavarian municipalities.

2 Related Work

The development of UDTs and their associated management systems has been a focal point of research, drawing from various domains to address the multifaceted challenges posed by urban complexity. In this section, we review relevant literature and ongoing efforts that contribute to the understanding and advancement of distributed UDTs and associated ecosystems.
Prior research has extensively explored the challenges inherent in managing urban complexity, focusing on integrating diverse data sources. JEDDOUB et al. (2023) discuss the gap between the theoretical concept of Digital Twins for cities and their current implementations. This includes the need for a standard definition for Urban Digital Twins and effective data integration methods to support the development and maintenance of Digital Twins in urban and geospatial contexts. Furthermore, the authors emphasize the significance of comprehensive UDTs and robust management systems in addressing these challenges. The management of digital resources within UDTs has been a topic of interest. KRITZINGER et al. (2018) and MENON et al. (2023) discuss the importance of a digital resource management system that spans both static and real-time data, analytics, and simulation tools.
MOSHREFZADEH & KOLBE (2016) describe the first development stages of the Smart District Data Infrastructure (SDDI), a framework for use-case driven data management in smart city projects, that was initially developed and applied in different districts in large European cities such as London, Paris and Berlin. Inspired by long-term experience in the implementation of spatial data infrastructures (SDI) in the geospatial domain, SDDI is based on a distributed infrastructure, where components communicate using open international standards. The framework encompasses technical, organizational, legal, and procedural aspects. CHATURVEDI et al. (2019) present the application of SDDI for the integration of various sensors, IoT devices, simulation tools and 3D city models and demonstrate its functionality in a secure distributed application using the Queen Elizabeth Olympic Park in London as a case study.
KNEZEVIC et al. (2022) point out the particular role of a central metadata catalogue for the management of UDT based on the SDDI framework. They list several requirements for data management in UDTs and demonstrate that existing catalogue systems in the field of SDI and urban data platforms only partially meet these requirements. The authors point out that the scope of SDI catalogues is limited to geo-information resources and that SDI catalogues focus on users and use cases related to the geospatial domain. Some of the requirements that are not fulfilled by SDI catalogues include the support of various resource types beyond datasets and services (e.g. sensor devices, software, projects, etc.), the capability to represent individual objects by individual catalogue entries and to establish semantic relations between catalogue entries (KNEZEVIC et al.

2022). Also LISOWSKA (2016) provides insights into the shortcomings of Open Data platforms in meeting the unique challenges posed by UDTs, e.g. the lack of standardized interfaces. In response to this gap, KNEZEVIC et al. (2022) propose an extended metadata catalogue tailored to the management of distributed UDTs and design an associated metadata schema as an extension of existing metadata standards.

3 SDDI core components and their role in a minimal ecosystem for managing distributed Urban Digital Twins

When a distributed UDT is considered to be an application-specific set of digital resources about the city distributed across all resource holders, it is essential to maintain a structured overview of the UDT at two distinct levels:

The *level of digital resources* needs to be addressed in order to describe the distributed components and their interrelations that compose a specific UDT. Digital resources include various types of datasets (e.g. point clouds, Building Information Models, virtual 3D city models), but also software components that provide the required functionalities for methods such as analyses, simulations, and visualizations (see Figure 1). Questions to be answered at the digital resource level include: What digital resources constitute the Urban Twin for a specific application? Who holds responsibility for each resource? Which datasets and urban analysis methods have been used to generate a specific result? What insights can be gained from application X for one's own UDT use case? To answer this kind of questions, a resource registry is required. Therefore, one of the main components of the SDDI is the resource registry (SDDI Catalogue), which serves as a central repository where all partners and interested parties can register their digital resources and specify relations between the resources.

Secondly, the *level of individual urban objects* must be taken into account in order to gain insights into the current state of the city, e.g., through visual exploration and to virtually test future scenarios using cascading simulators from different domains. This requires a virtual model of the city that provides digital representations for all the relevant physical objects like buildings, streets, vegetation objects, etc. In this virtual model each individual physical object of interest must have its digital counterpart. The digital object must have a stable identifier that can be used as an anchor for linking further information available for the physical object. This approach serves as a backbone for semantic enrichment of the individual registered objects (e.g. linking the sensor measurements for this specific object or enriching the object with simulation results). The VDM acts as a key element for information integration at the individual object level, for spatial visualization of the current state and of future states of the city, as well as for analysis and simulations involving the geometric, topologic, and semantic properties of the individual objects. The VDM is used and referenced by most applications and linked from other data resources where the level of individual object is relevant.

Due to their fundamental role in managing distributed UDT in the context of SDDI, the VDM and the resource registry are named "SDDI core components" (Fig. 1).

