Final report

1. Project details

Project title	Beslutningsstøttesoftware baseret på digitale tvillinger for energioptimering og drift af bygninger
File no.	64021-1009
Name of the funding scheme	Energiteknologisk Udviklings- og Demonstrationsprogram
Project managing company / institution	University of Southern Denmark
CVR number (central business register)	29283958
Project partners	KMD, COWI, Aarhus Kommune
Submission date	23 July 2025

2. Summary

Project summary:

The purpose of the project

The project addresses enhancing building energy efficiency and comfort by developing a Digital Twin (DT) platform. It demonstrated the integration of smart data ontologies and flexible data-driven energy models within the DT. The innovation lay in utilizing real-time data for smarter building management, predictive analysis, and scenario testing.

Results, conclusions and perspective

The most important results attained in this project are summarized in the list below:

- Successfully established a comprehensive project management structure and achieved effective dissemination through publications, presentations, and international conferences.
- Developed detailed reports on building energy and data modeling requirements, addressing the needs of Digital Twin applications.
- Created the Twin4Build Python package with an adaptable and effective building energy modeling framework, advancing energy modeling with a hybrid methodology and the SAREF4SYST ontology.
- Implemented an open-source data platform using FIWARE, incorporating new data models to enhance interoperability and context modeling.

- Developed the Digital Twin layer, integrating ML, data processing, and UI components, with milestones achieved for platform functionalities.
- Demonstrated the platform's effectiveness through case studies, showing improvements in system performance and energy management.

The reports, models, frameworks, and DT platform developed will inform the next phases of technical work, guiding the development and demonstration of advanced Digital Twin solutions. The key expected effects are:

- Enhanced building energy management and operational optimization.
- Improved accuracy in performance monitoring and forecasting.
- Increased adoption of Digital Twin technology in smart building applications, leading to more efficient resource use and energy savings.

Projektresumé:

Formålet med projektet

Projektet fokuserer på at forbedre bygningens energieffektivitet og komfort ved at udvikle en Digital Twin (DT) platform. Det demonstrerede integrationen af smarte data-ontologier og fleksible datadrevne energimodeller inden for DT. Innovationen bestod i at udnytte realtidsdata til smartere bygningsstyring, prædiktiv analyse og scenarietestning.

Resultater, konklusioner og perspektiv

De vigtigste resultater opnået i dette projekt er opsummeret i listen nedenfor:

- Succesfuldt etableret en omfattende projektledelsesstruktur og opnået effektiv formidling gennem publikationer, præsentationer og internationale konferencer.
- Udviklet detaljerede rapporter om krav til bygningens energiforbrug og datamodellering, der adresserer behovene for Digital Twin-applikationer.
- Skabt Twin4Build Python-pakken med et fleksibelt og effektivt energimodelleringsframework, der fremmer energimodellering med en hybridmetode og SAREF4SYST-ontologien.
- Implementeret en open-source dataplatform ved hjælp af FIWARE, der integrerer nye datamodeller for at forbedre interoperabilitet og kontekstmodellering.
- Udviklet Digital Twin-laget, der integrerer ML, databehandling og UI-komponenter, med milepæle opnået for platformens funktionaliteter.
- Demonstreret platformens effektivitet gennem case-studier, der viser forbedringer i systemets ydeevne og energistyring.

De rapporter, modeller, rammer og DT-platform, der er udviklet, vil informere de næste faser af det tekniske arbejde og vejlede udviklingen og demonstrationen af avancerede Digital Twin-løsninger. De vigtigste forventede effekter er:

- Forbedret energistyring og driftsoptimering af bygninger.
- Øget nøjagtighed i ydeevneovervågning og forudsigelse.
- Øget anvendelse af Digital Twin-teknologi i intelligente bygningsapplikationer, hvilket fører til mere effektiv ressourceudnyttelse og energibesparelser.

3. Project objectives

In future smart buildings, digitalization is going to establish new levels of efficiency, security and comfort. By having a wide range of sensors and meters everywhere, with a large database of digital information, buildings will transition from being a static reactive element in the energy sector to becoming a proactive key component with the ability to intelligently respond to the changes in the dynamic environment and connect efficiently with other buildings and infrastructures within smart communities and grids. To utilize and harness the benefits of the building sector digitalization and to respond to the increasing demands for energy efficiency, comfort and safety, we propose combining historical, real and forecast data from buildings into a context information model to describe and understand the building context better. This is achieved by representing the real-world assets as Digital Twins in the digital domain, allowing coordinated data-driven decision support over the whole building life cycle.

Although building digital twin technology is there for more than a decade now with substantial positive impacts in saving energy, cost and resources, such technology is yet to find common grounds in the Danish and European market due to major challenges and common practices that needs to be addressed:

- The key in fast adaptation and implementation of digital twins in the building market is establishing an automated, seamless and smooth transition and information carryover between open standard BIM formats and building energy models on one side and data context models on the other side. Dynamic models are the basis for building digital twins' predictive, forecasting, and scenarios testing services. The current building energy modelling practice is a hectic, expensive and time-consuming process, where energy consultants and modelers tend to develop the models manually from scratch from 3D representation to every single specification. This calls for the need for process automation with generic and flexible modeling approaches.
- There is an urgent need for a flexible, effective and user friendly open standard data platforms to handle and manage data which is generated within the building by various sources including different sensors, meters and IoT devices.
- Major efforts have been devoted in the recent years to identify guidelines and standards for proper BIM development and building data sets collection and storage, however little has been done in terms or identifying BIM and data models requirements for successful digital twin applications.

The current project addresses these challenges highlighted above in designing and establishing effective and flexible building digital twins. It advances the state of the art in terms of building information modelling and open standard data collection and management platforms through the design, development and demonstration of a first-of-its kind holistic Digital Twin platform for building applications. A simplified illustration of the proposed building digital twin framework and the main components are highlighted in Figure 1, along with information and knowledge flow.

As highlighted in Figure 1, the virtual building digital twin platform has two key pillars, 1) a building context information model integrating all sources of data collected within the building, and 2) a set of generic and adaptable grey-box building energy models. In terms of the energy modeling approach, grey-box models offer a balanced hybrid building energy modeling approach. Such models use physics equations to represent building behavior, but these are much simpler equations compared to the ones used for white-box models. Thus, they can be simulated faster. However, such simplified physics lead to a loss of accuracy, which is compensated through model calibration with data, similar to the black-box modeling approach. Therefore, a grey-box energy model offers a balance between the accuracy of a white-box model and the speed of a black-box model. In addition, it provides a demonstrated flexibility and effectiveness in the use for building operational management and control applications.

The ability of a Digital Twin to adapt to different phases in its lifecycle, ownerships, as well as use of the real asset require a common runtime, common implementations, and the interoperability. Current solutions are either site level or entire grid level as well as sensing (monitoring) is primitive and coarse. Finer sensing and corporative management under city management could be a different level of solution. The use of a Digital Twin Platform employing FIWARE solve the challenge in understanding the huge amount of streaming data coming from all the sensors and devices in the building. Due to this lack of understanding, a lot of sensor data is just stored but not used intelligently until now. The Digital Twin data model is generated by building a semantic knowledge graph in NGSI-LD to have an integrated data space for the information about building, energy, and human population behavior. Using the NGSI-LD model, the needed data models for a Digital Twin are identified and the respective runtime services and augmentations, that make the Digital Twin active, are created.

The Digital Twin platform ensures a smooth carryover of knowledge and information throughout the building stages and present a coordinated decision support solution over the whole building life cycle. The proposed integrated Digital Twin replaces the static BIM model with a dynamic BEM combined with real-time data to provide the following services:

1. Collecting, integrating and managing data generated in the building by various sources including sensors, meters and IoT devices within a flexible, effective and user friendly open standard context information model.
2. Real-time performance monitoring and automated continuous commissioning and fault detection enabling smarter facility management, efficient building operation, timely identification of malfunctions, anticipation of risks and heading off problems before they occur.
3. Strategy and planning support over the whole building life cycle through informing optimal decisions, running ‘What if?’ scenarios in advance, predicting impacts and testing different control and management patterns in virtual environment.

This project aims to design and develop a holistic digital twin platform for buildings applications and demonstrate the platform in three case study buildings. The development and demonstration activities is built upon the consortium partners’ research and practical experiences and activities in the field of building energy modeling and simulation, building context information, data integration and management and building information modelling along with findings from our previous and ongoing projects. As part of the development of the holistic digital twin, two applications are to be developed for automated transition from BIM to context information models on one hand, and to robust modular and flexible BEMs on the other hand. The European Commission highlighted that the current TRL of the technologies within project are at level 4, where this project aims to advance the this to level 6-7.

