A Lightweight Framework for Seamless Integration of Building Energy Simulations into Urban Digital Twins

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Abstract

Urban Digital Twins (UDTs) and Urban Building Energy Models (UBEMs) are increasingly used to support energy scenario analysis for building retrofits, greenhouse gas emissions reduction, district energy planning, and climate resilience strategies. However, the integration of these technologies is often hindered by data format incompatibilities, limited automation, and insufficient visualization capabilities. This research presents a modular, web-based framework that couples a dynamic Building Energy Simulation (BES) model with a UDT platform using lightweight, standards-compliant formats (e.g., CityJSON). The proposed workflow enables both automated and semi-automated processes, facilitating the visualization of simulation results such as heating demand at both building and district levels. Heating demand and other simulation results are integrated and visualized through an intuitive client-side interface, offering spatial and attribute filtering at multiple scales. The system supports user-provided data and integrates it into an intuitive client interface, enabling spatial filtering, attribute querying, and interactive analysis. Key contributions include the development of preprocessing workflows for data compatibility, integration structuration for simulation outputs, multi-scale visualization capabilities, and analytical tools for what-if scenario analysis. By bridging theoretical modeling frameworks with practical, standards-compliant deployment, this work advances the convergence of geospatial and energy modeling, providing a scalable and interactive tool for energy-aware urban planning. This coupling establishes a bidirectional feedback loop, where UDTs supply detailed 3D geometries, and UBEMs provide predictive energy insights, transforming digital twins into robust decision-support systems.

1. Introduction

Cities worldwide face severe challenges related to rapid urbanization and its effects on climate change. Buildings as major contributors to global energy consumption and greenhouse gas emissions, account for 34% of energy demand and 37% of energy-related carbon emissions. This concentration of energy consumption within urban areas poses significant challenges for city planners, energy managers, and policymakers that aim to cope with decarbonization goals while maintaining quality of life for residents. The complexity of urban energy systems spanning thousands of buildings with diverse years of construction, materials, and usage patterns makes comprehensive management nearly impossible through traditional approaches. Each building operates as part of an interconnected network, driven by neighbouring structures, local climate conditions, and occupant behaviours. Direct monitoring and optimization at the building level seem critical due to the scale of data required, the differences in the building stock across regions, and the computational demands of city-wide analysis. Given this challenge, the urge to develop innovative digital tools that help to understand and evaluate the energy consumption and demand is required. Urban energy planning relies on digital technologies to support the transition toward more sustainable cities. In this context, urban digital twins (UDTs) are emerging as key tools to manage, visualize, and analyse complex urban data. Many scholars have highlighted the potential of UDTs in energy simulation fields, namely positive energy districts, household consumption, heating demand, and greenhouse gas emissions, across various scales (Alva et al., 2024; Coors and Padsala, 2024).

However, the integration of these technologies into practical applications presents challenges, namely, data format incompatibilities (e.g., between geospatial and building energy datasets), visualization limitations, and the gap between simulation requirements and available urban data. This work aligns with the current discourse around developing Energy UDTs by ensuring a direct coupling between an UDT platform and a Building Energy Simulation (BES) model. This integration generates detailed energy data and enriches 3D city models with domain-specific attributes such as heating demand, supporting decisions related to urban heating and retrofitting planning. This research investigates how lightweight standards such as CityJSON and modern web technologies can bridge technical barriers related to data integration and interoperability, enabling the deployment of energy aware digital cities essential for meeting climate target and reduce the duplication of effort between stakeholders and data providers. Most urban-scale energy assessment tools rely on archetypes, degree-day methods, or benchmark data, which often overlook individual building characteristics such as geometry, thermal inertia, or usage patterns. In contrast, this work applies a more detailed, data-based simulation while remaining computationally efficient. Indeed, we use the geometric data from the UDT to feed an automated, parametric energy model. This coupling offers a scalable, standardized, and data-driven solution that bridges the gap between digital urban models and building-level thermal simulations. Furthermore, the reintegration of the simulation results back into the UDT for visualization and analysis improves the structuring, accessibility, and interpretation of energy data for planning and policymaking. The workflow is tested on a real urban district to assess its feasibility and potential for broader application.