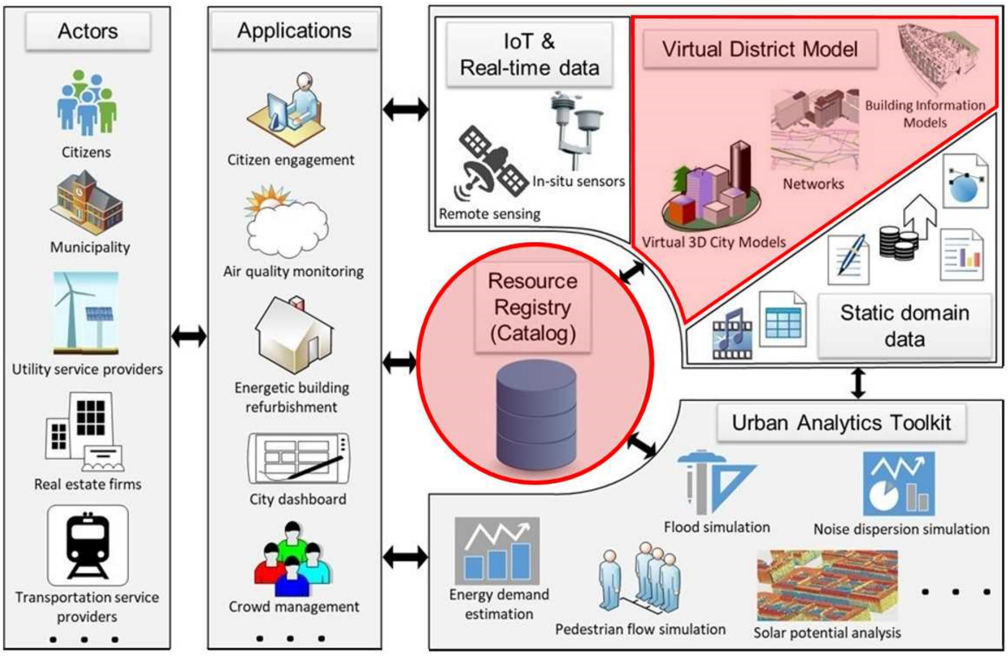

Fig. 1: SDDI framework overview with highlighted core components: SDDI catalogue and VDM (KOLBE et al. 2020).

In an SDDI-based implementation of a UDT, it is becoming apparent that an effective approach is to centralize the management and distribution of these core by one stakeholder while most digital resources will be offered within a distributed network of components by the different actors.
The second component is the *Virtual District Model (VDM*).
These two core components can therefore be described as a *minimal ecosystem for the implementation of distributed UDTs*. The entry barrier for implementing and operating the two core components should be as low as possible allowing small and medium sized municipalities to implement UDTs despite their limited financial and human resources.
The backbone of this proposed ecosystem is the synergy between extended metadata catalogues (SDDI catalogue) and semantic 2D/3D information models (VDM). This synergy forms the basis for managing the intricacies of distributed UDTs and provides a comprehensive framework for data integration and visualization.

3.1 SDDI Catalogue

The SDDI catalogue is a centralized hub, connecting diverse digital resources and providing a comprehensive overview with metadata describing their linkage to specific use cases. It is at the core of the SDDI and describes the connections of all other components of the SDDI. It is a central information point for all existing information resources, such as data, services, and applications, and provides a complete overview. It is an SDDI core component used across all use cases and during the operational phase of a UDT based on SDDI as well as during the SDDI implementation process.
The fundamental principle of maintaining a central repository for metadata, in which the distributed information resources are described in a standardized way, was adopted from the

concept of Spatial Data Infrastructures (SDI). Centralized platforms in a distributed environment are also addressed by the field of Open Data. As mentioned above, KNEZEVIC et al. (2022) explain that neither SDI catalogues nor Open Data platforms fully meet the requirements for the management of UDTs. The SDDI catalogue and its associated metadata schema therefore extend the capabilities of SDI catalogues and Open Data platforms. The SDDI catalogue helps to maintain an overview of the distributed information resources by registering all actors, all resources, such as data, software, IoT devices, sensors, applications, methods, and projects, in a standardized way. No data, applications, analysis methods etc. are stored in the catalogue itself, only the reference to where the digital resources can be found and how they can be used. The requirements for such a catalogue are, on the one hand, to restrict access to specific resources and, on the other hand, to ensure a uniform taxonomy and to provide proper search functionality and indexing to find relevant digital resources.

KNEZEVIC et al. (2022) proposed a metadata schema described by a UML class diagram for a catalogue suitable for managing UDTs. The most important class of the proposed schema is *InformationResource*, which has nine subclasses that can be instanciated to classify the digital resources used in UDTs *(Project, Online Service, Dataset, GeoObject, Device, Online Application, DigitalTwin, Software and Method)*. The metadata schema defines three types of relations between catalogue entries (*links_to, depends_on, child_of*). The data owner must provide a link to the original resource for each entry in the catalogue, as the catalogue is only intended to locate all information resources but not to store them. The catalogue entries and their relations form the basis for a knowledge graph that can be used for further analyses and indications of correlations across information resources. The organizations and the users in the catalogue represent the actors (Fig. 1), and the organizations are holders of rights to catalogue entries. This approach enables the distributed maintenance of catalogue entries within and across organizations and the linking of the digital resources used for a specific use case within the organization itself, but also with the digital resources used by other organizations. The proposed metadata model can be mapped to the DCAT2 standard allowing the SDDI catalogue to directly access and provide DCAT2 data. DCAT (https://www.w3.org/TR/vocab-dcat-2/) is a worldwide accepted RDF vocabulary called that was created to facilitate interoperability between data catalogues published on the web. With DCAT, datasets can be described in a catalogue based on a standard model and vocabulary to simplify the sharing of metadata from multiple organizations.

3.2 Virtual District Model

The VDM, the second SDDI core component, features digital objects for significant real-world elements in a district/municipality/region (e.g., specific buildings, roads, vegetation objects). VDM objects describe real-world elements regarding subject matter, spatial location, and shape, forming the basis for visualizing the current state of the city and creating *what-if* scenarios. The VDM is continuously updated using defined processes to correspond as closely as possible to the state of the real world. The VDM objects can be used to link information from a wide variety of sources and to spatially locate information (e.g., IoT data and results from urban analysis tools). An essential feature of the individual digital objects provided by the VDM is that they have stable identifiers that can be used as anchor points for semantic enrichment. The digital objects can therefore be enriched by data from different domains (such as urban planning, mobility, energy, and ecology), which enables a more comprehensive and detailed representation of the built environment and, thus, better analyses (KOLBE & DONAUBAUER 2021).

The VDM can be implemented as a 2D geoinformation system or a semantic 3D city model, both accessed via open, standardized interfaces such as OGC Web Feature Service or OGC API features. Realization in the form of BIM models is also possible. The VDM should be structured according to a standardized data model, such as CityGML to support semantic interoperability. For the realization of the VDM, it makes sense to use data from existing cadastres, in particular from official geodata, as a basis for as many VDM object types as possible, as data maintenance and other data governance processes have already been defined for these and the objects have stable identifiers.