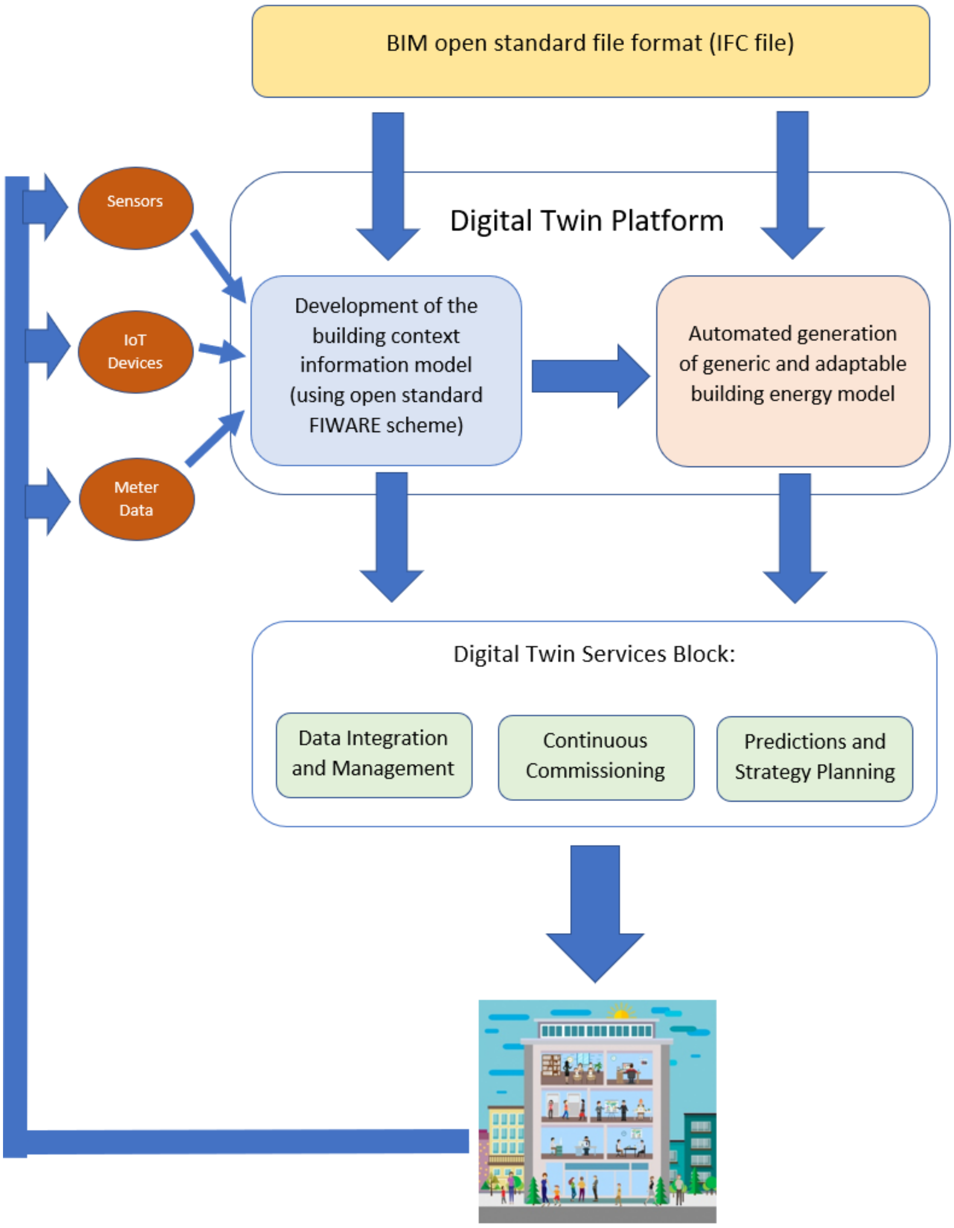


Figure 1. A simplified illustration of the proposed building digital twin framework and the main components

4. Project implementation

The project is composed of six interlinked work packages (WPs), with corresponding activities and sub tasks as presented below. Each task is defined so it also relates to a work package delivery. The links between different work packages are shown in Figure 2. Data and information can be transferred to other WPs before final delivery, in order to reduce time. Partial deliveries are coordinated between WP/task leads and project management. Timelines as well as WPs and tasks are presented in the GANTT chart. For each WP, milestones have been stated when applicable, to ensure project feasibility throughout the different phases.

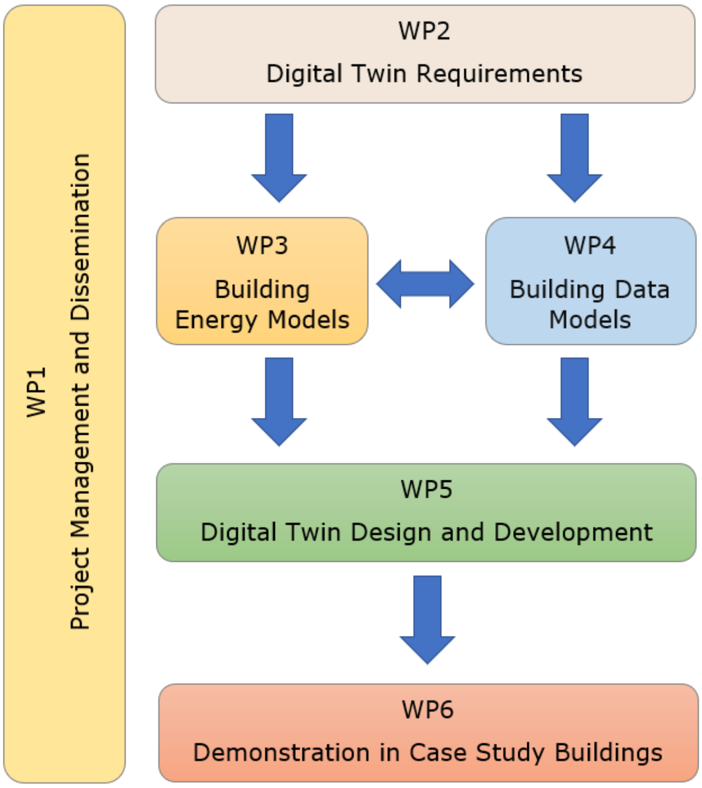


Figure 2. Overview of the project structure and WPs

In the sections below, a brief summary on the actual work carried out under each WP is provided:

WP1: Project Management and Dissemination

WP1 has been actively operational from the very beginning of the project and continued to drive its management and coordination throughout its entire duration. The project manager, Muhyiddine Jradi from the SDU Center for Energy Informatics, leads WP1 with the support of a dedicated steering committee that includes representatives from all key partners. The scope of WP1 is comprehensive, encompassing daily project management and coordination, continuous progress monitoring, risk management, project plan adjustments, periodic reporting, and the compilation of the final project report for EUDP.

A significant early achievement was the consensus among all project partners on the project acronym, ‘Twin4Build.’ This acronym reflects the project's core objectives and is instrumental in branding and communication efforts.

The primary focus of WP1's ongoing activities has been to ensure seamless coordination between the leads of the various work packages (WPs). This involves facilitating effective bilateral communications to ensure coherent execution of project tasks and alignment with overall objectives. Central to this coordination effort are the regular project meetings, which serve as critical touchpoints for discussing progress, addressing challenges, and planning next steps.

The initial project kick-off meeting, held in October 2021 at the University of Southern Denmark, marked the formal start of collaborative activities. During this meeting, it was agreed among all partners to schedule biannual common project meetings to ensure timely and comprehensive updates and discussions. These meetings have been conducted in various formats, including hybrid and physical sessions, hosted at multiple partner locations such as the University of Southern Denmark, Aarhus Commune, COWI, and KMD. This approach not only facilitates effective communication but also strengthens involvement and commitment from all partners. At least one physical meeting was held at each partner’s office to foster a more personal connection and engagement.

One of the major milestones under WP1 was the successful completion and delivery of the project collaboration agreement. This agreement was developed through extensive discussions and negotiations among all project partners and reflects a consensus on the terms and responsibilities governing the project. Additionally, a project webpage was established to serve as a central hub for information dissemination and public engagement.

WP1 is also dedicated to the dissemination of the project’s results, catering to both public and commercial interests throughout the project’s lifecycle. The dissemination efforts are designed to maximize the impact and visibility of the project outcomes.

In the initial phase, WP1 focused on establishing effective communication channels, including the creation of a dedicated project webpage and a shared digital folder. These platforms are used to distribute project descriptions, activities, documents, and specifications to project partners and external audiences. During the kick-off meeting, all partners committed to actively communicating the project’s goals and progress within their organizations and professional networks.

The dissemination strategy has resulted in the publication of a substantial number of research articles in leading international journals and conferences. These publications highlight the project's innovations and findings, contributing to the academic discourse and advancing knowledge in the field. Furthermore, industry-focused magazine articles have been produced to present the project’s ideas and major deliverables to practitioners, industrial bodies, and engineers, bridging the gap between research and practical application.

The project team has also actively participated in numerous national and international seminars and workshops. These events have provided opportunities to showcase the project’s progress, engage with stakeholders, and gather feedback.

The commercial partners involved in the project, COWI and KMD, have taken proactive steps to ensure the successful exploitation of the project results. Their efforts are aimed at facilitating a smooth transition from the development and demonstration phases to commercial and market inclusion.

To support this transition, the commercial partners have identified a preliminary user group of building owners who represent potential candidates for the implementation and application of the project solutions. This user group will play a crucial role in providing feedback, validating the project’s outcomes, and facilitating the adoption of the developed software.

The commercial partners have also been focusing on building a platform for knowledge sharing and collaboration within this user group. This platform will support ongoing engagement and ensure that the project’s results are effectively integrated into real-world applications. The user group will serve as a valuable resource for refining and optimizing the project’s solutions, ultimately contributing to their successful commercialization and market penetration.

WP2: Building Digital Twin Platform Requirements

WP2 has adhered closely to its scheduled timeline and has been successfully completed. This work package was pivotal in creating the optimal conditions and environment necessary for the successful development and implementation of Digital Twin platforms in future efficient and smart buildings and facilities.

WP2 aimed to establish a solid foundation for leveraging Building Information Models (BIMs) and integrating them into Building Energy Models (BEMs) within the Digital Twin framework. The work focused on two main areas:

1. **BIM Requirements and Functionalities**: The first focus area involved defining the specifications and requirements for BIMs tailored to Digital Twin applications. This process entailed evaluating current BIM design practices and ensuring a seamless transition from an Industry Foundation Classes (IFC)-based BIM schema to a BEM framework. The goal was to ensure that BIMs could effectively support and enhance the functionalities of Digital Twins in future smart buildings.
2. **Building Performance Data Requirements**: The second focus area concentrated on identifying the essential building performance data needed for effective monitoring and evaluation within the Digital Twin platform. This included specifying the minimum required data sets, such as information from building management systems, sensor data, energy meters, and people flow information. These data sets are critical for the real-time analysis and management of building performance.

As part of WP2, field interviews were conducted with a range of stakeholders, including potential clients, facility managers, building owners, and other relevant parties. The objective of these interviews was to assess their needs and expectations concerning future Digital Twin applications. This stakeholder engagement provided valuable insights into the practical requirements and challenges associated with implementing Digital Twin platforms.