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2. Background

2.1 Urban Building Energy Modeling and Simulation Tools

Urban Building Energy Models (UBEM) are tools for urban energy planning and management. UBEM is defined as a computational modeling approach that applies physical models of heat and mass flows indoor and outdoor buildings to predict operational energy use and environmental conditions for groups of buildings in urban settings (Reinhart and Cerezo Davila, 2016). UBEM supports scenario analysis for building retrofits, energy code compliance evaluation, district energy system planning, and urban heat island mitigation strategies. These capabilities collectively enable cities to develop comprehensive energy strategies that balance efficiency, sustainability, and resilience objectives (Hong et al., 2020). Different categories of building energy models can be identified. The first category is the non-physical top-down models that relied on standard profiles, degree-days method or are based on air temperature and benchmark data, limiting their ability to capture individual building characteristics and accurately predict peak loads. Their main advantage is to not require a lot of data, generally difficult to obtain when working at urban scale. In addition, two other categories exist: bottom-up models and highly detailed models. The first group bottom-up models are based on archetypes, statistical data and national or international standards. They allow to perform dynamic easy quick simulation of many buildings. The main drawback lies in the uncertainty in statistical data and the assumptions used for data enrichment. For instance, TEASER, is one of bottom-up models that is open-source tool for urban energy modelling of building stocks (Remmen et al., 2018). On the other hand, highly detailed models depend on complete thermal model equations and an accurate representation of the building's characteristics. While the results can be very precise, the significant time required for modelling often makes it impractical to apply these models to a large number of buildings. Moreover, to make this type of model operational, it requires detailed knowledge of numerous data points, which are generally not available at a large scale. In practice, various urban simulation tools and engines are used. For example, SimStadt is one of the commonly used simulation tools within the framework of implementing energy UDTs. It enables the analysis of solar potential, energy demand, and CO_2 emissions at the individual building level using a CityGML-based 3D city model. For space heating, the building model relies on a monthly energy balance approach applied to each building (Nouvel et al., 2015). The integrated model for the characterization of spatiotemporal patterns of energy consumption in neighborhoods and city districts offers to compute the hourly power and temperature requirements in buildings by integrating two bottom-up methods (statistical and analytical) (Fonseca and Schlueter, 2015). Furthermore, the BSTG-SG model aims to simulate household energy consumption prior to the implementation of energy-saving measures. It is an ensemble time-series model based on both observed and synthetic data. The building simulation software SIM-VICUS offers the integration of a dynamic building model with a dynamic district heating network model, along with a 3D visualization interface (Weiß et al., 2024).

This work aims to position itself between bottom-up models and highly detailed models. Specifically, it uses the IDEAS Modelica library from KU Leuven within the simulation platform Dymola to develop a fast, automated, and parametric modelling approach (Jorissen et al., 2018). The idea is to use the IDEAS building model, which is a detailed building model, but to automate its modelling process to make it scalable for large-scale use. It is parameterized using Belgian national standards to compensate for the lack of data. However, since it is fully configurable, as soon as real information becomes available, actual data can be used, removing the need to rely on statistical data, and increasing the results accuracy. The building model is a thermal inertial model, based on R-C model equations, requiring information on building geometric characteristics, envelope, usage, ventilation and control strategy. The model can output hourly thermal demand (both heating and cooling), annual thermal demand, estimated electricity consumption, and domestic hot water demand. Since the building's physics and thermal exchanges are accurately represented, refurbishment scenarios and their potential impacts can be analysed to estimate energy savings.

2.2 Urban Digital Twin

Urban Digital Twins represent a new paradigm in urban and geospatial fields, moving beyond static models toward dynamic, integrated, sustainable, and adaptive tools for city planning and management. They enable interactive visualization and advanced analysis across various domains and use cases (e.g., District-/City-Level Forecasting, Emergency Planning, Operational Optimisation, Participatory Planning, Policy Development, Scenario Modelling) (Alva et al., 2022). They are conceptualized as the digital representation of the real world, its urban objects, infrastructures and processes. They are characterized by the bi-directional connection between the physical and virtual environments, allowing interaction through dynamic data, primarily collected from IoT sensors. Various definitions can be found in the literature. However, in the geospatial domain, UDTs are commonly conceptualized as being built upon 3D City Models enriched with semantic information, thereby enhancing the analytical potential of geospatial data. These models are frequently integrated with near real-time data streams, which emphasize the dynamic nature of UDTs by enabling continuous data exchange between the physical and virtual environments. This integration facilitates a wide range of analyses, including simulations, forecasting, and visualizations, delivered through platforms such as web-based applications, analytical tools, or game engines. Ultimately, UDTs function as comprehensive, multiscale, and multitemporal data infrastructures, serving as one-stop platforms that combine heterogeneous datasets and models. This enables stakeholders to effectively investigate and address both current and emerging urban challenges across social, economic, and environmental dimensions (Jeddoub et al., 2024). Cities worldwide are adopting the emerging trend of developing open access 3D city models in CityGML standard. This has led to a wide diversity in methods for data 3D reconstruction, data integration levels, format translations as well as visualization tools. City2Twin is a standardized UDT platform developed in GeoScITY lab that integrates heterogeneous datasets, including 3D city models, point clouds, air quality data, and 2D sensor data (Rafamatanantsoa et al., 2024). The platform offers multiple data integration approaches. For instance, near-real-time data is integrated on the client side, while time series analysis is supported through OGC SensorThings API databases. City2Twin also enables users to bring their own 3D models and analyse them according to the attributes and spatial functionalities built into the UDT platform. The platform implements a three-tier architecture (CityJSON database, Flask server, and client side) and is designed to emphasize the openness, transferability, reusability, and maintainability of the UDTs.