If individual VDM objects like a specific building or sensor station are significant for a specific UDT use case, they can additionally be registered as individual objects in the SDDI catalogue.

4 Cloud-optimized development and deployment of an SDDI core component exemplified by the SDDI catalogue

As already mentioned, the SDDI concept was originally developed using the example of urban redevelopment projects in major European cities. The aim of defining and providing an open source implementation of a minimal ecosystem, as described in this article, is to lower the entry barrier for an SDDI implementation and thus also enable smaller municipalities to manage a UDT based on the SDDI framework. To enable more accessible deployment, which would potentially reduce the maintenance effort for smaller municipalities, we have implemented the minimal ecosystem as a cloud-based architecture using Docker[2] and Kubernetes[3] technologies. The implementation strategy is described in this section using the example of the SDDI catalogue.

A central element within a cloud-native architecture is a system for containerized applications' automatic supply, scaling, and management (orchestration). Kubernetes is a widely used open-source framework for orchestration that performs specific tasks and controls functions for services, processes, web services, applications, or workloads, considering the dependencies between them. Cloud orchestration combines services from the same or different cloud environments and providers forming an overall composition. The software is deployed onto a so-called Kubernetes cluster. Usually, the Kubernetes cluster is purchased as a managed service from a cloud provider but can also be operated in users' own IT infrastructure. The required software components can generally be sourced from software repositories, e.g., Github or Docker Hub. For the definition, installation, and updating of complex Kubernetes applications, so-called *Helm Charts* help manage them.

For the implementation of the SDDI catalogue, we are providing two software repositories, SDDI-Docker image[4] and SDDI Helm chart[5], that are publicly available as open-source software. The repository *SDDI-Docker image* contains an extended version of the CKAN catalogue software

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[2] https://www.docker.com/
[3] https://kubernetes.io/
[4] https://github.com/tum-gis/ckan-docker
[5] https://github.com/tum-gis/sddi-ckan-k8s

prepared for deployment in a Kubernetes cluster with the extensions required for managing UDTs based on the SDDI concept. The orchestration of the required software components from CKAN is mapped in a Helm chart. The *SDDI Helm chart* deploys a self-contained CKAN data catalogue with all of its required dependencies. This distributed software can even be evaluated and experimented with running a local Kubernetes cluster using e.g. Docker Desktop.
The SDDI catalogue has been implemented using the open-source catalogue system CKAN[6]. A set of SDDI-specific extensions expand the main CKAN functions. The extensions allow for implementing the extended SDDI metadata schema including the definition of relationships between catalogue entries, and the nine main categories for digital resources mentioned in Chapter 3.1, as well as the visualization of the knowledge graph, mentioned in Chapter 3.1. Additionally, the extended CKAN functionality enables to set different access rights for users, and allows for using spatial and temporal filters in catalogue queries.

5 Implementation of the SDDI framework in 17 Bavarian Municipalities – the TwinBy project

The Bavarian State Ministry for Digital Affairs supports 17 municipal projects in Bavaria, Germany, with the TwinBy[7] Project to develop individual UDTs for specific use cases based on the SDDI framework. Of these 17 projects, four joint projects and 13 individual projects are funded from four funding pots: Energy and Environment, Health and Mobility, Small Municipalities (up to 10,000 citizens), and cross-domain. The list of municipalities, their funding source, and the title of their use case can be seen in Table 1. The TwinBy project aims to create standardized accessibility and networking of data and applications. A qualification program, assistance in managing the SDDI process, and technical support for implementation help the municipalities in setting up their UDTs. The qualification program includes an SDDI guidelines document (DONAUBAUER et al., 2023) and shall ensure that the municipalities can continue working on their UDTs after the end of the project. The project runs from April 2023 to March 2024.

Table 1: Overview of funded Bavarian Districts, their funding source, and the title of their Use Case.

	Bavarian government districts	Funding	Name of the Use Case
1	Deggendorf-Plattling	Energy and environment	Smart rainfall management for the Deggendorf-Plattling regional center
2	Kulmbach District	Energy and environment	Intermunicipal 3D energy planning 4.0
3	Nordallianz - metropol region Munich north	Energy and environment	Twin planning NordAllianz
4	Schwabach City	Energy and environment	GUTI - Golden Urban Twin Information Schwabach
5	Forchheim City	Health and mobility	Frequency measurement combined with parking space management
6	Community Haar	Health and mobility	Intelligent mobility in Haar - controlling traffic flows in the town center

[6] https://ckan.org/
[7] https://twinby.bayern/

7	Aschaffenburg-Alzenau hospital association	Health and mobility	Simulation and development of a process control system for bed occupancy with a traffic light system
8	Schwandorf City	Health and mobility	Mapping of road traffic, parking guidance planning and promotion of e-mobility
9	Traunstein City	Health and mobility	Mobility House Traunstein
10	Community Feldkirchen	Small municipalities (up to 10,000 citizens)	AI due to the smart intelligence of smart infrastructure
11	Management community Fuchstal	Small municipalities (up to 10,000 citizens)	Smart road planning (AUF)
12	Markt Isen	Small municipalities (up to 10,000 citizens)	Municipal energy planning and management incl. Monitoring
13	Neunburg vorm Wald City	Small municipalities (up to 10,000 citizens)	Digital urban development
14	Pressath City (Oberpfalz)	Small municipalities (up to 10,000 citizens)	The digital mind
15	Markt Weisendorf	Small municipalities (up to 10,000 citizens)	Smart Village Weisendorf - opportunities for inner-city development in 3D
16	Aschaffenburg City	Cross-domain	Smart Data Dashboard
17	Kempten	Cross-domain	Further development and utilization of the existing system through SDDI

5.1 Use Case „Mapping of road traffic, parking guidance planning and promotion of e-mobility“ in the City of Schwandorf

The successful implementation of the minimal ecosystem will be illustrated using the city of Schwandorf’s use case as an example. Estimating the volume of traffic in Schwandorf city center is very complex. The traffic situation in large parts of the urban area will be challenging due to the many major construction sites planned over the next few years.

