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THE SPATIAL DATA INFRASTRUCTURE OF AN URBAN DIGITAL TWIN IN THE BUILDING ENERGY DOMAIN USING OGC STANDARDS

T. Santhanavanich*, R. Padsala, P. Würstle, V. Coors

Centre for Geodesy and Geoinformatics,
University of Applied Sciences Stuttgart
Schellingstraße 24,
70174 Stuttgart, Germany
(thunyathep.santhanavanich, rushikesh.padsala, patrick.wuerstle, volker.coors)@hft-stuttgart.de

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ABSTRACT:

As the world has more urbanized, cities need to assess and manage their building energy performances in order to achieve energy-reduction goals. The urban digital twins (UDT) offer promising solutions to this demand by providing valuable insights with qualitative and quantitative information about the building environment. The urban building energy data is not only measured from the equipped sensor devices but can also be simulated based on the analysis software. In this research, we aim to explore the development of the spatial data infrastructure (SDI) for managing building energy in the UDT application by employing the Open Geospatial Consortium (OGC) standards which increases the data usability and efficiency. In our concept SDI, the big data in the UDT application is managed with the OGC specifications as follows: OGC SensorThings API (STA) for data with Spatio-temporal characteristics, OGC API 3D GeoVolumes for 3D geospatial content delivery, OGC CityGML for virtual 3D city models, OGC API Features, Web Feature Service (WFS), and Web Map Service (WMS) for other 2D geospatial contents. This concept enables broad interoperability between multiple data layers and client applications. As a proof of concept, we developed the UDT application called with a highly visual and intuitive user interface using the proposed SDI concept as a part of the EnSysLE project in the study area of three regions in Germany: Ludwigsburg, Dithmarschen, and Ilm-Kreis. The proposed concept can be expanded to other UDT domains and on a larger scale in future work.

1. INTRODUCTION

Urbanization has significantly affected the environment and climate all over the world. This can be judged from the fact that cities alone are responsible for 70% of the world's energy consumption and its related environmental impacts in terms of emitted greenhouse gases. Despite the governments and world leaders implementing different adaptation and mitigation strategies to tackle climate change, it is clear that the world is drastically lagging behind in fulfilling global frameworks such as the United Nations sustainable development goals and the Paris Agreement. One particular reason often highlighted in different studies pertaining to this shortcoming is the lack of tools that allow stakeholders and decision-makers to analyze and visualize integrated urban energy data at different spatial scales linking different data silos (Miralles-Wilhelm, 2016). As often used previously in assessing the urban built environment from different scales, the use of geospatial technologies, in particular, the UDT platform, is considered an ultimate tool supporting the development of sustainable urban development. Amongst its many use cases, one in particular related to the present study is its robust means of bottom-up data integration and visualization of urban energy data. In this relation, the OGC has developed different open standards, such as the standardized semantic data model of CityGML to store and exchange city objects (buildings, land use, vegetation, water bodies, tunnels, bridges, etc.) as digital 3D city models. Also, the 3D Tiles format is developed to stream these 3D city models on the web. Moreover, a pool of standard web services from OGC, such as SensorThings API (STA), OGC API Features, and OGC API 3D GeoVolumes, allows the integration, query, and retrieval of required Spatio-temporal, static and dynamic datasets associated with the 3D city models on the web. Previous studies such as (Padsala et al., 2021), and (Würstle et al., 2020) have used a more traditional way of data integration, which is by enriching the original CityGML data model with necessary datasets by dumping it on a local database and then converting it to web streamable 3D Tiles format. The disadvantages of the current solution include 1. It causes an increase in the data size of the 3D city models according to the energy data, particularly the building energy dataset with the spatiotemporal characteristic such as an hourly building heat demand of each building. 2. data duplication as there will be multiple copies of the same datasets, e.g., datasets managed and relayed from the data owners and datasets that are dumped on a local database. With this perspective, this research tackles a method to optimize the data management of 3D city models with a connecting link to the OGC web services as a basis for developing the UDT application.

The rest of this paper is organized as follows. Section 2 explains the background of this research. Section 3 describes the concept of our paper. Then, Section 4 shows the implementation of this research in the real-world use cases as a proof-of-concept prototype. Section 5 concludes the research outcome.