2.3 Integration Approaches of UDTs and UBEM

A range of methods integrating UDTs with UBEM are currently available in practice to support energy analysis, carbon emissions evaluation, and energy planning at urban scale. Most of these methods rely on 3D city models, which are considered a fundamental source for storing and retrieving the parameters necessary for building energy simulation. However, while 3D city models provide a standardized and semantically rich data infrastructure for integrating building-related data, such as building function, construction year, and geometry, there are still significant challenges associated with their use in urban energy simulations. One of the main challenges lies in the heterogeneity and complexity of the data, particularly when multiple simulation results (e.g., energy demand, solar potential) are integrated into a single model. These outputs often originate from different tools and formats, complicating their harmonization within a unified framework. Moreover, visualizing and managing this data in an accessible way is challenging, especially for stakeholders like city administrators who rely on clear, interpretable results to support policy and planning decisions. To address that and the data interoperability issues, Energy ADE is developed as an Application Domain Extension of CityGML, offering a holistic and harmonized approach for integrating and managing energy-related information (Agugiaro et al., 2018). The Energy ADE closes the gap between geospatial and energy related information by extending the thematic CityGML data model with building energy classes and modules. Various urban simulations tools support the file reading and/or writing of the Energy ADE, namely SimStadt, CitySimPro, TEASER+. Although the Energy ADE mechanism has been introduced to support the extension of CityGML for domain-specific needs such as energy modeling, it still poses limitations. The ADE approach often requires complex data conversion processes, lack of open sources software, and the need for customized tools for accessing and visualizing the enriched data on web-based platforms. These barriers reduce the efficiency and scalability of using such enriched models in practical, real-time applications. Therefore, there is a growing need for lightweight, interoperable, and web-friendly solutions that can simplify data integration, improve visualization capabilities, and support decision-making workflows without sacrificing the richness of the underlying semantic information. In response to these technical challenges, several alternative approaches are tested in practices to manage and retrieve energy related information into UDT. For instance, on-the-fly energy simulations were implemented using SimStadt API by introducing the input parameters through a web interface (Rossknecht et al., 2023). Another method leverages the 3DCityDB to store and manage the simulation results in a centralized way. The data are retrieved using 3DCityDB Web Feature Service, or a customizable web interface (Gebetsroither-Geringer et al., 2025). A more recent approach is the use of modern OGC web service standards to build a fully interoperable Spatial Data Infrastructure (SDI) for UDT applications (T. Santhanavanich et al., 2022). Modern web service standards have revolutionized urban data access and processing capabilities, with the Open Geospatial Consortium developing next generation APIs that replace traditional web services with more efficient, RESTful approaches. These standardized web services enable seamless integration of distributed urban data sources, support real-time processing workflows, and facilitate interoperability between diverse modeling tools and platforms, making them essential components of contemporary UDT architectures. Efforts to enhance the practical use of the Energy ADE include the Energy ADE KIT profile, which focuses on steady-state energy calculations and offers a more feasible solution for city-scale energy assessments by balancing complexity and usability. In addition, energy extension for CityJSON (a lightweight, web-friendly encoding to CityGML) is demonstrated as a semi-direct mapping approach from the Energy KIT profile for space heating demand calculations (Tufan, 2022). Despite these advances, full Energy ADE implementations still require extensive data collection and technical expertise, limiting their practicality, whereas CityJSON energy extensions remain in experimental stages with limited integration into existing workflows. Consequently, many practitioners resort to ad hoc attribute additions within city models to balance flexibility and immediate usability. These developments underscore the critical need for lightweight, modular, and standards-compliant architecture that enable efficient management, interoperability, and visualization of heterogeneous urban energy datasets within UDT frameworks. In conclusion, while ADE-based models provided a solid and standardized foundation for semantic enrichment of 3D city models, the emerging energy-oriented UDT systems lies in the adoption of lightweight, modular, and standards-based architectures. These new approaches offer a scalable and interoperable framework for integrating simulation and sensor data, ultimately enabling more effective planning, monitoring, and intervention in complex urban environments.

3. Methodology

We have proposed a generic methodology to support the coupling of UDT and BES (see Figure 1). First, we prepare our geometry data while enriching the 3D model with various attributes necessary to meet the BES requirements. Then, we implement a parametric approach to run the simulation model. Finally, we integrate the simulation outputs back into the UDT (City2Twin), enabling detailed building analysis.

3.1 Study Area and Datasets

The selected case study is the Sart-Tilman district, located near Liège in Belgium. It includes the campus of the University of Liège, the village of Sart-Tilman and the science park. Given the studied area, composed of 1,661 buildings, the nature of the buildings is diverse, including schools, residential buildings, a hospital, shops, sports centers, and tertiary buildings such as administrative and industrial companies. This diversity provides an interesting case study to demonstrate the tool's versatility in adapting to various building types. Moreover, all these buildings were constructed at different times (between the 1970s and 2010s) and therefore show varying levels of insulation and energy performance. Changes in insulation can therefore be studied to assess their impact on variations in energy performance. The case study focuses solely on the energy demand for space heating, while domestic hot water is not modeled energetically, only water consumption is considered. For this purpose, UBEM requires geometrical and non-geometrical properties of buildings (refer to Table 1). Then, both the input parameters and predefined climate conditions are set according to the UBEM simulation tool. The weather file used is a TMY (Typical Meteorological Year) file from the Uccle weather station, the reference station in Belgium, adapted with local temperature, solar irradiation, and wind speed values to improve accuracy. This case study was selected for its size and data accessibility to test the feasibility, robustness, accuracy, and scalability of the coupling between the UDT and the BES model.