The purpose of the Schwandorf use case is to visualize the current traffic situation to analyze the traffic and develop concepts for traffic management and possible smart traffic control, which will lead to innovation and better use of data in the city for the city administration's operations. The use case is financed from the Health and Mobility funding pillar and is intended for road users, residents, and industry. The city of Schwandorf uses sensor technology to acquire data, which carries out the floating car data analyses. The optimization of the search for parking spaces leads to targeted traffic control.

All used digital resources are registered and linked in the SDDI catalogue. Masterportal, an open source tool-kit for creating geo web applications, is used as a visualisation component for the VDM.

5.2 Implementation of the SDDI catalogue for the Schwandorf City Use Case

In the TwinBY project, the municipalities are free to decide whether they set up their own instance of the SDDI catalogue or whether they use an instance provided centrally by the Bavarian State Ministry[8]. Schwandorf uses the centrally hosted instance.

In a first step, Schwandorf created an inventory of all digital resources and objects relevant for the use case as a simple spreadsheet table.

Then, the metadata of all digital resources and individual objects relevant for this use case were realized in the catalogue as catalogue entries and assigned to one of the main categories for digital resources mentioned in Chapter 3.1 and relations between the catalogue entries were set. The user interface of the running catalogue instance is shown in Fig. 2.

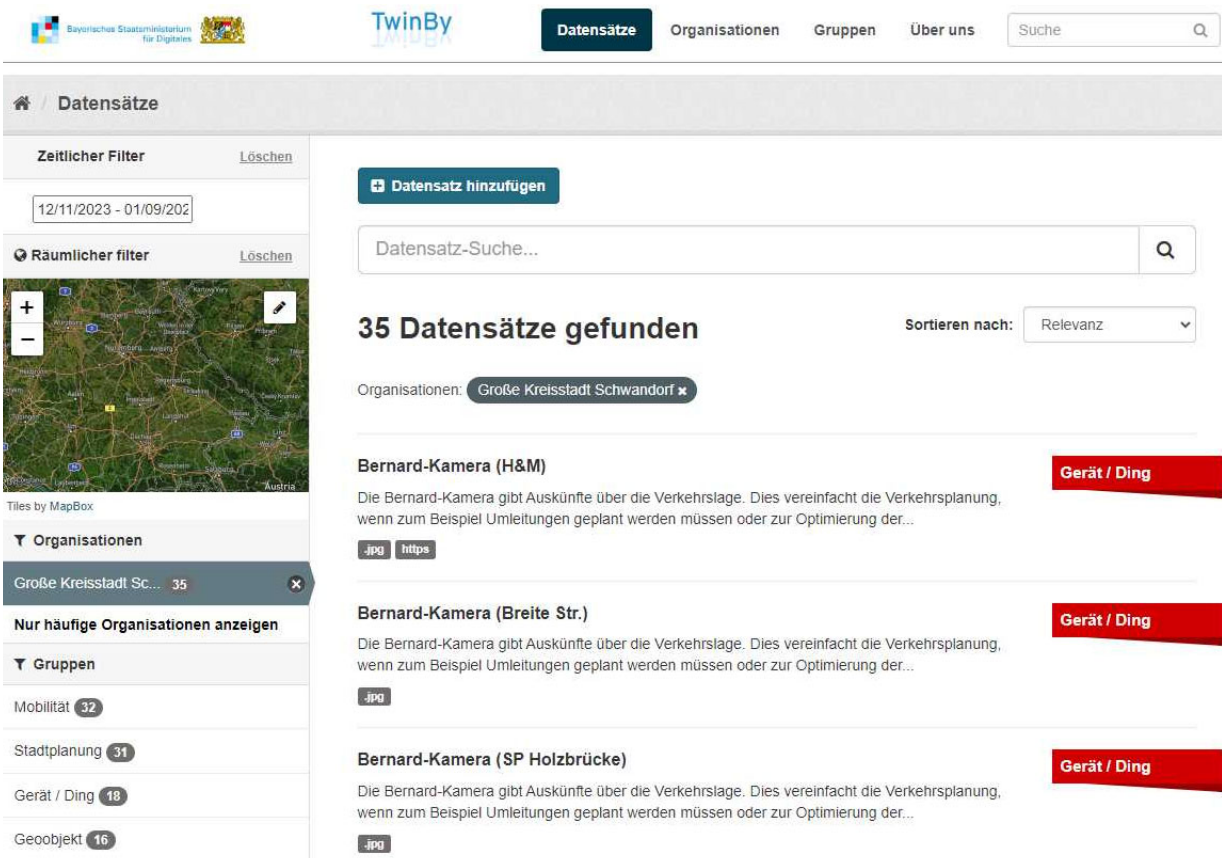


Fig. 2: An example of the catalogue view in the running instance for the city of Schwandorf [9].

Figure 3 illustrates the graph structure of catalogue entries. Different colours for the nodes have been used to represent the different main categories of digital resources. The gray symbol indicates the main category *Software*, the deep red symbol refers to *Device/Item*, pink to *Geoobject*, light red stands for *Digital Twin*, blue for *Online Service*, green for *Online Application*, and orange for *Dataset and documents*. In the example, only two types of relations between datasets are used