* Corresponding author

2. BACKGROUND

2.1 Urban Energy Simulation

To facilitate urban energy simulations, the SimStadt software[1] is used in this research. It depends on 3D city models in CityGML format (buildings and landuse) to perform urban energy simulation tasks. The source 3D city models in CityGML format that are used in the SimStadt simulation must have closed solid geometries, which can be evaluated and fixed with the CityDoctor software[2] to perform heat and cooling energy demand simulation. Additionally, there is also a need for attribute data, other than the geometry, such as building function and year of construction, to calculate the building physics and thermal transmittance between building surfaces (Nouvel et al., 2015). These attribute data can be sourced from other geographic information system (GIS) layers and be injected into the CityGML data. This process is externally processed using the Feature Manipulation Engine (FME) workflow to overlay between external GIS sources and the ground surface of the CityGML building datasets.

Overall, SimStadt provides the possibility of modular workflows to simulate energy data including building heat demand (Nouvel et al., 2015), roof-top solar energy potential (Würstle, 2018), ground-mounted solar energy potential (Bao et al., 2022), regional biomass potential (Bao et al., 2020), and life cycle assessment of building construction and refurbishment (Weiler et al., 2017). After the process, SimStadt provides simulated building energy results in comma-separated values (CSV) format, which is usually injected into buildings or building parts of the CityGML model. The enriched CityGML is converted into the steaming format for visualization. For instance, Figure 1 shows the simulated roof-top solar energy potential on each building part of the CityGML model visualized on the 3D web-based application. However, this visualization approach has a limitation. The injection of simulated data into the original CityGML datasets and its 3D tile conversion have to be processed repeatedly whenever the simulated result is updated with new parameters or updated data sources. In this research, we make use of the OGC SensorThings API standard to manage the simulated energy data as an external database associated with the CityGML database, as explained in Section 3.

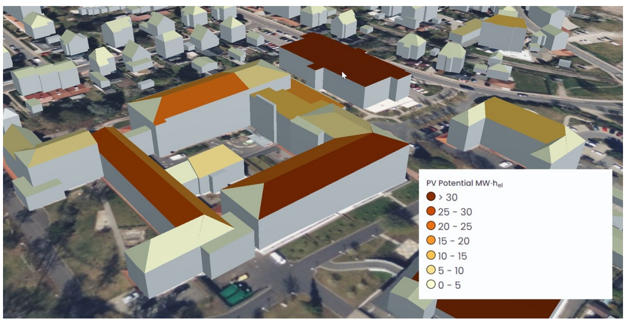

Figure 1. The simulated roof-top solar energy potential of the 3D building models in the area of Ilm-Kreis, Germany using SimStadt software.

[1] https://simstadt.hft-stuttgart.de/
[2] https://www.citydoctor.eu/

2.2 3D Data Steaming and Visualization

With the advancement of web technologies, the graphical information can be visualized on web browsers while taking advantage of the multi-threading capability and rendering process via graphics processing unit (GPU) on modern browsers. This allows a 3D geospatial dataset to be represented on the web, built upon the foundation of the web technologies HTML5 and WebGL (Feng et al., 2011). In the context of the urban data platform, the 3D city models in CityGML format have been used as an essential part of the spatial data infrastructure (Kolbe et al., 2005) and visualized on the web in 3D Tiles format (Kilsedar et al., 2019). In this research, we focus on the use of the Cesium JavaScript (CesiumJS)[3] open-source WebGL JavaScript library. It supports 3D geospatial data natively and is also capable of visualizing massive amounts of data and combining heterogeneous datasets together in various domains, e.g., mobility (Santhanavanich et al., 2018), urban energy simulation (Deininger et al., 2020), urban environment (Ebrahim et al., 2021), etc. In this research, the UDT procedure is realized using the CesiumJS-based 3D application to present the 3D geospatial data for urban energy related contexts.