The key activities completed under WP2 include:

- **A2.1 Specification of BIM Requirements and Functionalities for Digital Twin Applications**: This activity involved detailing the requirements and functionalities needed for BIMs to effectively support Digital Twin applications. This specification ensured that BIMs are aligned with the needs of Digital Twin platforms, facilitating a smooth integration process.
- **A2.2 Specification of Building Data Sets Requirements for Digital Twin Applications**: This activity focused on identifying and specifying the necessary building performance data sets required for the Digital Twin platform. It ensured that the data collected is comprehensive and suitable for real-time monitoring and analysis.
- **A2.3 Field Interviews with Stakeholders**: Interviews were carried out with potential clients, facility managers, building owners, and other stakeholders to gather insights into their needs and demands. These interviews helped shape the development of Digital Twin platforms by incorporating real-world perspectives and requirements.
- **A2.4 Documentation of Building Digital Twin Platform Requirements**: The requirements for the Building Digital Twin platform were highlighted and documented in detailed reports. These reports provide a comprehensive overview of the necessary specifications and functionalities, serving as a guide for the development and implementation of Digital Twin solutions.

WP2's successful completion has laid a critical groundwork for the subsequent phases of the project. By clearly defining BIM requirements, data set needs, and stakeholder expectations, WP2 has ensured that the Digital Twin platforms are designed to meet practical requirements and provide significant value to end users. The insights gained from field interviews and the detailed specifications developed will be instrumental in guiding the development of Digital Twin solutions that are both innovative and practical.

WP3: Development of Building Energy Models for Digital Twin Applications

WP3 focuses on developing dynamic, generic, and adaptable building models for Digital Twin applications and establishing a workflow for the automated creation of building energy models from IFC-based BIMs. This work package is essential for creating scalable and flexible energy models that can enhance the functionality of Digital Twins in smart buildings.

1. **Building Energy Modeling Framework Development**

WP3 began with the creation of a robust building energy modeling framework designed to support the automated development of scalable and generic energy models for Digital Twin applications. This framework provides a foundational structure for integrating and analyzing building energy data.

A semi-automated workflow was established to facilitate the transition from BIM to building energy models. This workflow combines black-box space models and grey-box energy system and component models, ensuring that both general and specific aspects of building energy systems are accurately represented.

To support Digital Twin-integrated energy models, the SAREF4SYST ontology was identified as a key tool. SAREF4SYST provides a generic framework for representing system topology and interactions. It uses three primary classes—System, Connection, and ConnectionPoint—and nine associated properties to define and model system relationships.

2. **Indoor Temperature Forecasting Models**

The initial phase involved developing scalable indoor temperature forecasting models. A case study was conducted using an 8500 m² university building in Denmark. An extensive dataset was compiled, including sensor data from 76 rooms, which encompassed indoor temperature readings, CO2 concentrations, radiator valve and damper actuations, and outdoor ambient conditions.

Building on the initial work, the project explored the impact of thermal space coupling on data-driven indoor temperature forecasting. The performance of isolated versus coupled Long Short-Term Memory (LSTM) model architectures was evaluated across 70 spaces in the case study building. An open-source tool was developed to automate the extraction of space topology from IFC files, facilitating the identification of adjacent spaces for coupled modeling.

3. **Generic Energy Modeling Framework**

An innovative and flexible energy modeling framework was developed based on the SAREF ontology. This framework incorporates the SAREF4BLDG extension, which includes various models for typical building systems and devices, such as spaces, space heaters, dampers, and coils. The framework is designed to be adaptable and extensible, accommodating a wide range of building energy systems.

4. **Real Case Study Implementation**

The modeling framework was applied to a real case study involving a teaching room and its associated heating and ventilation systems. The framework enabled the calibration of data-driven models for components such as space heaters, heating coils, and recovery units using operational data from the building. Two key services—continuous commissioning and scenario testing—were implemented as Digital Twin services, demonstrating practical use-case applications.

5. **Indoor CO2 Concentration and Ventilation System Models**

The framework was also utilized to model ventilation air system components and CO2 concentrations within spaces. Grey-box and black-box modeling techniques were applied to create data-driven models based on operational data, including damper positions, CO2 concentrations, occupancy, and airflow measurements.

6. **Open Source Repository and Model Library Expansion**

Significant work has been done to enhance the open-source GitHub repository associated with the project. This includes expanding the library of models to include thermal grey-box models for zones and coils, as well as a general wrapper for Functional Mockup Units (FMUs). A major contribution is the development of an automated algorithm for generating and calibrating energy simulation models. This algorithm matches patterns from a model library with patterns in semantic models, facilitating the automated creation and tuning of models. This development is the result of collaboration with Lawrence Berkeley National Laboratory (LBNL).

WP3 has made substantial progress in developing adaptable building models for Digital Twin applications. The work has provided a comprehensive framework for energy modeling, introduced innovative forecasting and modeling techniques, and enhanced the capabilities of the open-source repository. These advancements are crucial for improving the accuracy and efficiency of Digital Twin platforms in smart buildings.

WP4: Development of Building Data Models for Digital Twin Applications

WP4 focuses on developing flexible and systematic data models to support building Digital Twin applications. This work package is crucial for enabling effective data collection, integration, management, and sharing across various systems and devices within smart buildings.

1. **Open-Source Data Platform Identification and Implementation**

The initial phase of WP4 involved identifying and implementing an open-source platform for Digital Twin applications. The chosen platform is based on FIWARE, a cloud-based open-source system designed to facilitate data sharing and provide a foundation for developing intelligent algorithms. FIWARE was selected for its ability to support the integration and management of diverse data sources, making it a suitable choice for developing and managing building data models. The successful identification and implementation of the FIWARE platform have enhanced data-sharing capabilities and provided a robust foundation for integrating intelligent algorithms within the Digital Twin framework.

2. **Development of a Holistic Context Information Model**

A significant achievement in WP4 was the development of a comprehensive context information model. This model uses the NGSI-LD standard, which is aligned with the SAREF ontology and its extensions, including SAREF4BLDG and SAREF4SYS. The model was designed to ensure interoperability across different systems and comply with the Minimal Interoperability Mechanisms (MIMs) defined by the Open Agile Smart City (OASC) community. This approach guarantees that the model can accommodate data from Building Information Modeling (BIM) and meet the requirements of Building Energy Models (BEM), thereby facilitating seamless integration and data exchange. The creation of a holistic context information model based on the NGSI-LD standard and the SAREF ontology has ensured interoperability and compliance with MIMs. This model supports the integration of data from BIM and meets BEM requirements, enabling effective data management and utilization.

3. **Application Development for IFC-Based BIM to Context Information Model Transition**

WP4 also focused on developing an application to facilitate the transition of data from IFC-based BIM to the context information model. This application was designed in response to the specific needs outlined in TWIN4BUILD-REQ-002. During the development process, it became evident that IFC files alone do not contain all the information required for a complete energy model. This highlighted the necessity for additional or alternative data sources to fully populate the Digital Twin Data Model. The application aims to bridge this gap by integrating supplementary data sources and ensuring comprehensive data coverage. The development of the application has addressed the challenge of incomplete data coverage. This application facilitates the integration of additional data sources, ensuring that the Digital Twin Data Model is fully populated and functional.

WP4 has made significant advances in establishing a flexible and systematic approach to data modeling for Digital Twin applications. The work completed under WP4 lays a strong foundation for managing and utilizing building data effectively, supporting the development of advanced Digital Twin solutions.

WP5: Building Digital Twin Platform Development

WP5 focuses on developing a comprehensive Building Digital Twin solution that leverages the advancements from WP3 and WP4. This work package is dedicated to integrating automated and adaptable building energy models with a standardized open-source platform to create a holistic digital twin framework.

1. **Design of the Holistic Building Digital Twin Framework**

WP5 aims to design a holistic Building Digital Twin framework that combines IFC-based BIM open-source files, data ontology, and energy modeling. This framework is built on the foundation established in WP3, which involved developing automated and adaptable building energy models, and WP4, which focused on designing building data models within the FIWARE platform.

The digital twin solution provides several key services:

- **Real-time Performance Monitoring**: Tracking the real-time operational status of building systems.
- **Continuous Commissioning and Fault Detection**: Automated identification of inefficiencies and faults.
- **Scenario Testing**: Running simulations to assess various operational scenarios.
- **Future Predictions**: Forecasting future performance and energy consumption.

The findings from WP3 and WP4, along with the defined services, form the core of the digital twin platform.

2. **Development and Implementation of Digital Twin Architecture**

WP5 has progressed through the initial phase of converting the requirements and architecture into a complete digital twin solution, utilizing potential open-source software (OSS). The digital twin architecture is structured in three primary layers:

1. Data Layer:
- FIWARE Integration: The first tier of the architecture uses FIWARE to handle data collection and integration. FIWARE serves as the foundation for the data layer, facilitating seamless connectivity with IoT sensors.

2. Twin Layer:
- Mathematical and Machine Learning Models: This layer includes the development of mathematical models and machine learning models for temperature, valves, air, energy, etc. It also handles the output transmission to the visualization layer.
- Visualization Layer: The visualization layer presents data in a user-friendly graphical format.

3. UI Layer:
- User Interface: This layer interacts with the twin layer and retrieves data from the database or internal caching system. It is designed to provide an intuitive interface for users to interact with the digital twin system.

Detailed Activities

1. ML Layer Activities:

Heating System Simulation Implementation:
- SQLALCHEMY Utilization: Employed SQLALCHEMY for managing historical and future heating system simulations.
- Custom Components Development: Created components to fetch forecasted data for future simulations.
- Data Pipelines Creation: Developed data pipelines using Python for processing, validation, and ingestion.
- History Data Ingestion: Implemented methods for custom history data ingestion into the database.

  - CI/CD Pipelines: Established CI/CD pipelines for deploying Twin4Build components, using Docker and Kubernetes.
  - What-If Scenario Feature: Implemented a feature to simulate various scenarios for the heating system.

Ventilation System Implementation:

  - Design and Implementation: Designed and implemented ventilation systems for multiple rooms, enhancing the overall system's functionality.

2. <u>Data Layer Activities:</u>

Integration of Energy Meter Data:

  - Nifi Flow Integration: Integrated energy meter data with Nifi Flow to ensure smooth data flow.

Kafka Data Ingestion Integration:

  - Kafka and Nifi Flow: Integrated Kafka data ingestion with Nifi Flow for efficient handling of data streams.