[8] https://sddi-katalog.bayern/

[9] https://sddi-katalog.bayern/organization/grosse-kreisstadt-schwandorf

– *links to* illustrated with black colour and *depends on* illustrated with light red. The relationship type *links to* is used to connect interdependent resources, and the relationship type *depends on* connects catalogue entries that are dependent on the existence of another information resource (KNEZEVIC et al. 2022).
The city of Schwandorf uses special cameras with an optical object recognition system for monitoring, control and management purposes in order to identify cars, pedestrians, and cyclists. Since the cameras are essential for the use case, each of them is registered as an individual entry in the catalogue with the category *Device/Item* (*Camera_XY*). The cameras are mounted on lampposts (*Lamppost_XY*) which are registered individually as *Geoobjects* with their geolocation. The catalogue entries for cameras and lampposts are connected in the catalogue with the relation type *links to*. Addtionally, ground parking sensors are used. The used ground sensors (*Ground_Parking_sensor_YZ*) are also registered individually as *Device/Item* and linked to the parking garage (*Parking_Garage_YZ,* main category *Geoobject*) where they are installed. Both sensor types have a different API interface (*Parking data-API port, Camera data-API port*), so both APIs are registered under the main category *Online Service*, and connected to devices with *links to* relationship. The sensor measurements provide the results in a dashboard (*Grafana Dashboard for Schwandorf Use Case*) registered as an *Online Application* and connected with *links to* relationship to the online service from which the data is used to generate dashboards. The tool used to create the dashboard (*Grafana Software*) can also be found in the catalogue as an entry in the main category *Software*.
Another entry in the main category *Software* is the *Masterportal* software, which is used in Schwandorf as visualisation component of the VDM. *Masterportal Schwandorf,* the instance of the Masterportal software running in Schwandorf, is registered as an *Online Application* and is linked with the software *Masterportal* with *links to* relationship. The Schwandorf Masterportal visualizes the measured values of the sensors (*Grafana Dashboard for Schwandorf Use Case*) and the *3D building models (LoD2)*.
The use case of the City of Schwandorf also shows how the distribution of digital resources among different stakeholders can be realized using the catalogue: The State Mapping Agency of Bavaria owns and provides the *3D building models (LoD2)* dataset. The corresponding software manufacturers provide the software systems (*Masterportal Software* and *Grafana Software*). The City of Schwandorf manages the other datasets mentioned. These different stakeholders are registered in the catalogue as separate organizations, and their users are responsible for the maintenance of the respective datasets.
All these catalogue entries are used for the use case of the *Digital Twin Schwandorf*. According to the definition of the distributed UDT as a set of digital resources about the city, the Digital Twin of Schwandorf's use case is represented by a collection of catalogue entries (KNEZEVIC et al., 2022). The *Digital Twin Schwandorf* is represented by a catalogue entry with the category "Digital Twin" and all resources used to create the *Digital Twin Schwandorf* are linked to this catalogue entry using the *depends on* relation.

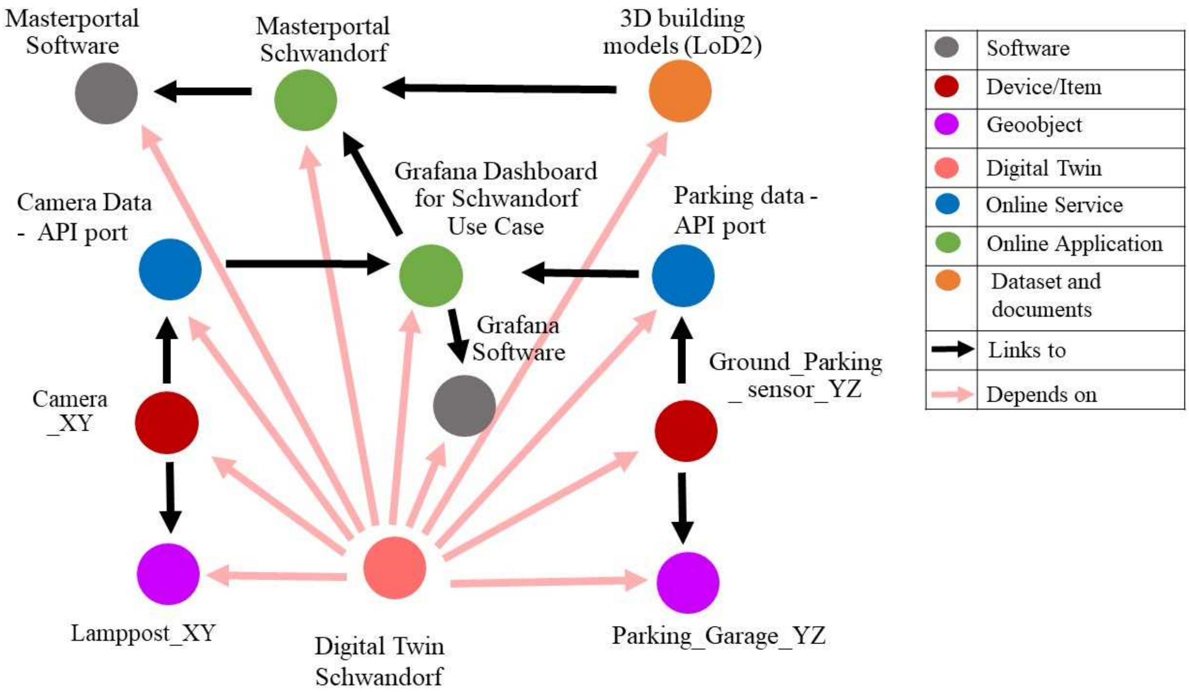


Fig. 3: Illustration of catalogue entries and their relationships realized as a graph in the catalogue for Schwandorf Use Case.

Fig. 4 shows an example of the catalogue entry for one of the cameras. Each catalogue entry contains a title that is unique in the catalogue. The description is a detailed text outlining the digital resource.

The *Data and resources* tab contains two images (*Kamera Marktplatz* and *Kamera Marktplatz Nahaufnahme*) and a documentation file for further information on the device specification. The metadata attribute tags can later be used to make it easier to search for specific digital resources. Further metadata fields contain for example information about the author and the responsible person, as well as the temporal and the spatial extent of the digital resource. In the example of the camera, this information can be used, e.g., to specify when the sensor was installed. Figure 4 shows the spatial extent (Räumliche Ausdehnung) field, where the red pictogram indicates the position where the sensor is installed. When creating a catalogue entry, the user can draw and edit the spatial extent of the dataset as a point or polygon on the map, select a predefined spatial region, or insert an extent in GeoJSON format. This information makes it possible to filter the datasets using a spatial search query. Other metadata fields are defined as suggested in the metadata model presented in KNEZEVIC et al. (2022).