Towards this goal, the CityGML data source must be prepared for the 3D visualization optimization. The source 3D city models in CityGML format are efficient as an exchange format which is deliverable as one file package but has a drawback on the web streaming due to its large package size and no supported visual web library (Würstle et al., 2020). The CityGML has to be converted to other formats fitting for the web streaming, such as Esri Indexed 3D Scene Layer (I3S), Cesium 3D Tiles (Blut et al., 2019, Koukofikis et al., 2018). These data formats are based on the GL Transmission Format (glTF), which is the runtime 3D asset delivery for 3D scenes and models developed by the Khronos 3D Formats Working Group (KhronosGroup, 2022). In this research, we focus on using a 3D Tiles data format that is compatible with visualizing on the CesiumJS-based application. The tools that allow data conversion from CityGML to 3D Tiles includes: ① the Feature Manipulation Engine[4] (commercial), ② virtualcitySUITE[5] (commercial), and ③ JavaScript-based citygml-to-3dtiles[6] (open-source). The essential step during this process is to verify the uniqueness of the building ID of the entire dataset in all areas, as these IDs are used as an associated link to an external dataset in the database (Santhanavanich and Coors, 2021).

As an evolutionary step after the 3D data has been prepared in the streaming format, the data can be hosted as a service conformed to the OGC API 3D GeoVolumes specification. The idea behind the development of 3D GeoVolumes specification is that instead of accessing 3D data from different vendors, users can use this specification to manage the data heterogeneity and access data with a unified API retrieval method which provides a 3D dataset in streamable format to client systems. This specification was developed during the OGC 3D Container and Tiles pilot (Miller et al., 2020), and the OGC Interoperable Simulation and Gaming Sprint (Daly and Serich, 2020, Daly and Phillips, 2021) which are potentially be a common standard in the near future. The overview of the GeoVolumes resource path is shown in Table 1 which conforms with the OGC API-Common[7] foundation resources, including landing page,

[3] https://cesium.com/platform/cesiumjs/
[4] https://www.safe.com/fme/
[5] https://vc.systems/en/
[6] https://github.com/njam/citygml-to-3dtiles
[7] https://ogcapi.ogc.org/common/

Resource Path	Description
/	Landing page in JSON or HTML.
/conformance	Conformance in JSON.
/api	API definition in JSON.
/collection	All 3D collections in JSON or HTML.
/collections?bbox=*bbox*	Filtered 3D collections matching the defined bounding areas or volumes (*bbox*) in JSON or HTML.
/collections/*container*	3D Collections of the specified *container* in JSON.
/collections/*container*?bbox=*bbox*	Filtered 3D collections of the specified *container* in JSON matching the defined bounding areas or volumes (*bbox*) in JSON or HTML.
/collections/*container*/*format*	3D resources of the specified *container* in the requested *format* such as 3D Tiles or I3S.

Table 1. The path and result from the OGC API 3D GeoVolumes resources.

conformance declaration, and collections. Being part of the OGC API family of standards, the GeoVolumes gives a benefit to sharing, consuming, and filtering the 3D geospatial resources through the web using the defined resource-centric APIs.

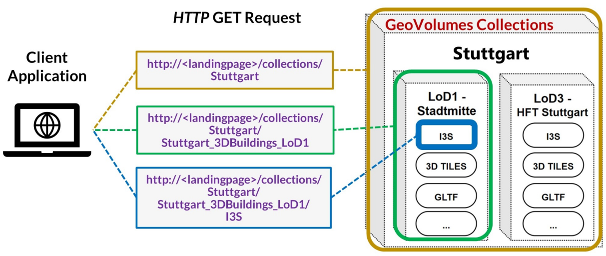

Figure 2. The OGC API 3D GeoVolumes hierarchical resource architecture and its associated HTTP resource path.

The OGC API 3D GeoVolumes constructs the 3D datasets in collections of data which can be spatially grouped by (but not limited to) their administrative boundary as shown in Figure 2. GeoVolumes's collection can be requested via API, which can be achieved through querying by name or their 3D spatial bounding volumes. Moreover, each collection may contain 3D resources in single to multiple 3D formats, level of details (LOD), and bounding volumes. As an example shown in Figure 2, the GeoVolumes collection "Stuttgart" represents the 3D dataset in the Stuttgart area, which contains 3D resources in LoD 1 and LoD 3 in different areas of the regions in the same collections.