Scaling IoT Sensor Data Integration:

  - Expansion: Extended IoT sensor data integration to cover data from 20 rooms, improving the comprehensiveness of data collection.

Integration of Elpris API:

  - Energy Rate Information: Integrated the Elpris API with Nifi to retrieve real-time energy rate information.

3. <u>UI Layer Activities:</u>

Development of Heating System UI Wireframes:

  - Wireframes Creation: Designed wireframes for the what-if scenario feature of the heating system, facilitating user interaction.

Dashboard Creation:

  - Dashboard Development: Created dashboards for effective monitoring and management of multiple rooms, enhancing user experience and operational oversight.

Overall, WP5 has successfully developed a holistic Building Digital Twin solution, integrating key components from WP3 and WP4 into a comprehensive framework. The work has established a multi-layer architecture that supports real-time monitoring, fault detection, scenario testing, and future predictions.

WP6: Demonstration in Case Study Buildings

WP6 focuses on the demonstration and implementation of the digital twin platform developed in WP5 across three diverse pilot case study buildings. This work package is designed to evaluate the practical applicability of the digital twin solution in real-world settings, encompassing various building types, uses, and locations. The initial selected pilot buildings include:

1. **University Teaching Building**: OU44 at the University of Southern Denmark (SDU) in Odense, Denmark.
2. **Public Building**: Dokk1 in Aarhus Municipality, Denmark.
3. **Healthcare Building**: Helse Bergen hospital, Norway.

The demonstration process is structured into two distinct phases:

- **Phase 1: Simulation Environment Testing**

  - **Digital Twin Emulator Development**: The initial phase involves the creation and testing of a digital twin emulator for the teaching building at SDU Odense. This emulator is designed to simulate various operational strategies, scenarios, and predict their impacts throughout the building's lifecycle. The aim is to refine and validate the digital twin's capabilities before deploying it in real-world environments.

- **Phase 2: Real-Time Implementation**
    - **Deployment and Testing**: The second phase entails the real-time deployment of the digital twin platform in the Dokk1 building and the healthcare facility in Norway. This phase focuses on practical application and assessment of the platform's performance in live settings.

Due to changes in the selection of case study buildings, the demonstration activities have been adjusted while maintaining the planned phases. The completed activities under WP6 are as follows:

1. **Lab Testing in University Building (OU44, SDU, Odense)**
    - **Single Classroom Implementation**: The digital twin was initially implemented in a single classroom within the OU44 building at SDU. This demonstration showcased real-time services including performance monitoring, indoor climate forecasting, and system performance analysis.
2. **Expansion to a Building Section**
    - **Coverage of 24 Rooms**: Building on the initial lab testing, the digital twin implementation was expanded to encompass an entire section of the OU44 building. This section includes 24 rooms, such as offices, meeting rooms, and classrooms. The expanded demonstration involved:
        - **HVAC System Performance Monitoring**: Real-time monitoring of the HVAC system's performance.
        - **Operational Optimization**: Implementation of strategies to optimize system operation.
        - **Forecasting and Planning**: Forecasting and planning actions based on the digital twin's insights.
3. **Floor Section Implementation at New OUH, Odense**
    - **Kitchen and Offices Building**: A digital twin of a floor section in the kitchen and offices building at the New Odense University Hospital (OUH) was developed and demonstrated. Key aspects included:
        - **Automated Energy Models**: Showcasing the framework for automated energy models as the backbone of the digital twin application.
        - **SAREF Ontology Application**: Utilization of the SAREF ontology and its extensions (SAREF4BLDG and SAREF4SYST) to represent and interact with important devices and components such as heating, cooling, and ventilation systems.

The results and findings from the digital twin demonstrations in the three case study buildings are comprehensively reported and documented. This includes detailed performance assessments, the effectiveness of the digital twin in real-world applications, and insights gained from the implementation process.

Challenges and Risks:

The demonstration phase of the project has exhibited major challenges and risks throughout the project lifetime. First of all, the impacts of COVID 19 have indirectly affected the launch of the project, as all partners were just starting to come back to 'normal' operation and delivery, with major negative impacts from the COVID

19 period. However, the project team has maintained communications at the start of the project, even though virtually, and managed to ensure a smooth kick off of the project.

Case Study for Demonstration

One of the primary risks involved the completion of case study demonstrations for the developed digital twin platform. This challenge necessitated changes in the selection of case study buildings and adjustments to the demonstration setup. Specifically, WP6, which involves the demonstration in case study buildings, faced two notable adjustments:

- **A6.3**: Implementation and demonstration of the developed Digital Twin platform in the Dokk1 public building in Aarhus.
- **A6.4**: Implementation and demonstration of the developed Digital Twin platform in Helse Bergen hospital in Norway.

Due to delays in receiving data and building specifications, these two demonstration activities were reassigned to new case study buildings: the full-scale demonstration in the OU44 teaching building at SDU Odense and the kitchen and office building at the new Odense University Hospital (OUH). Although the case study buildings were changed, the technical activities, deliverables, and milestones remained unaffected. Aarhus Municipality, originally intended to provide a case study for full-scale demonstration, faced delays and administrative issues, leading to the shift in focus to SDU. Aarhus Municipality continued to contribute to solution design, feedback collection, platform development, and overall discussions, but did not have case study demonstration responsibilities.

Coordination and Implementation Risks

The project faced significant risks related to maintaining effective coordination among all involved parties. With partners from diverse backgrounds, sizes, types, and applications, ensuring seamless collaboration was challenging. These risks were mitigated through direct coordination between the project manager and the steering committee, regular meetings, timely reporting, and active engagement of each partner at every stage and decision point. This approach proved effective, leading to the successful completion of technical work packages WP2 and WP3, and achieving the set milestones and deliverables. The diverse expertise of the project partners was crucial for successful implementation and demonstration.

Cybersecurity Risks

A significant risk that emerged was related to cybersecurity, particularly affecting SDU. The increasing threat of cyber-attacks impacted the rate, capacity, and security of data sharing and the integration of software components and platforms across partner systems. For instance, integrating the Twin4Build tool with the OPCUA data collection platform at SDU encountered severe issues due to stringent cybersecurity constraints. This risk threatened the timely finalization of the implementation in the case study.

To address this, the IT team engaged in direct communication with partners to develop and implement an alternative solution for data flow, sharing, and communication. This proactive approach allowed for the resolution of integration issues and ensured the continuation of the project despite the cybersecurity challenges.

5. Project results

The aim and objective of the project was obtained in accordance with the original project plan highlighted in the Gantt chart developed at the project design phase. The Project was split into 6 WPs, five technical WPs in addition to a management and dissemination WP. The general results from technical WP's are briefly described below. In addition, the work and activities carried out as well as the deliverables of the project were reported and documented in reports and published papers.

The project has a list of technical milestones that have governed the activities and deliveries. In the sections below, a brief summary on the main results and findings obtained under each of the WPs is provided:

WP1: Project Management and Dissemination

The aim of WP1 to provide a proper and effective management of the overall project progress on various perspectives, including technical and economic aspects. In this regard, this WP has resulted in the creation of detailed project activity plans, daily project management and coordination, project progress monitoring reports, risk management plan, periodic project reporting to EUDP and the development of the final project report. Muhyiddine Jradi from SDU Center for Energy Informatics has served as the project manager. In addition, a steering committee was formed with the responsibilities to oversee and ensure the project progress throughout the different phases in addition to monitoring and evaluating the progress of tasks and deliverables. In addition, for each WP, a WP leader is appointed by the project management, and was responsible of preparing detailed WP-plans in accordance with overall project plans, leading WP work and reporting to the project manager.

In terms of project group meetings, a project kick-off meeting was held at the University of Southern Denmark in October 2021, and it was agreed among all the partners to hold common project meetings timely every half year with full participation from all partners. Thus, 6 project group meetings were held, with three physical meetings at COWI in Lyngby, Aarhus Kommune, and KMD in Ballerup.

A major milestone under WP1 is the completion and delivery of the project collaboration with the contribution and confirmation of all project partners **(M1)**.

Additionally, WP1 aims at an effective and wide dissemination of the project's results, in both public and commercial interest, during the whole project period.

The project team has reported the project idea, technical approach, methodology and findings throughout the project life. The dissemination activities have resulted in a list of published project papers in international journals, conferences, and technical magazines, listed below, and attached to this report as appendices in addition to others under development. Each partner has contributed to this from different angles and considering its own network and business. KMD and COWI have been active in reaching out to users and solution potential target groups, including housing companies and municipalities. In addition, SDU has been active in disseminating the project knowledge and solution in journal papers, conference presentations, seminars, and magazine articles. In addition, the project leader has presented the project in various meetings and venues abroad, including conferences in China, US, UK, and Portugal. Also, the project idea and approach were presented by the project leader at the IEA EBC Technical Day in Copenhagen in June 2023. The project leader has also presented the project at the IEA EBC meetings of Annex 89 in Berlin and Annex 91 in Vienna in 2024.

In addition, an article 'Digitale tvillinger I byggeriet' was published in HVAC magasinet. This is to ensure that the message and the project idea and approach reach not only to academic journal papers and reports readers but also to consultants, engineering, practitioners, authorities and public bodies. Also, various project aspects and findings were presented in multiple international conferences as presented in the list of presentations below.

It shall also be mentioned that the dissemination phase will be extended to even after the project final report, where the project commercial partners and the public partners are willing to present and disseminate the project findings in related workshops and seminars in Denmark after the project completion.

In addition, the commercial partners have set an initial list of a users' group of building owners as a potential group for the project solution implementation and application by the project commercial partners. This work group will provide a platform for knowledge building and sharing, serving as candidates for implementing developed software after the project ends.

The major deliverables attained under WP1 are as follows:

- D1.1 A project working plan based on the project application
- D1.2 Collaboration agreement
- D1.3 Periodic reports to EUDP
- D1.4 Project meetings and coordination between partners
- D1.5 Communication & dissemination plan for the project
- D1.6 Presentations and Seminars
- D1.7 Articles and Publications

WP2: Building Digital Twin Platform Requirements

The work under WP2 followed the time plan very well and the following deliverables were attained:

- Specification of building energy modelling requirements and functionalities for Digital Twin applications
- Specification of building data modelling requirements for Digital Twin applications
- Carrying out field interviews with potential clients, facility managers and building owners to assess the needs and demands

As a result of WP2 work and activities, milestones (**M2)**, (**M3)**, and (**M4)** are met on time.