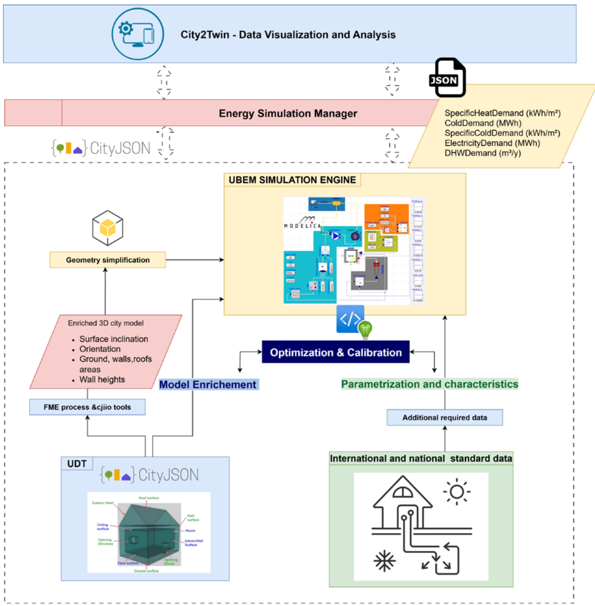

Figure 1. Methodology overview of coupling UDT and BES.

3.2 Data Preparation

The 3D city model is created using Roofer, the latest version of Geoflow. The 3D reconstruction process in Roofer takes 2D building footprints and point cloud data as input to generate 3D buildings at different levels of detail. The reconstruction algorithm provides several attributes, including volume, roof type, slope, and azimuth, among others. However, to meet the simulation requirements, the 3D city model went through an FME (ETL process) pipeline, which allowed us to calculate additional attributes such as ground surfaces, wall heights and orientations, and roof surfaces. Furthermore, the model incorporates all information associated with ground surfaces, as well as the building function.

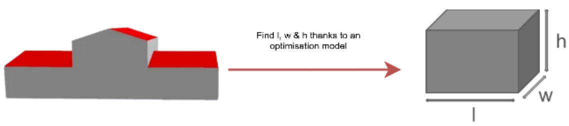

Figure 2. Model simplification from LoD 2.2 to LoD1.

3.3 Heat Demand Simulation

The heating demand simulation is performed using the IDEAS Modelica library from KU Leuven within the Dymola simulation platform. The model is easily parametrizable dynamic building energy simulation model to facilitate access to energy data through intuitive visualization. The geometric data and descriptive nature of the individual buildings captured by the UDT is used as input for the energy simulation model, in parallel with Belgian standards used to define all other model parameters, such as building thermal envelope, occupancy levels, lighting, electricity and domestic hot water consumption, setpoint temperatures, and ventilation systems. All these parameters are easily customizable and can be replaced by real data when available. The detailed LoD 2.2 model provides accurate building geometries with ground, walls and roofs surfaces, orientations and inclinations, as well as volume and height of the building. However, to ensure reasonable computation times and simplify the modelling process, an abstraction is applied: complex geometries are replaced with rectangular parallelepipeds (see Figure 2). This simplification preserves the main thermal exchange surfaces and heated volume while reducing geometric complexity.

UBEM properties	Input parameters	Sources
Geometrical	Building id	3D city model
	Face "A" orientation	3D city model
	Area of surfaces	3D city model
	Length, width, and height of the building	3D city model
	Number of storeys	3D city model
Non-geometrical	Window-to-heated-floor area ratio	(Michael and Heracleous, 2017)
	Heating Capacity	An established rule
	Occupancy	Article R.143-2 du Code de la Construction et de l'Habitation
	Comfort temperature	Circulaire 8746 Fédération Wallonie-Bruxelles, SPW énergie
	Mechanical ventilation airflow rate	SPF santé publique
	Building's n50 value (air permeability indicator)	TABULA library
	Material and construction composition	TABULA library
	Electric load profiles	energuide.be
	Domestic hot water consumption	Energie Plus Le Site
Additional parameters	Year of construction	3D city model
	Building function	3D city model
	Weather file (local temperature, solar irradiation, wind speed)	Sart-Tilman weather station

Table 1. Input parameters and their data sources.

Once the simulation is complete, the results are structured to be reinjected into the UDT for visualization and analysis. Two simulation scenarios are executed to evaluate annual energy performance across the building stock. The standard scenario represents current building conditions using existing envelope properties and thermal characteristics. The main outputs are the annual heating demand per building and the specific annual heat demand (in kWh/m²), which allows buildings to be classified by energy performance category and to identify those that would most benefit from renovation. The insulation scenario applies enhanced thermal performance measures specifically to buildings classified between energy classes C and G according to the Belgian Energy Performance Certificate (EPC). Simulation outputs are structured as JSON files containing annual heating demand values in MWh, specific heating demand in kWh/m²/year, and additional energy metrics for each building identified by its unique ID (refer to Figure 3).