2.3 Spatiotemporal Data

In the urban energy simulation application, the simulated energy data includes the spatiotemporal dataset, which is collected over space and time, such as the hourly or monthly heat demand of each building. The accumulation of this type of dataset causes the growth of data in size. Thus, efficient solutions to deal with this type of data are needed (Chandola et al., 2015). To address this, the Dynamizers concept was introduced to manage the dynamic data related to the 3D city models in the CityGML format (Chaturvedi and Kolbe, 2016). However, managing dynamic data directly in the CityGML model has some drawbacks, including i) data dependency of the CityGML models at the sensor locations, ii) the difficulty of managing the dynamic dataset from different parties as the 3D city models and sensor models usually have different owners. In this research, we propose using the OGC SensorThings API standard (STA) to manage the Spatiotemporal data of SimStadts energy simulation as a solution that is independent of the 3D city model. STA had been approved as one of the standardized protocols by the OGC (Liang et al., 2016). It provides a representational state transfer (REST) application programming interface (API) for managing heterogeneous data from various sources and devices with the comprehensive data model as in Figure 3, showing a simplified version of the STA entity model.

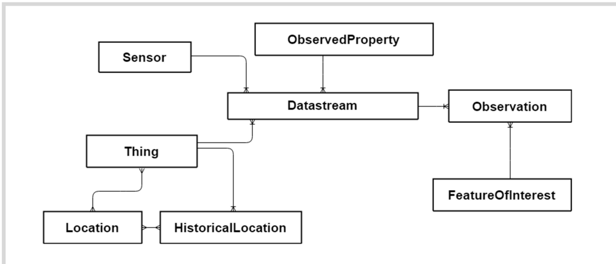

Figure 3. The simplified data model of the STA.

In the STA, there are in total of eight entity types in the data model. The `Thing` entity defines a physical object in the real world, with its position data collected in the location entity. The data produced by each thing has their data type described in the `ObservedProperty` entity, while the metadata of the sensor is stored in the sensor entity. Each set of `Thing`, `Sensor`, and `ObservedProperty` entities links to the `Datastream` entity which used to collect the time-series data in the `Observation` entity. Each `Observation` has one `FeatureOfInterest` entity to store the data target as a point, line, or polygon feature. After STA has been implemented, the client application can get the data via the resource path as shown in listing 1. STA had been widely applied to manage the heterogeneous data in our past research works in fields of mobility (Santhanavanich et al., 2018, Santhanavanich et al., 2020b), urban environmental (Ebrahim et al., 2021), and health (Santhanavanich et al., 2020a). Accordingly, the STA can optimize data delivery of spatio-temporal data to urban energy applications. The data modeling of STA's entities for the urban energy application is explained in Section 3. The implementation of STA is explained in Section 4.

Listing 1. Example of the STA Endpoint URL

```
http://[IP Address]:[Port]/[STA Name]/
[Version]/[SensorThings Entities]/
?STA_Query=[query options, limiting,
filtering, or re-ordering]
```

3. CONCEPT

The core concept of this research developes a connection between the 3D city models and OGC web services to optimize the performance of the 3D urban energy visualization platform.

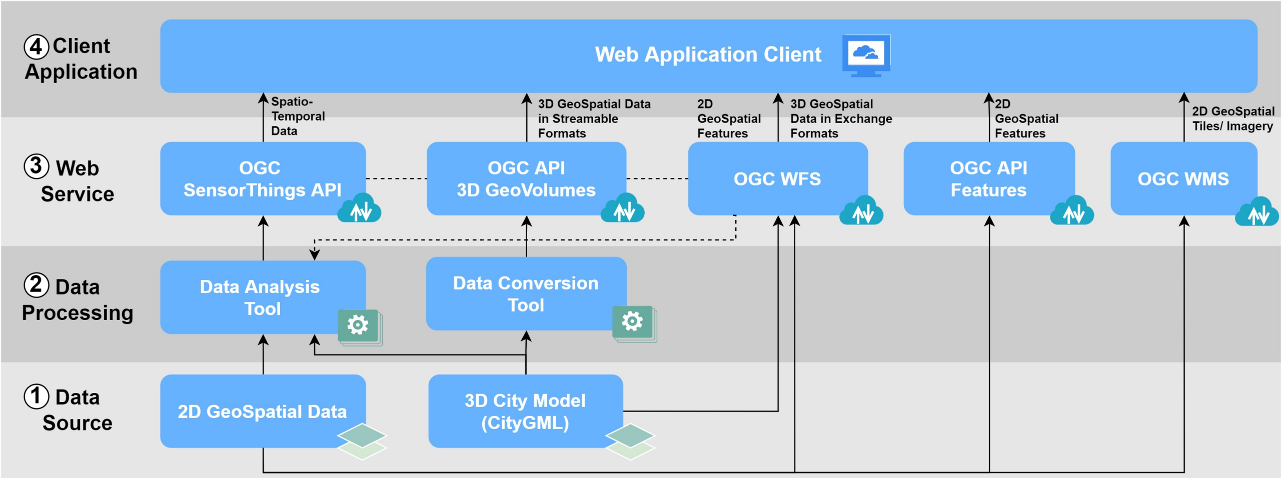

Figure 4. The conceptual SDI for the UDT application in the building energy domain.