The key output of WP2 is the development of three reports as follows:

1. A report on the energy modelling requirements for Digital Twins applications.
2. A report on the data modelling requirements for Digital Twins applications.
3. A feedback report summarizing the key findings of the field interviews with owners and clients

The three reports developed under WP2 will be used as a basis for the technical work and the development and demonstration activities in the next project phases and the rest of the technical WPs.

WP3: Development of Building Energy Models for Digital Twin Applications

Under WP3, a comprehensive building energy modeling framework was developed to facilitate the automated creation of scalable and adaptable energy models for digital twin applications. This framework represents a significant advancement in integrating Building Information Modeling (BIM) with building energy modeling (BEM) to support dynamic and efficient digital twin environments.

Key Achievements

1. **Hybrid Methodology Development:** The development process highlighted a hybrid methodology that combines black-box space models with grey-box energy systems and component models. This approach enables a more nuanced representation of building dynamics, facilitating better integration and performance prediction.

2. **Utilization of SAREF4SYST Ontology:** The SAREF4SYST ontology was integrated to provide a universal framework for representing system topologies and their interactions. This ontology supports the development of models that accurately reflect the physical and operational relationships within building systems.

3. **Indoor Temperature Forecasting Models:** Initial work focused on creating accurate indoor temperature forecasting models. A well-performing architecture was identified, which provided reliable temperature predictions for various rooms with a 24-hour prediction horizon. This architecture demonstrated the potential for effective climate control and energy management.

4. **Development of an Open-Source Tool:** An open-source tool was developed to automate the extraction of space topology from IFC files, allowing for the identification of adjacent spaces. This tool supports the selection between isolated and coupled architectures based on their performance in specific subsets of spaces.

5. **Modular and Adaptable Model Architectures:** The proposed model architectures, which include both isolated and coupled versions, exhibit modularity and adaptability. The coupled architecture outperformed the isolated one in approximately 84% of the investigated spaces, with notable improvements under various operational and climatic conditions.

6. **Innovative Energy Modeling Framework:** A flexible and innovative energy modeling framework was designed, based on the SAREF ontology and its extensions. This framework incorporates models for typical systems and devices, such as spaces, space heaters, dampers, and coils. It also includes methods for linking and simulating component models, providing dynamic simulations of building systems.

7. **Application and Proof-of-Concept:** The framework was applied in a case study involving a teaching room and its associated heating and ventilation systems. It was also used to model ventilation air system components and CO2 concentration in spaces. A proof-of-concept demonstration validated the framework's effectiveness and feasibility.

Main Output

The culmination of WP3 activities is the creation of **Twin4Build**, a Python package for data-driven and ontology-based modeling and simulation of buildings. This package, available on GitHub at https://github.com/JBjoernskov/Twin4Build, represents a novel tool in building energy modeling and digital twin technology.

As a result of WP3 work and activities, milestone **(M5)** is met.

The successful completion of WP3 and its milestones has laid a strong foundation for subsequent work packages and demonstrated significant advancements in building energy modeling and digital twin applications.

WP4: Development of Building Data Models for Digital Twin Applications

Under WP4, significant progress was made in the development and implementation of an open-source data platform for Digital Twins, based on the FIWARE platform. This cloud-based, open-source system is designed to facilitate data sharing and provide a robust foundation for intelligent algorithms and applications. Emphasizing transparency, flexibility, and community development, the FIWARE platform supports open APIs and employs a common data model aligned with the OASC Minimal Interoperability Mechanisms (MIMs) principles.

FIWARE's architecture leverages the NGSI-LD API, a modern standard for context information management that enables a linked data system and enhances interoperability between various systems. This API supports real-time data sharing and integration, making it a cornerstone of the platform’s functionality.

To ensure semantic interoperability, data context models were defined according to the NGSI-LD standard and were based on the SAREF (Smart Appliances REFerence) ontology. SAREF provides a standardized model for the smart appliances domain, facilitating the seamless exchange and understanding of information among devices. The SAREF ontology's extensions, SAREF4BLDG and SAREF4SYS, were specifically developed for building and system-related data, respectively, enhancing their applicability in Digital Twin applications.

As part of WP4, new data models were developed to extend the SAREF ontology for building-specific applications. These models include:

- **Building**: Represents the overall structure and its characteristics.
- **BuildingSpace**: Defines different spaces within the building, such as rooms and hallways.
- **CommunicationAppliance**: Covers devices used for communication within the building.
- **Compressor**: Details the components involved in the cooling systems.
- **Condenser**: Represents the components responsible for heat dissipation.
- **Controller**: Encompasses devices that control various building systems.
- **CooledBeam**: Details components involved in the cooling systems.
- **CoolingTower**: Represents components for cooling towers.
- **Damper**: Covers components for regulating airflow in HVAC systems.

These data models have been published and are available in the smart cities data models repository: Smart Data Models - S4BLDG.

As a result of the work completed under WP4, milestone **(M6)** has been successfully achieved.

WP5: Building Digital Twin Platform Development

WP5 focuses on the development and implementation of the Digital Twin layer for the Twin4Build platform, designed to support advanced smart building models and their associated networks. This work package integrates the generic building energy modeling framework and data models developed in WP3 and WP4, respectively, to create a cutting-edge digital twin platform for building systems and components. The developed digital twin architecture, shown in Figure 3, and its functionalities are detailed in the appendices of this report, but a summary of the key achievements across the three layers of the digital twin is provided below:

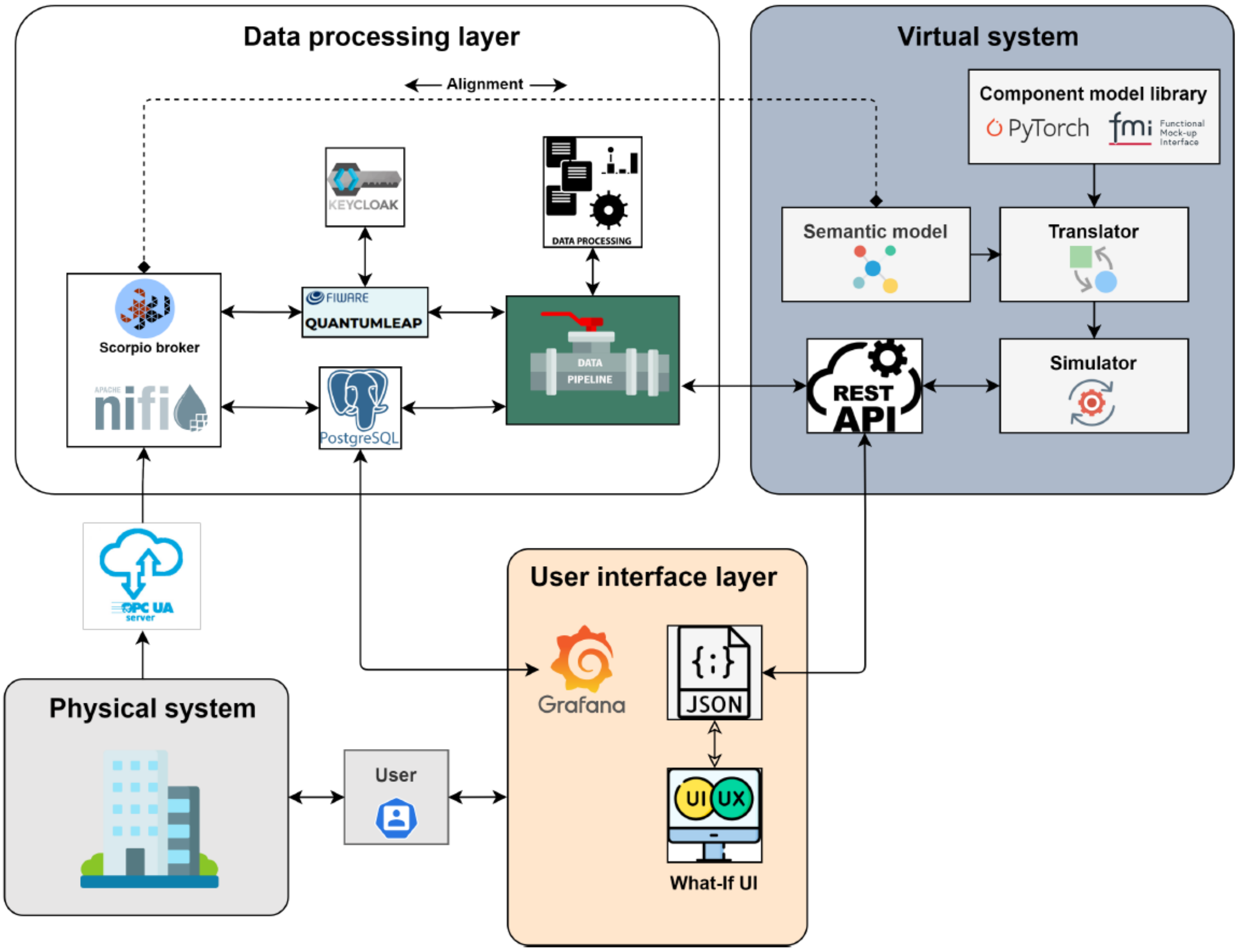


Figure 3. Architecture of the DT platform and the information flow between high-level components. Adapted from

ML Layer Activities

- **Simulation of Heating System Behavior:**
  Successfully simulated both historical and future heating system behavior, allowing for comprehensive analysis and optimization of system performance.
  Integrated DMI (Danish Meteorological Institute) forecasted data to enhance the accuracy and reliability of future simulations, improving predictive capabilities.
- **Data Processing Pipelines:**
  Established efficient data processing pipelines that ensure smooth and reliable data flow for simulation purposes, facilitating real-time analysis and model updates.
  Developed custom history data ingestion capabilities to handle project-specific data requirements, ensuring tailored and precise data integration.
- **Development and Deployment:**
  Implemented CI/CD (Continuous Integration/Continuous Deployment) pipelines to streamline the development and deployment processes of each Twin4Build component, enhancing overall project efficiency.
  Utilized Docker and Kubernetes for scalability, ensuring that the Twin4Build platform can handle varying loads and adapt to different operational scales.
- **What-If Scenario Feature:**

Developed a what-if scenario feature that provides flexibility and insight into heating system performance under diverse conditions, supporting scenario-based analysis and decision-making.