3.4 Managing and Integrating Simulation Results into City2Twin

To manage the simulation outputs, we develop a simulation manager logic that allows as to structure and integrate the simulation outputs into the UDT. To cope with the architecture of our UDT and to enrich the platform with various datasets while creating an adaptive and user-friendly energy UDT, we focus on developing data integration approaches on the client side.


```
{
  "BE.WL.GEOREF.006196EF-660A-4125-B497-E51992AEB711-0": {
    "HeatDemand (MWh)": 54.88090133666992,
    "SpecificHeatDemand (kWh/m^2)": 244.3433074951172,
    "ColdDemand (MWh)": 2.578068733215332,
    "SpecificColdDemand (kWh/m^2)": 11.478198051452637,
    "ElectricityDemand (MWh)": 4.601852893829346,
    "DHWDemand (m^3/year)": 54.75,
    "Number of Occupants": 3,
    "Construction_year_assigned": 1944,
    "Optimization Results": {
      "error_surface": [
        3.2771446957853075e-10,
        3.079289923717006e-10,
        1.232945170558647,
        2.9901769066355334e-10,
        9.411158043799746
      ],
      "error_volume": 27.11120194332855
    }
  },
```


Figure 3. Snapshot of the JSON simulation outputs.

This approach provides users with the flexibility to visualize one or multiple 3D models as well as one or multiple simulation files, empowering them to conduct customized analyses and better meet their specific requirements. Before integrating the simulation data into the platform, we establish a set of rules to ensure a seamless and standardized integration process. Each building was assigned a unique identifier to enable direct linkage between the simulation data and the 3D city model. We also agreed on the use of specific data formats (i.e., CityJSON for the 3D models and JSON for the simulation outputs) to maintain consistency and interoperability. The simulation results included key attributes such as the specific heating demand (kWh/m²) per year for each building and the total annual heating demand (MWh). Following the Belgian EPC framework, we defined eight energy classes (from A+ to G) and added an additional category for buildings with no heating needs, such as annexes. The corresponding attributes (heating demand, total heat demand, and energy class) were written back into the 3D city model as extra attributes in accordance with the CityJSON specifications. To further analyse the simulation results, we produced bar charts illustrating the average heating demand per building type and the distribution of buildings by energy class, enabling a clear and accessible interpretation of energy performance across the campus. To fully demonstrate the capabilities of the UDT platform, we integrate two heating demand simulations (standard and insulation scenarios). The platform is configured to support many simulation scenarios, and the user interface adapts according to the scenario to be visualized, allowing users to toggle, visualize, and analyse multiple scenarios simultaneously. Based on these scenarios, we have carried out a comparative analysis to assess changes in the distribution of buildings across energy classes before and after energy retrofit, which primarily involved roof and wall insulation, as well as window upgrades (glazing and frames). Additionally, we presented the reduction in heating demand achieved through this renovation, offering insights into the potential energy savings and performance improvements enabled by targeted retrofitting. This makes it possible to quantify the impact of certain efforts from both an energy and economic perspective, and to provide guidance on which buildings would be the most relevant to retrofit, as well as where to focus renovation efforts, such as roofs, walls, floors, or windows.

4. Results and Analysis

4.1 Data Visualization

For visualization purposes, we implement a color-coded classification framework that associates energy performance classes with distinct visual representation. Each energy class is assigned to a specific color based on the standard energy rating conventions. Buildings are color-coded according to their calculated energy class, determined from specific space heating demand values. The UDT processes the energy simulation output and dynamically maps the corresponding color to each 3D building geometry. An interactive legend with checkboxes was developed for each energy class, allowing users to show or hide buildings by class. When a user selects or deselects a checkbox, the system updates the 3D scene in real time to reflect the changes. Furthermore, to support comparative analysis, we also developed a multi-scenario toggle interface that allows users to import different simulation scenarios, and switch between them seamlessly (see Figure 4.a). This interface enables smooth loading for standard (see Figure 4.b) and insulation scenarios (see Figure 4.c), where both the 3D building colors and the associated analytical charts update in real time according to the selected scenario.

4.2 Data Analysis

To support comprehensive energy performance evaluation and retrofit decision-making, several analytical tools were developed that enable multi-scale assessment of energy simulation results. The analysis logic operates through progressive layers of complexity, beginning with basic dataset visualization and advancing to sophisticated comparative assessment and individual building-level analytics that quantify insulation impact across each individual building.

Simulation outputs charts: The analysis feature first enables interactive visualization of energy simulation datasets through automated chart generation. Upon successful data upload, the platform provides checkbox-controlled chart display functionality that generates statistical visualizations of the building energy performance (see Figure 5).

Distribution chart: The primary analysis tool generates energy class distribution charts that categorize buildings according to Belgian EPC standards (see Figure 6).

Analysis of average heating demand by building function: This analytical component aggregates energy performance by building function categories, calculating average heating demand per typology extracted from CityJSON "NATUR_DESC" attributes (refer to Figure 7).

Insulation impact analysis - scenario comparison mode: Once both scenarios are loaded via the multi-scenario toggle interface, users can access advanced comparison tools through the "Show Insulation Impact Charts" feature. This analysis framework generates detailed visualizations to assess the impact of retrofitting measures.