Bernard-Kamera (H&M)

Gerät / Ding

Die Bernard-Kamera gibt Auskünfte über die Verkehrslage. Dies vereinfacht die Verkehrsplanung, wenn zum Beispiel Umleitungen geplant werden müssen oder zur Optimierung der Ampelschaltung. Die Kamera ist am Stromnetz angeschlossen und Eigentum der Stadt Schwandorf.

Daten und Ressourcen

Kamera Marktplatz
Bild der Bernard Kamera am Marktplatz. — Entdecke

Kamera Marktplatz Nahaufnahme
Nahaufnahme der Bernard Kamera am Marktplatz. — Entdecke

Webseite Bernard Gruppe
Webseite des Herstellers der Bernard Kameras zur Verkehrsanalyse. — Entdecke

Dieser Katalogeintrag ist explizit mit anderen verbunden. Um weitere Informationen zu erhalten, gehen Sie bitte auf **"Verknüpfungen"** (auf den Link oder auf Register "Verknüpfungen" oberhalb der Überschrift des Katalogeintrages klicken).

Kamera | Verkehr | Verkehrszählung

Zusätzliche Informationen

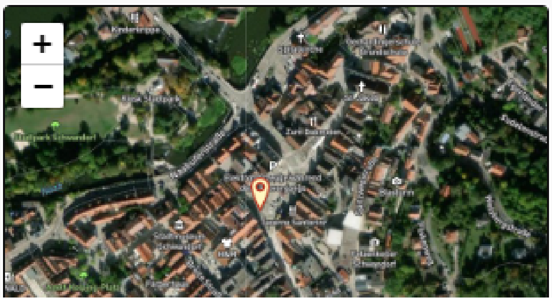
Feld	Wert
Autor	• Author: [redacted] Author Email: [redacted]
Verantwortlicher	• Maintainer: [redacted] Maintainer Email: [redacted] Phone number: [redacted] Role: Experte
Sprache	Deutsch
Version	
Start des Gültigkeitszeitraumes	
Ende des Gültigkeitszeitraumes	
Räumliche Ausdehnung	**Räumliche Ausdehnung** 

Figure 4 Example of a catalogue entry and its metadata for the City of Schwandorf Use case.

5.3 Implementation of the VDM for the City of Schwandorf Use Case

The following data and formats are used as the basis for Schwandorf's VDM. Only two object types are currently used as reference objects: Roads and buildings. The roads are defined in GeoJSON format with line geometry and a small set of thematic attributes. Sensors are referring to a specific road object and provide the information on traffic flow situation. The data collected from sensors are used for creating dashboards. This semantic enrichment of the road object can be used for various simulations, e.g. which traffic volume can be expected at a certain time of a day on a certain day of the week when the road is under construction. Besides the road objects, *basemap.de web grid*[10] from the Central Geotopography Office (Zentralstelle für Geotopographie - ZSGT) is used as a background map for 2D visualization. The basemap.de web grid is available as a WMS and WMTS service, that will also be found as catalogue entries, which enables the visualization of German maps in various zoom levels accordingly to the corresponding international standards of the Open Geospatial Consortium.

The LoD2 representation with its spatial and thematic attributes in CityGML is used to display 3D building models. The 1m resolution Digital Terrain Model as GeoTIFF is used to display the terrain model. These two datasets are used for the 3D visualization. Both datasets are provided by the Official Mapping Agency of Bavaria.

In this use case, the Masterportal is used as a visualization component of the VDM. Masterportal is an open-source 2D/3D (geo)viewer software, designed for seamless integration with Web Map Services, Web Feature Services, and Web Catalogue Services. It serves as a virtual backbone for interactive map services for the public web and government purposes. Each master portal instance has specific configuration files that define used services, such as the geodatabase URL, addresses and parameters of the layers which should be loaded into the viewer (DEGKWITZ et al. 2021). It utilizes a foundational 2D map (extendable to 3D) to display diverse information. Users can dynamically tailor the map content by toggling the visibility of different layers. One such instance is set up for the use case of the city of Schwandorf.

In Figure 5, it is possible to see a 2D map where the streets for which the live traffic data are available are highlighted in yellow. In the Masterportal, it is possible to select these objects, and and to display dashboards where sensor measurements are available. On the right-hand side of Figure 5, it is possible to see two diagrams for cars, pedestrians, and cyclists.

Figure 6 shows the visualization of LoD2 and terrain models owned and provided by the Official Mapping Agency of Bavaria. The buildings are displayed as individual objects with their attributes. In the viewer, it is possible to select each object and, in the pop-up window, view their thematic data.

Currently, the visualization does not use other sources for its enrichment, but this represents a good starting point for other use cases, e.g. if the parking space counter is linked to a specific parking garage, it may be possible to see how many empty spaces are left in a particular parking garage represented as a separate geo-object.