- **Ventilation Systems Integration:**
  Successfully integrated ventilation systems to optimize indoor air quality across various rooms, contributing to a healthier and more comfortable indoor environment.

Data Layer Activities

- **Energy Meter Data Integration:**
  Facilitated real-time integration of energy meter data to enable accurate monitoring and management of energy consumption, improving resource efficiency.
- **Data Ingestion and Processing:**
  Streamlined the data ingestion process to enhance data processing efficiency and scalability, supporting extensive data analysis and system performance monitoring.
- **Coverage and Analysis:**
  Expanded coverage to enable comprehensive monitoring and analysis of building conditions across multiple rooms, providing a holistic view of building performance.
- **Energy Rate Data Access:**
  Integrated access to energy rate data, enabling informed decision-making regarding energy usage and cost optimization, supporting financial and operational efficiency.

UI Layer Activities

- **Wireframes Development:**
  Created detailed wireframes for the what-if scenario feature of the heating system, ensuring a clear and user-friendly interface for exploring different scenarios.
- **Interface Design:**
  Designed a user-friendly interface that facilitates intuitive exploration of heating system performance under various conditions, enhancing user interaction and experience.
- **Dashboard Creation:**
  Developed comprehensive dashboards that provide real-time insights into building conditions, enabling efficient management and optimization of resources.

As a result of the work carried out under WP5, milestones **(M6)**, **(M7)** and **M(8)** have been successfully met.

WP6: Demonstration in Case Study Buildings

WP6 focuses on the demonstration and implementation of the digital twin platform developed in WP5 across three diverse pilot case study buildings. The demonstration process is structured into two distinct phases, Phase 1: Simulation Environment Testing and Phase 2: Real-Time Full Scale Implementation.

1. **Emulator Living Lab Case**

The first activity in this WP is the demonstration of a digital twin emulator in a teaching building at SDU Odense. As part of the lab testing of the digital twin solution developed in WP5, the DT has been implemented in a single classroom in the university building OU44 at SDU, Odense, demonstrating real-time services such as performance monitoring and forecasting of the indoor climate and system performance. The considered classroom is heated with radiators, and the supply air flowrate is controlled through demand-controlled ventilation (DCV), where the damper opening is actuated based on the measured CO2 concentration in the room. Shades are installed on the building facade to avoid overheating during the summer months. The actuation signal of the space heater valves, dampers, and shades is controlled centrally by the Building Management System

(BMS). The classroom is equipped with multiple sensors, namely, temperature, CO2, valve position, damper position, and shade position. In addition, a heat consumption meter is installed on the radiators.

The overall architecture of the platform is made up of four high-level groups. The physical system is the asset to be managed, where the IoT devices such as indoor climate and flow temperature sensors, energy consumption and flow meters, valve and damper position sensors and actuators, etc. play a major role, as they allow for continuous and automated data collection and feedback that can be processed in the virtual system. The role of the virtual system is to mimic the physical system as closely as possible through an accurate dynamic simulation model to enable different services such as continuous commissioning, operational optimization, and scenario testing. These services are exposed to the user of the platform through the user interface layer. The data processing layer acts as the communication link between the physical and virtual systems by collecting, cleaning, and storing data.

As part of the DT implantation, real-time performance monitoring was demonstrated by comparing virtual and physical sensor and meter readings for the indoor temperature of the classroom and valve position of the space heater, as shown in Figure 4. Here, anomaly behavior was detected on a period with an open window, which could potentially yield energy savings of 115 kWh, or 30% of the monthly heating consumption, had the anomaly been detected earlier. As a second service, real-time forecasting of 24 hours was demonstrated, forming the basis for operational optimization. Finally, scenario testing was demonstrated by comparing baseline operation with three alternative operation strategies in terms of indoor comfort and consumed energy.

(a)

(b)

Figure 4. Dashboard in the Grafana interface showcasing real-time performance monitoring of the classroom. (a) Two days of normal operation. (b) An anomaly detected, most likely caused by an opened window.

2. Full-scale Teaching Building Case

Building on the success of the initial lab testing, the digital twin implementation was expanded to cover a larger section of the OU44 building, which includes 24 rooms such as offices, meeting rooms, and classrooms. This broader demonstration showcased the digital twin's scalability and flexibility in real-world applications. A key focus of the expanded implementation was the real-time monitoring of the HVAC system, allowing for continuous assessment of its operational status, energy consumption, and overall performance. By tracking these parameters, the system provided insights into indoor climate conditions and highlighted opportunities to improve efficiency.

Additionally, the demonstration introduced advanced control strategies aimed at optimizing HVAC operations. These strategies leveraged dynamic adjustments based on occupancy patterns, real-time environmental data, and predictive analytics to reduce energy consumption while enhancing indoor comfort. The expanded deployment not only highlighted the digital twin's capacity to integrate with complex building systems but also demonstrated its potential to improve decision-making through real-time operational insights. This initiative set the stage for future expansions across other sections of the building, supporting long-term goals of enhanced energy efficiency and sustainable building management at OU44.

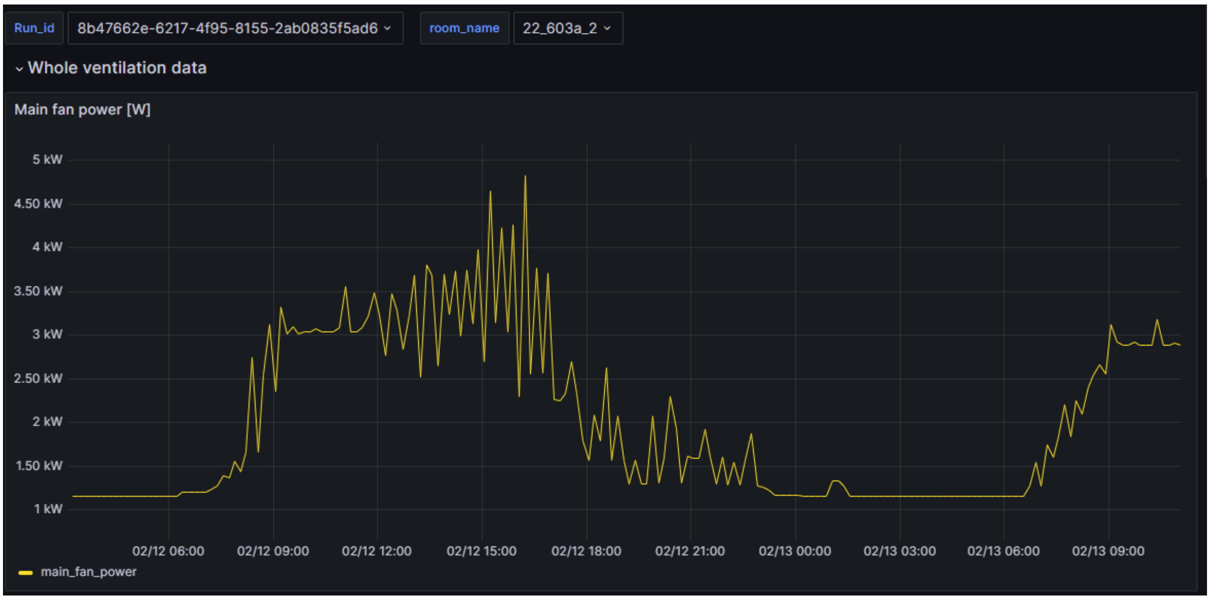
The building's ventilation system consists of four nearly identical subsystems, each featuring a central air handling unit (AHU) that supplies air to classrooms, study rooms, and offices through demand-controlled ventilation (DCV). In contrast, bathrooms and auxiliary rooms are ventilated using a constant air volume (CAV) approach. To model and optimize these ventilation systems, the Twin4Build Python package, developed in WP3, was employed to create a data-driven and ontology-based simulation. This model aimed to predict energy usage and specific room conditions for systems composed of a central AHU and individual room-level variable air volume (VAV) boxes, which control the flow of fresh air into each room.

The model integrates multiple room-specific simulations to predict the air flow rate based on a customized control model for each space. By summing the air mass flow rates from all rooms, the total ventilation flow rate is estimated, which in turn is used to calculate energy consumption through a fan model. The ventilation model was designed using the Twin4Build Python framework, which leverages the SAREF ontology and enables API-based integration for deployment in cloud environments. Simulation is powered by the Twin4Build algorithm, and the FastAPI library supports containerization and remote deployment of the model.