Class Migration Distribution Analysis: This first comparison tool shows how buildings change energy classes after insulation is applied, helping to understand the impact of the retrofit. The analysis is divided into two main parts:

Class Migration Distribution Analysis: This tool quantifies energy class migration by how buildings transition across

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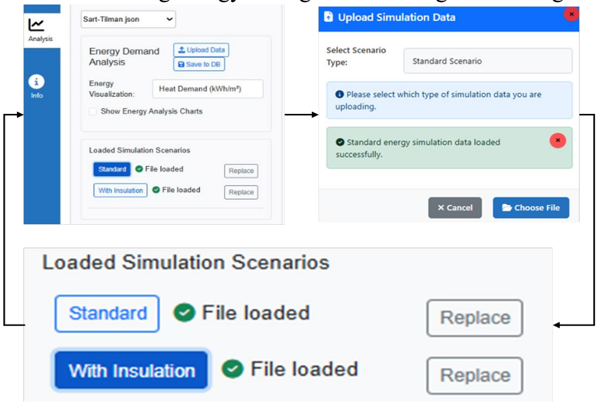
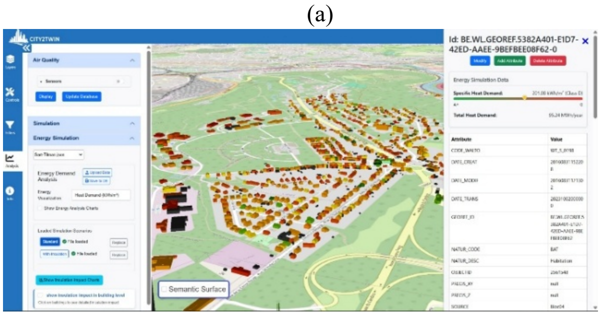
energy performance categories following insulation implementation (See Figure 8.a).

Percentage Gain Analysis Heat Demand Reduction Distribution: This tool categorizes buildings based on their percentage improvement ranges, illustrating the distribution of energy savings achieved through insulation (see Figure 8.b).

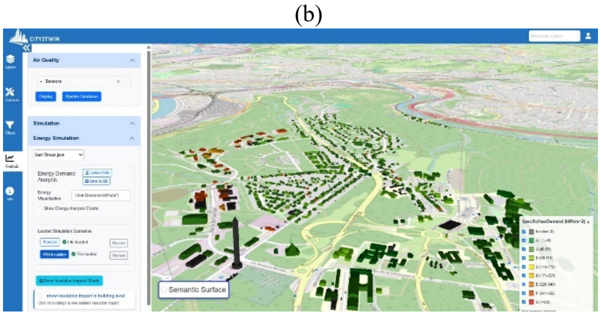
Building level visualization and analysis: Interacting with individual buildings through enabling analytics mode. The user selects a specific building to retrieve the key performance metrics including energy savings and building class changes.



(a)



(b)



(c)

Figure 4. City2Twin: Heating demand integration: (a) data loading workflow, (b) Standard scenario (c) Insulation scenario for buildings classified between energy classes C and G according to the Belgian EPC.

Figure 5. City2Twin checkbox-controlled chart for switching and filtering buildings according to their energy classes.

An interactive gauge diagram is also created to show the percentage of improvements and retrofit effectiveness (see Figure 9).

Additional UDT built-in features: City2Twin, in addition to its implemented and dedicated energy features, offers other spatial and attribute-based filtering functions. After mapping the 3D city model with the simulation results, the data is written and stored back into the CityJSON file, which creates a new enriched CityJSON file containing the energy attributes.

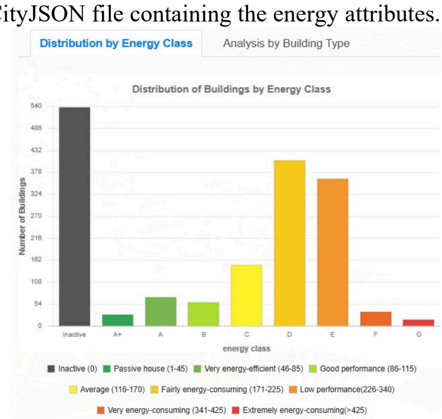


Figure 6. Distribution of campus buildings by energy class.

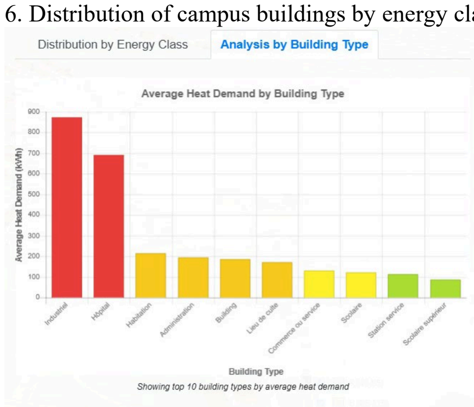


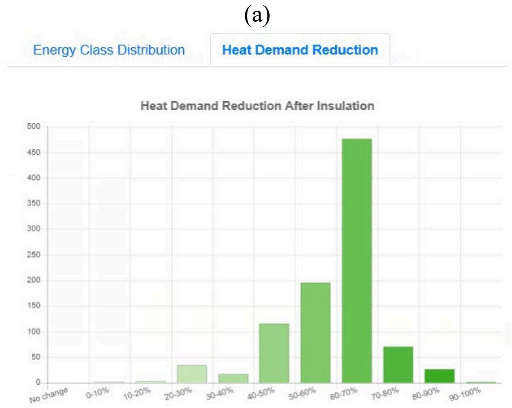
Figure 7. Average heating demand per building function.