[10] https://basemap.de/en/web_raster/

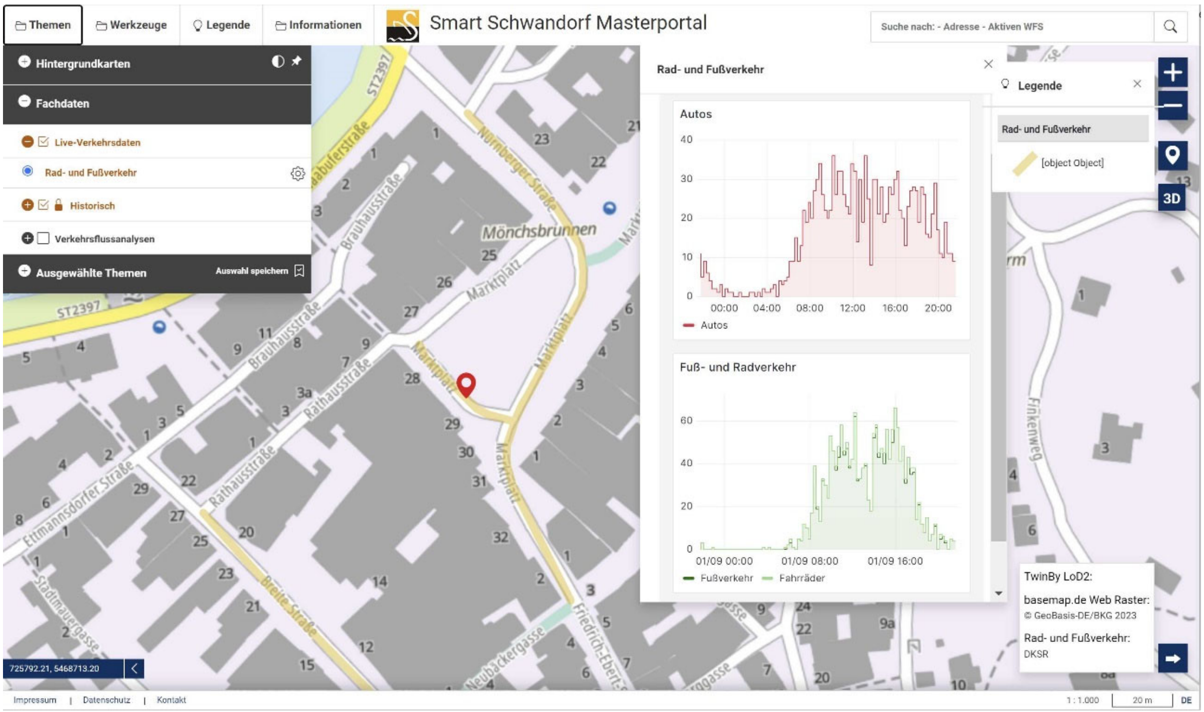


Figure 5 Example of the Masterportal view for the Makrtplatz street with sensor information for cars, pedestrians and cyclists. A red pictogram shows the selected road segment for which the sensor measurements are available.

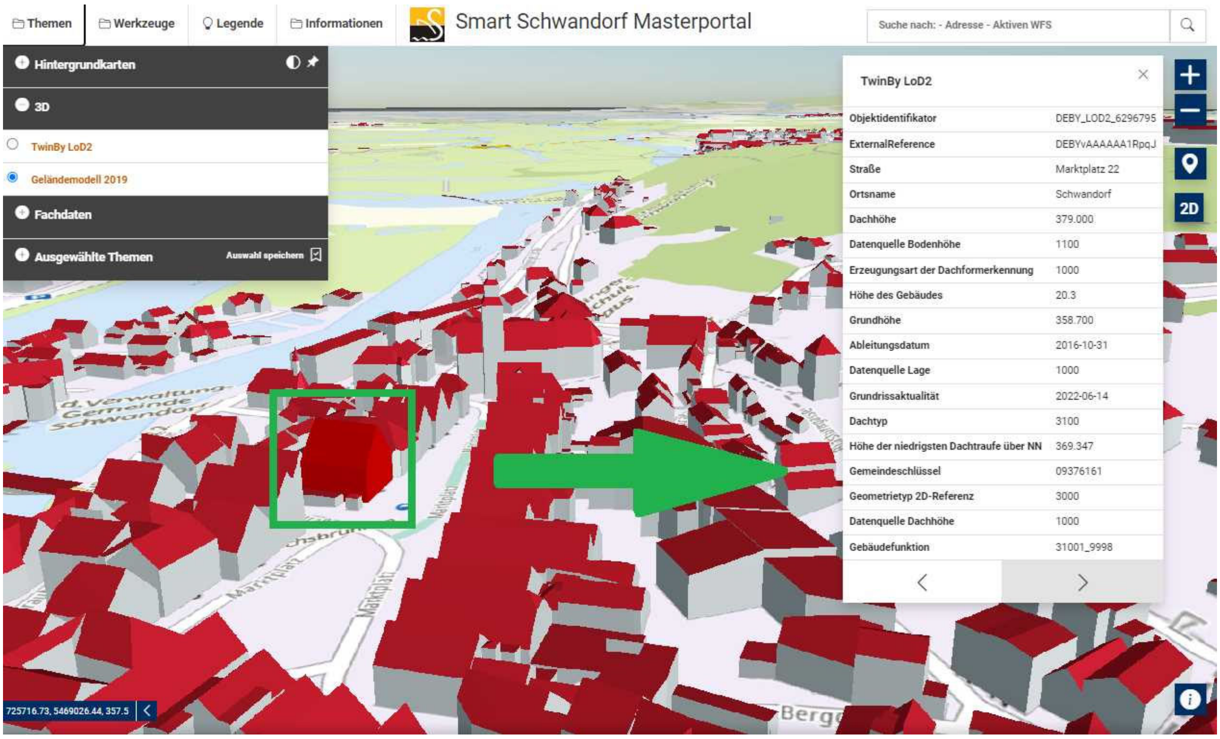


Figure 6 Example of the Masterportal 3D viewer where one 3D object is selected and its attributes are shown.

5.4 Review of the Schwandorf Use Case with respect to the SDDI minimal ecosystem

The Schwandorf use case demonstrates that it is possible, based on a minimal ecosystem, to generate a UDT in a relatively short time and with relatively low effort. An analysis of the technical implementation with regard to the technical requirements of the SDDI framework can be found in Table 2.

Table 2: Analysis of the technical implementation with regard to the technical requirements of the SDDI framework.