This concept was first introduced to connect sensor data to the 3D city models using the link of unique identification (ID) and was called "CityThings". In CityThings, 3D city models have their unique ID stored in the STA in the `Thing` entity. With this connection, it enables the OGC standardized REST API access to the 3D city models and extends the CityGML data model to handle the heterogeneous and dynamic data, and becomes relevant in the UDT application development (Santhanavanich and Coors, 2021). To implement this concept in the context of UDT application in an energy domain, the overall SDI had been constructed consisting of four main layers, including data source, data processing, web services, and client application, as shown in Figure 4.

① **Data Source** includes 3D city models in CityGML format, which are used for the energy simulation and converted to 3D Tiles for 3D visualization. The land use data is an external GIS data that is converted to the CityGML dataset to enrich its information for the simulation process. In this architecture, external sources can be expanded and vary in data formats and types for further data analysis of the 3D city models.

② **Data Processing** includes the data analysis and data conversion tools. Our data analysis model simulates the building energy profile such as heat energy demand, electric load, and rooftop solar energy potential using the SimStadt simulation platform as explained in Section 2.1. The results from SimStadt are in a standard tabular format with the relative building or building part ID, which includes static building properties (e.g., specific space heating demand kWh/m^2/yr) and spatiotemporal or time-series data (e.g., hourly heating demand). The static building properties can be stored directly back to the building model in CityGML or pass them to the 3D Tiles format during the data conversion process. On the contrary, the time-series datasets are relatively large compared to the data model itself. They are imported to the STA server according to the STA conceptual model (Figure 3).

The data conversion part covers the building model conversion from CityGML to 3D Tiles format to be published on the OGC API - 3D GeoVolumes services as explained in Section 2.2. During the data conversion process, the 3D city models can be optimized as follows: ① reducing decimal places of all geometry coordinates to a precision level of the client application (10 Centimeters), ② storing the simulated energy data using the STA with an associated connection to the city models as explained in Section 3, and ③ removing all unnecessary surfaces such as ground surfaces, outer-ceiling surfaces, outer-floor surface from the visualization models as only roof surface and wall surfaces are needed to visualize in the 3D client application.

③ **Web Services** are the core section that interconnects between databases and client applications in a standardized way. All web services are based on the OGC web services standard. The STA manages the building energy data, which has spatiotemporal characteristics. According to the STA data model (Figure 3), it can be applied in the context of building energy data as explained in Table 2. In more detail, each building can be registered as a physical object with a unique ID in the `Thing` entity in STA. In the same way, the energy simulation tool or sensor devices are registered as a measurement tool in the `Sensor` entity, and the data type is registered in the `ObservedProperty` entity in STA. Each combination of these three entities creates a unique `Datastream`. The temporal data of each building is stored in the `Observation` entity which each of `Observation` matches with particular `Datastream` and `FeatureOfInterest`. In this work, the FRaunhofer Opensource SensorThings Server[8] (FROST-Server) has been used as the STA implementation. This server is implemented on top of the PostgreSQL database management system. With the installed STA system, client layers can communicate via `HTTP GET` protocol to query the building energy data based on the unique ID of the building or building part. Then, the responding data is sent back to the client in the JSON format.

In addition to STA, the OGC API 3D GeoVolumes service is used as a service for delivering 3D geospatial contents in the streamable formats from the hierarchical structure as described in Section 2.2. The implementation of 3D GeoVolumes has been developed as an open-source software hosted at our university repository (Santhanavanich, 2021). To efficiently stream the 3D data, only necessary attributes are stored in the server: the building geometry, ID, and the attribute fields with value required to be used as a categorized field. The origin 3D city models are stored in the database system for CityGML, such as 3DCityDB[9] and GeoRocket[10]. The 3DCityDB is used in this research. On top of the 3D database, the OGC Web Feature Trans-

[8] https://github.com/FraunhoferIOSB/FROST-Server
[9] https://www.3dcitydb.org/3dcitydb/
[10] https://georocket.io/

SensorThings Entity	Description
Thing	A building or building part with associated CityGML ID.
Location	Central geo-coordinates of each building or building part.
Sensor	A metadata of sensors equipped in the building or simulation tools.
Observed-Property	Data type of the data generated from each sensor or simulation tool.
FeatureOf-Interested	Central geo-coordinates of each building or building part (Same as Location).
Datastream	Information of each data stream (e.g., data stream name, unit of measurement, etc.).
Observation	Spatiotemporal data generated from each sensor or simulation tool.