The newly created CityJSON files are valid and comply with the CityJSON 2.0 specifications. Users can also save the new file locally and use it in other third-party software. Thus, the integration of the proposed BES model to the UDT offers a tool capable of accurately representing buildings, enabling the extraction of reliable consumption data or the development of energy retrofit studies by taking advantage of the data potential of UDTs. This is particularly valuable, as data collection remains one of the major challenges in large-scale building modeling.

5. Discussion

This work presents the integration of an UDT with an easily parametrizable dynamic energy simulation model to facilitate access to energy data through intuitive visualization. The aim is preliminary to investigate and to assess the technical feasibility of coupling the BES with the UDT. City2Twin can integrate various data to retrieve heating demand information and make energy consumption analysis at the campus and building levels. One of the key strengths of this work is the integration at the client-side level according to the simulation data structuring developed in the front-end. Users have the possibility to bring their own data (i.e., simulation results and 3D city models) then the platform take charge of the mapping, the integration and the management of the data into analytical information. Furthermore, the spatial, attribute filters and the visualisation parameters developed in the UDT platform gives the users a range of features and functionalities to manipulate their data. The current workflow involves both automated and semi-automated processes. Specifically, the coupling between the UDT and the BES model is not fully automated. This is primarily due to the need for intermediate preprocessing steps, such as the geometric simplification of the 3D city models from LoD2.2 to rectangular parallelepipeds, which are required for compatibility with the BES model.

(a)



(b)

Figure 8. (a) Distribution of buildings across energy classes before and after insulation and, (b) Reduction in heating demand achieved through insulation.

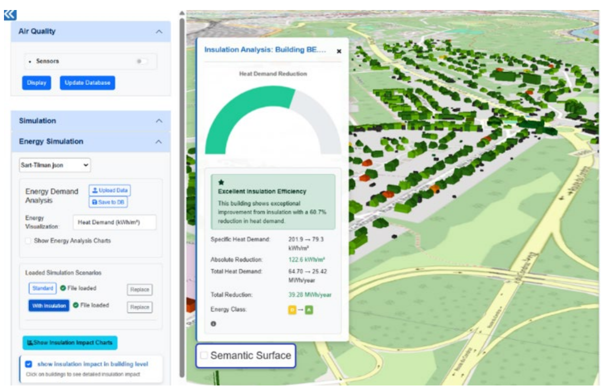


Figure 9. Gauge diagram per building showing the percentage of improvements and retrofit effectiveness.

These simplifications are carried out through an optimization process prior to simulation. Additionally, the input parameters file for the BES model is configured semi-automatically within a Python environment before the energy simulation is automatically launched in Dymola from the Python framework. Parameters such as weather data, occupancy schedules, and material properties are assigned based on the building characteristics provided by the UDT. All these parameters remain manually adjustable, offering flexibility and control, though this can limit the degree of automation currently achievable. In addition, the integration and mapping of simulation results back into the UDT are fully automated, as long as the UDT model and the BES output files share consistent and matching unique building identifiers. This ensures seamless visualization of the simulation outcomes within City2Twin. As part of our future work, we aim to develop a fully automated pipeline by leveraging the BES model's server-side API. In this approach, users would be able to dynamically define input parameters via the client interface, run simulations on demand, and receive the results in real-time as JSON responses, ready for immediate visualization. Such an approach will enable a more interactive, user-driven system and support a scalable deployment of simulation workflows within UDT applications. This initial study did not seek to evaluate the model's reliability. Further work will be needed to calibrate and validate the model to obtain more accurate results. The results presented here primarily serve to illustrate the workflow's technical feasibility and the potential of the tool to produce usable outputs for integration into UDT applications. It is important to note that several key input parameters required for the BES were not available and had to be derived from secondary sources such as literature or statistical assumptions. For example, the year of construction, a key parameter of building performance, was not present in the original dataset and had to be approximated. Moreover, the thermal modeling approach assumed a single thermal zone per building, which is a simplification that may be insufficient for large or complex structures where multiple thermal zones would yield more accurate simulations. Additionally, the categorization of building functions was rather coarse, and greater granularity in building usage types may be necessary to enhance the representativeness and reliability of the results. These limitations highlight the need for improved data availability and more detailed semantic enrichment of the 3D city model to support robust and reliable energy modeling in future iterations of the system. Nevertheless, at this stage of the study, we are actively engaged in identifying and collecting more accurate input data and improving its overall quality. In short, the integration of the proposed BES model to the UDT offers a tool capable of accurately representing buildings, enabling the extraction of reliable consumption data or the development of energy retrofit studies by taking advantage of the data potential of digital twins. This is particularly valuable, as data collection remains one of the major challenges in large-scale building modeling.

6. Conclusion and Perspectives

The coupling of the UDT model with the BES model represents a successful first step towards establishing a Building Energy UDT data infrastructure. This approach allowed us to use the UDT both to improve energy simulation models and to further enhance the UDT itself by increasing the amount of information it provides. The graphical visualization of results at the urban scale helps highlighting the outputs of the building energy simulation tool. The integration process is user-friendly,

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offering intuitive and flexible data integration into the platform without being constrained by rigid structures such as Energy ADE. This work has proven valuable to building energy modeling experts by enabling advanced user interactions with the simulation tool or data. This work deserves to be continued and further developed on several levels. Validating the results using real data collected on the campus would help demonstrate the model's accuracy and strengthen its credibility for conducting impact studies. In addition, a solar potential analysis should be integrated to explore the possibility of achieving full or partial self-sufficiency based on the calculated energy demand. This solar analysis would also showcase the technical capabilities of the UDT platform, particularly its ability to retrieve individual rooftop semantic surfaces along with their respective areas and inclinations.