Component	SDDI requirement	Schwandorf Use Case
System Architecture	Distributed systems, components communicate via open, internationally standardized interfaces using open, internationally standardized data models.	Requirement is mostly fulfilled: UDT is based on a distributed system, some components communicate via open, internationally standardized interfaces (e.g. communication between Masterportal and its map data sources), with regard to the sensors, MQTT is used as an open standardized protocol, however the API of the sensors is open but not standardized.
SDDI Catalogue	The SDDI metadata schema (KNEZEVIC et al., 2022) is used. DCAT-AP2 is used as a metadata standard.	Requirement is fulfilled.
VDM data model	Usage of a standardised data model as data structure of the VDM, e.g. CityGML.	Requirement is partly fulfilled. The LoD2 building objects are structured according to the CityGML standard, however the data model of the street employed network is not standardized.
VDM API	Access to VDM via OGC Web Feature Service / OGC API Features.	Requirement is not fulfilled. The objects of the street network are available in the GeoJSON format. The API of the sensors is not standardized.

6 Conclusions and Future Work

The experience gained from the implementation of UDTs for comparatively small municipalities based on the SDDI framework allows conclusions to be drawn on the following aspects, among others:

1) Composition and cloud-based implementation of the minimal ecosystem: The minimal ecosystem for the technical implementation of an UDT based on the SDDI framework consists of the SDDI catalogue and the VDM with visualization component. While all 17 municipalities used the cloud-based SDDI catalogue implementation, different software products were used to implement the VDMs. The assumption that smaller municipalities prefer an externally hosted solution has proven to be true. However, it turned out that some municipalities were overwhelmed even with the relatively low costs of renting a cloud environment. Consequently, the original idea of providing a separate catalogue instance for each of the 17 municipalities was abandoned in favour of a catalogue hosted centrally for all 17 municipalities. However, this observation must be considered in connection with the fact that the full benefit of the catalogue was initially not recognized by all municipalities (see user experience). Nevertheless, the use of cloud technology (Docker, Kubernetes) for the implementation of the SDDI catalogue has proven to be worthwhile.

This kept the efforts for the provision of the central catalogue low. The service provider can deploy predefined system components "with a single line of code" without the need for elaborate installation and configuration. The fact that the SDDI catalogue is available as open-source software also enables municipalities not funded by the TwinBy project to implement and manage an UDT with a low entry barrier. As the Schwandorf use case demonstrates, sensors are often used in the implementation of UDT. Therefore, the question arises whether the minimal ecosystem should also include a cloud-based open-source sensor data stack, such as the one used by the Hanseatic City of Hamburg (FISCHER et al., 2021) or developed within the research projects SAVeNoW[11] and CUT[12].

2) User experience: When the catalogue instance was launched, users complained about the effort of registering their digital resources and hardly recognized the benefits of documenting their UDT using the catalogue. However, when the catalogue reached a certain number of entries, all participants recognized the added value of this approach. Users got an overview of the information owned by other organizations and within the use case and area of interest. They learned that already created catalogue entries lead to data reusability, reducing the effort for each additional use case to be implemented.

3) Added value of the SDDI catalogue: Municipalities can share their knowledge, ideas, and experiences more quickly as they all use the same structure to manage the information available in their organization. The SDDI catalogue enables decentralization, where data does not need to be stored in a central platform; only metadata is recorded.

It serves as a platform for municipal cooperation. This centralization facilitates easy access to a comprehensive overview of available resources within the urban environment. It promotes transparency for users by providing information about which stakeholders are providing real-world information about real-world objects. The catalogue helps maintaining an organized overview of distributed information resources by registering all resources in a standardized way. The catalogue does not store the actual data or applications but provides references to where the data can be found and how they can be used. This approach ensures that the catalogue remains a lightweight and efficient tool for resource management. The catalogue supports a distributed maintenance approach (multi-tenancy), enabling organizations to independently manage and link their catalogue entries. Organizations serve as holders of rights to catalogue entries, providing a structured approach to ownership and responsibility. With the information, users can get an overview of the activities in a local community. By analysing organizations and users and their digital resources registered in the catalogue key stakeholders for specific topics can easily be identified.

Furthermore, the municipal administration can use the catalogue as a showcase to demonstrate its activities regarding digital transformation to other stakeholders, especially to their citizens. However, the benefits of the resource register do not end at the boundaries of local government, which is responsible for managing their own UDT. Stakeholders outside the municipal administration can gain new ideas thanks to transparency, which can already be achieved from the

[11] https://savenow.de/

[12] https://www.connectedurbantwins.de/en/

first use case registered in the catalogue. Last but not least, other municipalities and organizations can use the catalogue to find blueprints for their use cases, as the UDTs for specific use cases with all their components and their interrelationships are made transparent.
4) Added value of the Virtual District Model (VDM): The VDM is used to represent essential elements of the real world. Depending on the use case, the VDM supports different levels of visualization, from basic representations to more enriched and detailed models. Its comprehensive forms of representation provide the basis for visualizing current conditions that offer a rich and detailed representation of the physical environment. In addition, the VDM helps with spatial visualization, enabling stakeholders to understand the spatial relations between different elements within the municipality. The VDM supports enriching 3D city models with additional semantic information. This enrichment enables a more comprehensive and detailed representation of the built environment and supports better analysis and decision-making in different areas. The VDM can be implemented in different forms, and its flexibility allows it to be adapted to different technology and application contexts and ensures broad accessibility and usability. The virtual district model is essential because it provides a dynamic, detailed, accurate representation of urban elements. It serves as a basis for information integration, spatial visualization, and analysis, contributing significantly to the effectiveness and usefulness of the SDDI.
Taking into account the observations described above, our future work will focus on further improving the user experience with the SDDI catalogue. Areas we are already looking at are:

- the management of sensors in the catalogue in light of the fact that UDTs can consist of a very large number of individual IoT sensors, which can lead to an overload of the catalogue with the current approach of registering each sensor individually;
- providing an AI-based assistant for the creation of catalogue entries and searches in the catalogue using Large Language Models (LLM);
- represent the linked catalogue entries in the form of a knowledge graph in order to use graph-based algorithms to provide functionalities for quality assurance of catalogue entries, to uncover dependencies between digital resources and to assess the importance of individual digital resources for a specific UDT.

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