Table 2. Explanation of each SensorThings entity to store the building energy data from measured sensors and simulation tools.

actional Services (WFS - T) server is deployed to allow client applications and data analysis tools to query 3D city models. Because, there is no open-source implementation of the WFS-T for CityGML datasets in 3DCityDB, the current implementation is based on virtualcitySUITE commercial software. For other 2D geospatial data, the GeoServer open-source server[11] is used to publish the data directly from the PostgreSQL database storage as OGC WFS and OGC API Features services with the required extensions installed. Optionally, the PyGeoAPI[12] is an open-sourced application to publish the OGC API Features service. Lastly, the GeoServer also allows the geocache of the 2D geospatial data and provides the 2D geospatial data as an imagery services such as OGC WMS or OGC API Tiles, which dramatically reduces the loading time of 2D geospatial data on the web. However, the OGC API Tiles has not been evaluated in this research yet according to the time constraint. To sum up, the OGC services not only efficiently provide availability of geospatial contents to client applications, but also allow the data analysis layer to query the geospatial data in the specified bounding volumes.

④ **Client application** is the developed UDT application that consumes and illustrates the data from the web service layer. In the back-end server, data requests are made using the OGC standard web services described in Section 2.2. In this research, the UDT application in the domain of building energy so-called "EnSysLE" has been developed and explained in Section 4.

4. USE CASES

The use cases are developed as part of the EnSysLE project with the aim of tackling how local and national energy systems behave in relation to each other and studying the potential for renewable energies. In this research, three different counties in Germany are selected as the studied areas, including Dithmarschen (DM), Ludwigsburg (LU), and Ilm-Kreis (IK), as shown on the map in Figure 5. The selection had been made according to the data availability, their different land use percentage, and their widely-spread geolocation over the country, which have mixed climatic conditions. This selection gives a complete view of the renewable energy potential from different regions and characteristics of Germany.

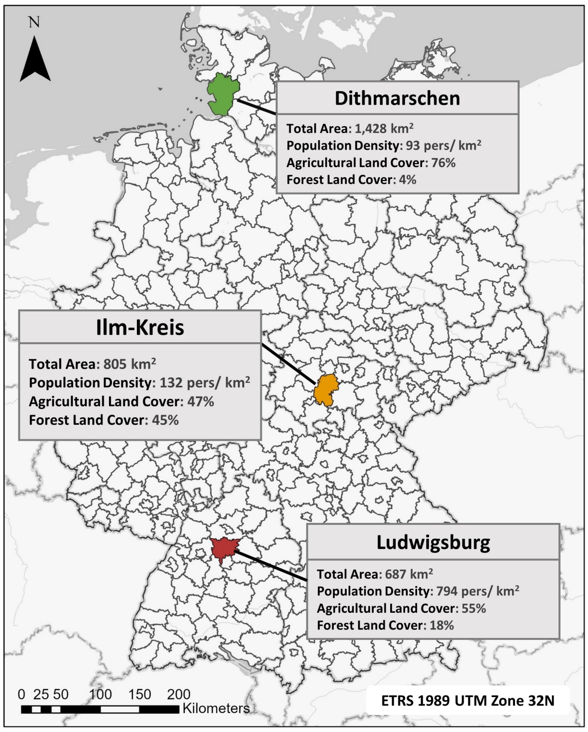

Figure 5. The three selected case study regions in Germany.