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References

Agugiaro, G., Benner, J., Cipriano, P., Nouvel, R., 2018. The Energy Application Domain Extension for CityGML: enhancing interoperability for urban energy simulations. Open geospatial data, softw. stand. 3, 2. https://doi.org/10.1186/s40965-018-0042-y

Alva, P., Biljecki, F., Stouffs, R., 2022. USE CASES FOR DISTRICT-SCALE URBAN DIGITAL TWINS. Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci. XLVIII-4/W4-2022, 5–12. https://doi.org/10.5194/isprs-archives-XLVIII-4-W4-2022-5-2022

Alva, P., Mosteiro Romero, M., Stouffs, R., 2024. Estimating Operational Greenhouse Gas Emissions in the Built Environment using an Urban Digital Twin: Sustainable City Management Tool for Decarbonisation of Cities.

Coors, V., Padsala, R., 2024. Urban Digital Twins Empowering Energy Transition: Citizen-Driven Sustainable Urban Transformation towards Positive Energy Districts. The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences XLVIII-4-W10-2024, 51–56. https://doi.org/10.5194/isprs-archives-XLVIII-4-W10-2024-51-2024

Fonseca, J.A., Schlueter, A., 2015. Integrated model for characterization of spatiotemporal building energy consumption patterns in neighborhoods and city districts. Applied Energy 142, 247–265. https://doi.org/10.1016/j.apenergy.2014.12.068

Gebetsroither-Geringer, E., Padsala, R., Hainoun, A., Agugiaro, G., Biernat, S., Reber, A., Smetschka, B., Gao, W., Horak, D., Falay, B., Coors, V., 2025. A Participatory Planning Framework using Urban Digital Twins Supporting the Co-Creation of Flexible, Positive Energy Districts.

Hong, T., Chen, Y., Luo, X., Luo, N., Lee, S.H., 2020. Ten questions on urban building energy modeling. Building and Environment 168, 106508. https://doi.org/10.1016/j.buildenv.2019.106508

Jeddoub, I., Nys, G.-A., Hajji, R., Billen, R., 2024. Data integration across urban digital twin lifecycle: a comprehensive review of current initiatives. Annals of GIS 0, 1–20. https://doi.org/10.1080/19475683.2024.2416135

Jorissen, F., Reynders, G., Baetens, R., Picard, D., Saelens, D., Helsen, L., 2018. Implementation and verification of the IDEAS building energy simulation library. Journal of Building Performance Simulation 11, 669–688. https://doi.org/10.1080/19401493.2018.1428361

Michael, A., Heracleous, C., 2017. Assessment of natural lighting performance and visual comfort of educational architecture in Southern Europe: The case of typical educational school premises in Cyprus. Energy and Buildings 140, 443–457. https://doi.org/10.1016/j.enbuild.2016.12.087

Nouvel, R., Brassel, Bruse, Duminil, E., Coors, V., Eicker, Robinson, 2015. SIMSTADT, a New Worflow-driven Urban Energy Simulation Platform for CityGML City Models.

Rafamatanantsoa, B.P., Jeddoub, I., Yarroudh, A., Hajji, R., Billen, R., 2024. City2Twin: an open urban digital twin from data integration to visualization and analysis. The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences XLVIII-2-W8-2024, 387–394. https://doi.org/10.5194/isprs-archives-XLVIII-2-W8-2024-387-2024

Reinhart, C.F., Cerezo Davila, C., 2016. Urban building energy modeling – A review of a nascent field. Building and Environment 97, 196–202. https://doi.org/10.1016/j.buildenv.2015.12.001

Remmen, P., Lauster, M., Mans, M., Fuchs, M., Osterhage, T., Müller, D., 2018. TEASER: an open tool for urban energy modelling of building stocks. Journal of Building Performance Simulation 11, 84–98. https://doi.org/10.1080/19401493.2017.1283539

Rossknecht, M., Santhanavanich, T., Hilaire, L., Padsala, R., Dabirian, S., Eicker, U., Saad, M., Jacovella-St-Louis, J., 2023. TESTBED-18: Building Energy Data Interoperability Engineering Report.

Santhanavanich, T., Padsala, R., Würstle, P., Coors, V., 2022. The spatial data infrastructure of an urban digital twin in the building energy domain using ogc standards. ISPRS Ann. Photogramm. Remote Sens. Spatial Inf. Sci. X-4/W2-2022, 249–256. https://doi.org/10.5194/isprs-annals-X-4-W2-2022-249-2022

Tufan, Ö., 2022. Development and Testing of the CityJSON Energy Extension for Space Heating Demand Calculation.

Weiß, D., Tribulowski, K., Hirth, S., Hirsch, H., 2024. Case Studies On The Application Of Building Simulation Software SIM-VICUS Within The Real Planning Process. E3S Web of Conf. 562, 10001. https://doi.org/10.1051/e3sconf/202456210001