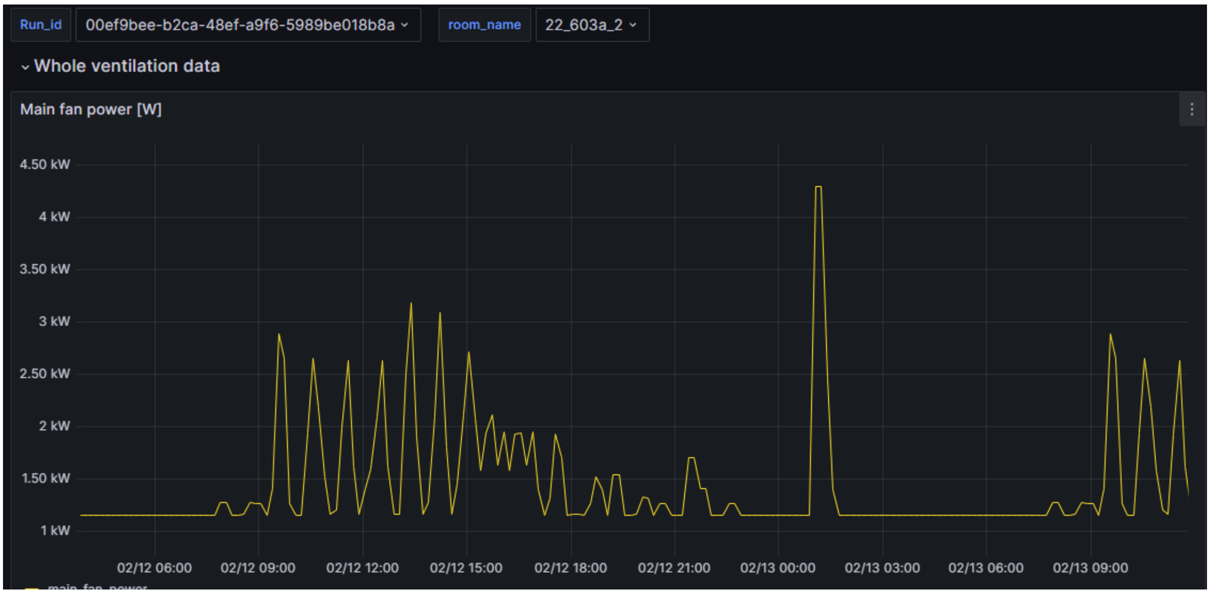
To evaluate various control strategies, different room ventilation controller models were developed. These included a purely data-driven controller, a rule-based controller (RBC), and a proportional-integral-derivative (PID) controller. The data-driven control model replicates the building's current control strategy based on operational data, providing a baseline for future strategy evaluations and energy consumption analysis. The RBC and PID controllers, on the other hand, allow for the testing of alternative operational scenarios, offering insights into energy consumption patterns and facilitating the fine-tuning of more energy-efficient strategies.

The ventilation system model, along with its control algorithms, was integrated into the digital twin platform developed as part of the Twin4Build project. This integration enables real-time performance monitoring of the ventilation system at various levels of granularity. Additionally, the platform features "what-if" scenario simulations, where individual simulation runs are tracked by unique identifiers (run_id). This functionality allows users to explore the outcomes of different operational strategies and gain insights into their impact on energy efficiency.

One notable case study tested the replacement of all existing controllers with a simple rule-based controller that employed more relaxed CO2 setpoints. The results demonstrated a significant reduction in total energy consumption. Further analysis revealed that the energy savings were not solely due to the relaxed CO2 setpoints but also from the reactivation of demand-controlled ventilation in several offices, where this feature had been previously deactivated. By dynamically adjusting ventilation based on real-time occupancy data, the digital twin estimated that certain offices required ventilation at only 45% of their full capacity for brief periods throughout the day, along with saving around 28% on heating and electricity consumption for the HVAC unit, aligning more closely with actual occupancy profiles, as reported in Figure 5.



(a)



(b)

Figure 5. Ventilation system fan power consumption as reported in the (a) base case scenario, and (b) upgraded control strategy scenario.

This case illustrates the power of the digital twin platform in optimizing building ventilation systems. Through continuous monitoring, advanced control strategies, and simulation-based insights, the platform successfully reduced energy consumption while maintaining indoor air quality. The success of this implementation paves the way for broader adoption of digital twin technology in HVAC optimization, contributing to long-term energy efficiency goals and sustainable building management practices.

3. OUH Case

To demonstrate and evaluate the proposed energy modeling and simulation approach, an actual case study building is considered in this paper. The case study is a two-story building within Nyt OUH in Odense. The ground floor contains the hospital kitchen, whereas the first floor includes office spaces, meeting rooms, and changing rooms. The hospital itself is situated in an open area, while the case study building is next to the main hospital and is exposed to outdoor environmental conditions on most of its outer surfaces. The first floor of the building comprises six office spaces, with floor areas ranging from 18 m2 to 31 m2. These offices are equipped with desks, computers, monitors, and multiple lighting sources. The number of occupants varies from single-person offices to shared offices that can accommodate up to six people. Two large meeting rooms with an area of 46 m2 are separated by a folding wall, allowing them to be combined into a single larger space. The first floor also contains two separate changing rooms with areas of 21 m2 and 42 m2. These changing rooms have 2 and 6 walled toilet stalls, respectively. Furthermore, the floor contains shared staff accommodation with an area of 82 m2 and a kitchenette. Other facilities on this floor, such as a stair wall, elevator, and multiple single-stall toilets, are not considered during the demonstration. Table 1 presents a summary of the spaces, including their respective areas, their designated use, and occupancy. Each of the spaces is equipped with multiple sensors and systems, including sensors that measure temperature, CO2, radiator valve positions, and damper positions. The first floor has a dedicated ventilation system with a capacity of 11,000 m3/h, equipped with a rotating heat exchanger and cooling- and heating water coils. The building is supplied by district heating with an outdoor-compensated supply water temperature, operating between 50 and 60 °C when the outdoor temperature is between -12 and 5 °C.

A semantic model is employed to represent the physical system in a comprehensive and machine-readable format. The information contained in the semantic model includes the system topology, relationships, and equipment properties of various elements. The semantic model is organized using the so-called triple construct, denoted by subject→ predicate→object. The component library contains the building blocks from which the simulation model is automatically assembled. It consists of modular, self-contained gray-box and black-box models for which inputs and outputs can be connected in different configurations and adapted based on specific use cases. This is achieved using a so-called signature pattern attached to each component model. The signature pattern acts akin to a blueprint of the component model, describing the semantic context in which the model applies and how it connects to other components. The semantic model serves as the basis for automatically generating the simulation model by matching and connecting component models. After model generation, parameters not mapped from the semantic model are estimated using Monte Carlo Markov Chain (MCMC) sampling. A five-day winter period from December 2023 is used to sample the posterior distribution for the estimated model parameters. The data includes measurements from all sensing devices. The predictions of the calibrated model achieved on average mean absolute errors of 0.4 °C for temperature, 32 ppm for CO2 concentration, 0.06 for valve position, and 0.04 for damper positions across various zones, demonstrating its accuracy and reliability.

Using the DT setup, a concrete example demonstrating how changes to the semantic model directly and automatically affect simulation model predictions was carried out, illustrating the potential of closely integrating semantic and simulation models within a DT environment. This concept is used to explore alternative system configurations that can improve the indoor environment of the building. As noted earlier, the heater in one of the spaces is found to be greatly undersized and is constantly operated with a fully open valve. In addition, the room temperature never reaches the desired setpoint of 21 C. Five scenarios are compared: #1: the baseline, i.e., the current system configuration and operation; #2: the current system configuration with an increase in supply water temperature to 65 °C; #3: adding an additional heater of the same model to space 4; #4: adding an additional heater to space 4 but of a larger model; and finally, #5: A combination of #2 and #3 where both a space heater is added and the supply water temperature is increased. For each scenario, the model and specifications of the replaced or added heater are varied according to actual models available on the market and are based on the EN442 standard.

Results show that Scenario #2, with the increased supply water temperature, reduces the setpoint violation to 320.99 Kh, a reduction of 17%. However, the heating output of the currently installed space heater is still insufficient to meet the desired setpoint. Scenario #3 with an additional heater of 432W shows a reduction of

74%, while scenario #4 with a larger space heater of 744W has an even further reduction of 83%. Finally, scenario #5 shows that an additional space heater of 432W combined with an increase in supply water temperature provides the largest reduction of 85%, as shown in Figure 6.

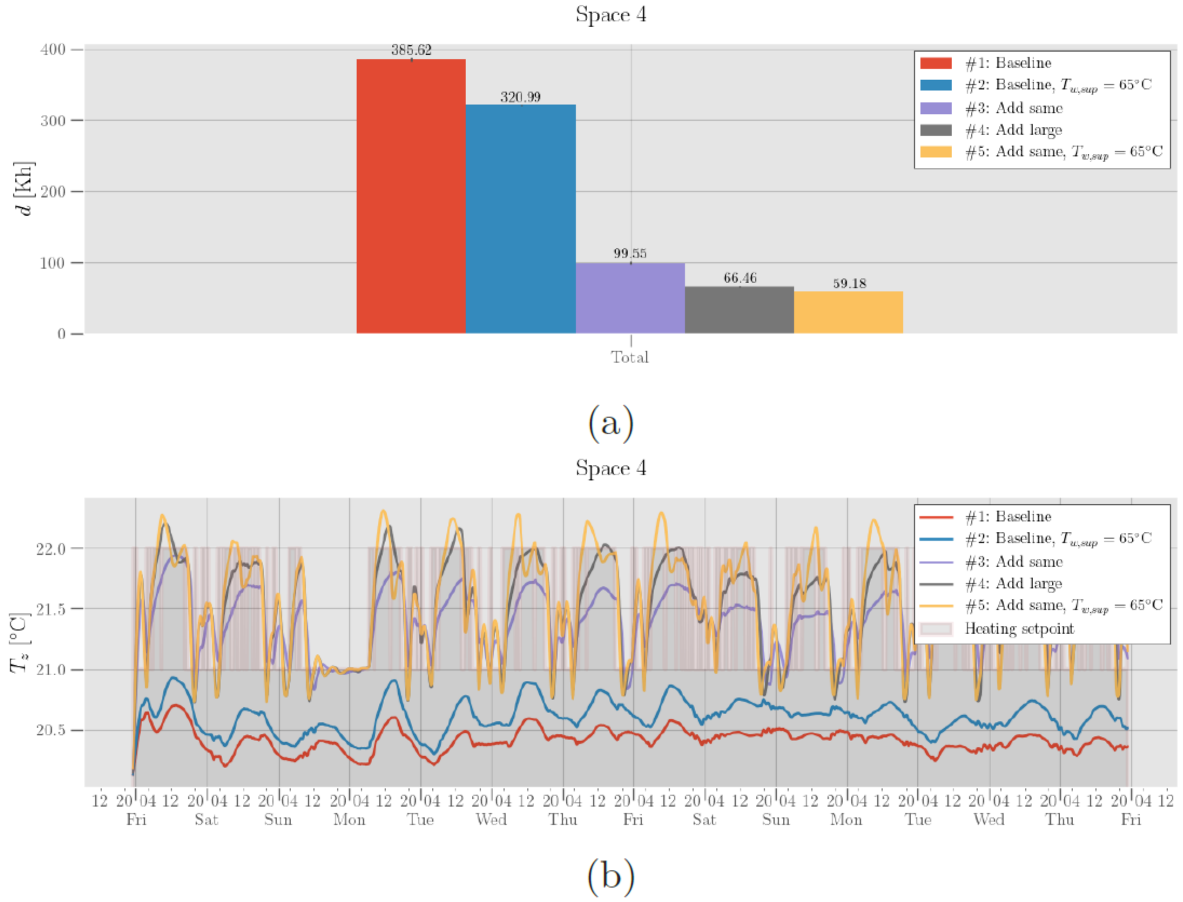


Figure 6. Impact of four scenarios on indoor comfort in Space 4 over a two-week period. (a) Accumulated setpoint violations in Kelvin-hours per scenario. (b) Predicted indoor temperatures compared to historical setpoint profile.