The EnSysLE UDT application is implemented based on the proposed system architecture (Figure 4). The SimStadt energy simulation tool is used to analyze the building energy profile, such as electric load, heating demand, roof-top solar power potential, etc., from the CityGML 3D city models in the database. The energy profile per building is generated covering one year range which contains one record, 12 records, and 8,670 records in yearly, monthly, and hourly resolution, respectively. For this reason, the data becomes relatively large at the regional or city level. In terms of data storage, the CityGML and simulated building energy data are stored on the server-side storage, as shown in the topper part of Figure 6. The CityGML 3D city models are converted to the 3D Tiles streamable format to visualize on the application. Even though, 3D Tiles data format supports the compressed attribute data within 3D Tiles building models directly, the enormous size of simulated building energy data causes a huge size of 3D Tiles dataset which affect the web application performance. To deal with this issue, the data is optimized by keeping the 3D model size as compact as possible during the 3D data conversion process using the concept explained in Section 3. The final optimized 3D model data has been reduced in size by approximately 84%, as shown in the bottom part of Figure 6. As a result, the optimized 3D Tiles are used to visualize 3D building models on the UDT application, which dramatically improves the UDT application performance compared to the regular 3D Tiles model.

The EnSysLE UDT application is a 3D web application built based on the CesiumJS library. It visualizes 2D and 3D geospatial data and allows the user interaction to view or edit the data attributes of 3D building models. The OGC web services for streaming 3D data models is implemented as explained in Section 2.2. The logic of this application is shown in the sequence

[11] https://geoserver.org
[12] https://pygeoapi.io

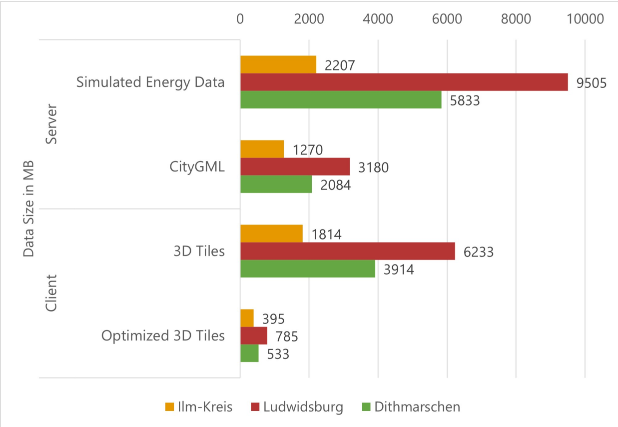

Figure 6. A chart illustrating the data size of the server-side data storage (Simulated Energy Data and CityGML) and the data for client-side rendering (3D Tiles and Optimized 3D Tiles) of the three selected case study regions.

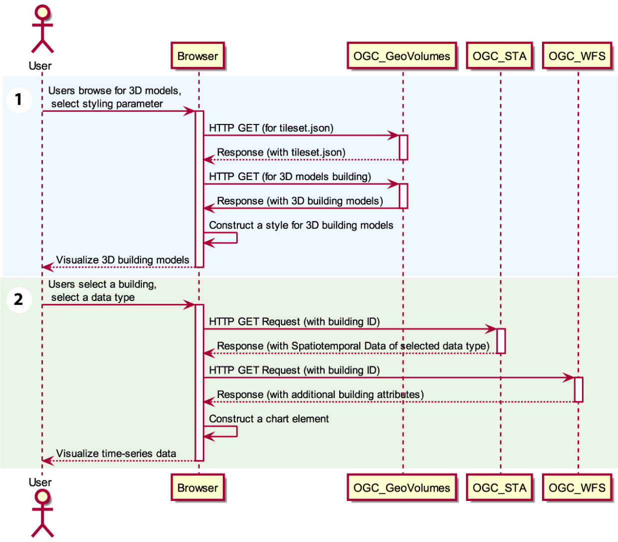

Figure 7. A sequence diagram of example user interactions in the EnSysLE UDT application.

diagram in Figure 7 which separated into two main parts. In the first part (Figure 7-①), users open the application to load the 3D city models from the OGC API 3D GeoVolumes server. The 3D city models are loaded according to the bounding volume of the user's current view. Then, the styling of city models is computed on-the-fly using the data stored in the 3D city models. The next part (Figure 7-②) is where the linked connection between building model, STA, and WFS are used. This happens when users select a building to explore its associated temporal data and additional attributes. The temporal data is queried from the STA with the linked building ID stored in the STA's `Thing` entity. In the same way, additional data of building model can be queried from the WFS using linked building ID.

In the user view, the developed application allows users investigate data in the energy context of per selected parameter in multiple perspectives. In the building scale, the application will enable users to illustrate the building properties by several energy parameters such as specific space heating demand, rooftop solar energy potential, electric demand, etc. When users click on the individual building, a new section pops up illustrating user-selected parameters in hourly or monthly resolution as shown in Figure 8. The temporal and additional data of 3D city models are requested by the application back-end to STA and WFS as shown in Figure 7-②. In a broader level, the application allows users to display the overview energy potential on a regional scale in parallel to a building scale. As an example in Figure 9, the aggregated building specific space heating demand on each parcel is visualized. It is pre-styled on the server-side and loaded to the application as tile imagery through the OGC WMS to boost the application performance.

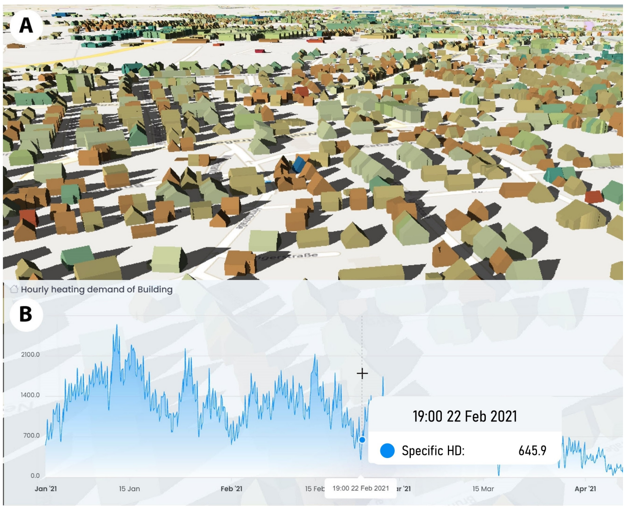

Figure 8. A visualization in the EnSysLE UDT application illustrating A: 3D city models styled according to the calculated specific space heating demand (kWh/m^2/yr), B: the pop-up window showing hourly heating demand (kW) of the selected building.

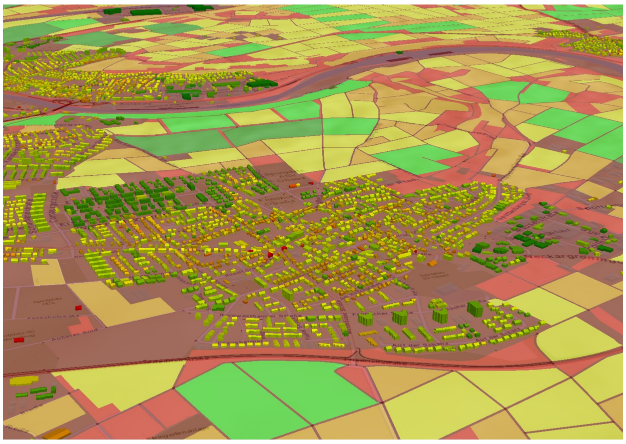

Figure 9. A visualization in the EnSysLE UDT application illustrating the building specific space heating demand (kWh/m^2/yr)) per building and per land use parcel in the area of Ludwigsburg.

The EnSysLE UDT application is hosted on our university repository and available online[13], however, only some data types are shown on the live application according to the strict data protection laws in Germany.

[13] https://transfer.hft-stuttgart.de/pages/ensysle/application/index.html

5. CONCLUSION

This research presents an overview of the UDT application development in the building energy domain using the 3D city models and OGC standards. The core concept of this work is how all geospatial data have been managed and delivered to users using OGC standardized specifications in the web service layer and associations between 3D city models and the spatiotemporal data. Using the standard solution not only increases data usability and efficiency but also decreases overall costs to integrate data from various sources and expand the UDT application system. In the use case, we successfully implemented the UDT application representing the temporal energy data on a scale of the building and regional level in three counties in Germany. As a result, our method has been proved to significantly improve the loading efficiency of geospatial data in UDT applications. With this concept architecture, the application can be expanded in terms of area coverage and data type varieties in future work, while the application performance must be observed on a larger scale. The client application can be implemented as a mobile-based application for more flexible accessibility or a game-engine-based application for more realistic visualization. This proposed concept will also be implemented in the OGC Testbed 18[14] innovation program activities on the topic of Building Energy Spatial Data Interoperability. In addition, the concept can be expanded to develop the UDT applications to cover other aspects, such as simulations and interventions in real-world scenarios in other domains.

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