In summary, significant improvements of the indoor comfort in this specific area can be achieved through simple measures such as installing additional space heater capacity and increasing the supply water temperature. The example presented in this section shows how different system configurations can be explored through changes in the semantic model only. As the semantic model represents the actual physical equipment and system topology of a building, a potential user only needs knowledge of the real system to test strategies. Hence, all abstractions specific to the simulation model (connections, inputs, outputs, parameters, etc.) are hidden away from the user. In comparison, performing such calculations in traditional energy simulation software such as EnergyPlus requires tool-specific expert knowledge, e.g., which parameters or inputs to change and how the different model abstractions map to physical changes in the real building.

As a result of WP6 work and activities, milestones **(M9)**, **(M10),** and **(M11)** are met.

6. Utilisation of project results

The project marks a significant advancement in the field of smart building energy management and optimization. Its modular, scalable nature, combined with strong industry partnerships, positions it to be a leader in the energy-efficient solutions market. As the project moves forward, ongoing development, testing, and refinement will ensure that it has a lasting impact on both national and international building sectors, driving improvements in energy efficiency and sustainability across the industry.

1- Demonstration and Real-World Impact

The project has already begun demonstrating its results through one emulator case and two actual case study buildings. These demonstrations highlight that the developed solutions are being utilized in real-world applications even before the project's official completion. This early adoption underscores the potential for further deployment and the foundation for future technical development and commercial exploitation.

While the project activities and planned deliverables have been met within the planned three-year project lifetime, the technical work carried out, along with the findings obtained, will serve as a basis for future technical innovations and commercialization. The results will, to varying degrees, be utilized by all project partners, including research organizations, commercial entities, and public partners.

2- Future Development and Technical Advancements

The technical work conducted, along with the design and development of the proposed Digital Twin platform and its corresponding technical components within the ontology-based energy modeling framework and data context information models, has paved the way for further investigations and future advancements. As this Digital Twin is the first of its kind in the field of smart building energy management and optimization, the initial version will inevitably require ongoing enhancements, refinements, and updates. Thus, additional testing of the platform and its components is still necessary.

Although the platform was successfully demonstrated in three case studies, the number of cases and the timeframe for testing within the scope of the project were somewhat limited. To fully evaluate the platform's potential, it is essential to extend testing to a broader range of buildings with different types, uses, applications, and system configurations. Schools, office buildings, healthcare facilities, citizen centers, city halls, libraries, and other public buildings are promising candidates for further deployment and testing. These buildings are often unique in their design, usage, and the systems they integrate, presenting a valuable opportunity to challenge the tools and assess their versatility.

Continued testing and development of the Digital Twin solution will be critical for achieving effective market penetration and commercial success. A key question that remains is determining how much data is required from a building for the platform to serve as a robust basis for continuous commissioning, fault detection, diagnostics, and performance optimization. Different buildings will have varying levels of metering and sensor networks, which could influence implementation strategies.

These are important and natural questions that organizations such as SDU are well-positioned to explore. Further research will be essential to address these challenges and build upon the technical results of the project.

3- Commercial Exploitation and Market Flexibility

Regarding the commercial exploitation of the project results, the developed solution offers flexibility in its implementation. It can be deployed as a comprehensive Digital Twin (DT) package or as standalone applications, with each component individually implemented based on the specific needs of the case study, building type, and customer preferences. This flexibility enables the project’s commercial partners to leverage the development and demonstration outcomes across a wide array of applications, offering diverse options and services to their clients.

The project team anticipates that the results will be ready for market within a year after project completion. This includes both the full technology solution and its individual system features, comprising the three developed tools and applications. The solution will be offered by KMD and COWI to their existing and potential new customers within the building sector. Additionally, it will be promoted through articles on the companies' websites, social media platforms, and video presentations featuring feedback from pilot studies.

The first version of the solution is expected to be ready for deployment in Danish projects within a year of project completion. While some additional setup may be required to ensure stability for international markets, global commercialization is anticipated to follow shortly after the Danish release.

In addition to the field testing carried out by COWI and KMD during the project, the technology is expected to be implemented in other buildings post-project. Both companies will offer the solution as a service to their broad customer base, which includes a mix of existing and new clients. Several municipalities, including Copenhagen, Aalborg, and Odense, have already expressed interest in the solution and the potential added value it offers.

Furthermore, it is anticipated that the technology will gain wider adoption by other companies following the initial promotion during the project period and continued marketing efforts after the project concludes.

4- Strengthening Partnerships and Market Leadership

The project will strengthen the collaboration between KMD and COWI, as it represents an initial step in unlocking the potential of data harvesting and advanced analytics for building performance evaluation and assessment. This solution is applicable across a wide range of target segments, including new construction projects, building renovations, and retrofit projects. Companies adopting the solution will immediately benefit from its ability to enhance energy efficiency and reduce CO2 emissions, contributing to their green initiatives.

KMD views this project as a strategic asset that will enhance its portfolio, solidify its market position, and help it stay ahead of competitors in a field where current solutions are either limited to site-level or entire grid-level implementations. Additionally, current sensing technologies are often rudimentary, and building data collection, storage, and management practices are inconsistent due to siloed efforts and the lack of standardized data models. The modular nature of the digital twin ecosystem, along with its standardized context information platform, enables seamless data collection from various vertical systems and devices within buildings. This platform facilitates efficient data management, open integration, and interoperability with other platforms or third-party solutions, making the ecosystem highly adaptable and scalable.

The use of a Digital Twin platform powered by FIWARE addresses the challenge of processing and making sense of the vast amounts of streaming data generated by building sensors and devices. Currently, much of this data is collected but not utilized intelligently. The proposed software solution in this project will be the first of its kind, allowing for more effective use of sensor data.

COWI, a leading Danish consulting company with a mission to create sustainable societies, sees this project as an opportunity to leverage its expertise in engineering, economics, and environmental science. COWI operates not only in Denmark, Norway, and Sweden, but also has a significant presence in the US, UK, and the Middle East. The company provides a wide range of services, including commissioning, energy optimization, and digital asset management strategies. In this domain, competitors such as Rambøll, Sweco, Niras, and AFRY are also active. While some competitors have started developing digital twin setups, their focus has primarily been on linking static data. The approach proposed in this project, which links a dynamic baseline with real-time sensor data, is unique in the market. This will position COWI as a leader, offering a continuous commissioning service through a digital twin platform, making it the first in the building energy consultancy sector to do so.

Although the project has not yet led to a direct increase in turnover or employment, it is expected that once a decision is made to proceed with the final commercial implementation phase, the project outcomes will see direct commercial utilization in line with the expectations of the original application. Following further testing and assessment, the commercial partners will be well-positioned to develop concrete business plans and go-to-market strategies.

5- Market Risks and Mitigation Strategies

One of the key market risks for the commercialization of the project solution is that the demand may not meet expectations after project completion. However, a guiding principle for the project team throughout its lifecycle has been to ensure that deliverables are driven by industry and customer needs. With increasing pressure for energy efficiency and environmental sustainability in the building sector, there is a consistent demand for innovative solutions that reduce energy consumption, optimize performance, and lower operational costs. The project's industrial partners already serve a national and international customer base that continually seeks proactive, automated, and innovative services to meet their sustainability goals. As a result, they anticipate growing demand for the proposed technology in the coming years.

Additionally, the technology is versatile, as it can be sold as a stand-alone product or integrated into existing solutions, further expanding its market potential.

Another significant risk that could hinder the exploitation of project results is the potential lack of qualified staff to implement the developed solution. The project team has been aware of this challenge from the outset. To mitigate this risk, KMD's technical design and development teams, along with NEC, have been deeply involved throughout all stages of the project. This involvement has included their active participation in the solution's preliminary testing and demonstration within the case study buildings. Similarly, COWI's staff have collaborated closely with all partners, working to adapt existing sensing solutions to meet the new system's requirements.

Thanks to this collaborative approach, the project team is confident that they will have the necessary expertise and capabilities to implement the solution successfully after the project concludes.

6- Impact on Energy Efficiency and the Building Sector

The project is expected to have a profound impact on energy efficiency in the building sector, providing value throughout the entire tool chain:

- **Building Owners and Clients**: The DT platform will ensure that buildings are energy efficient from day one and throughout their lifecycle, preventing hidden losses and inefficiencies.
- **Facility and Building Managers**: The platform will offer continuous monitoring and tracking of building operations, exposing errors, faults, and issues at various levels and enabling timely interventions, which will prevent energy losses and reduce inefficiencies.
- **Energy Consultants and Contractors**: The platform will provide a coordinated approach to support strategic decision-making throughout the building's life, allowing consultants to run "What if?" scenarios and make informed decisions that ensure energy-efficient operations.
- **City Planners, Authorities, and Decision Makers**: The solution will aid in energy-efficient and optimal planning, design, and operation within the built environment. The scalability of the DT platform will enable long-term benefits, helping city planners identify the most resource-efficient strategies for reducing energy consumption and fossil fuel use in communities. The platform will also aid in city planning and energy network upgrades by evaluating various strategies and predicting their impacts.

7- Alignment with National Energy Strategies

The project aligns with several Danish national energy strategies, including the government's goal of achieving a fossil-free energy supply by 2050. Given the building sector's significant contribution to energy consumption, the project addresses this national priority by advancing energy-efficient solutions. The project also aligns with Danish ICT regulations, promoting the integration of digital tools in the construction sector. By extending the use of BIM from a static design tool to a dynamic model for building operation, the project supports national efforts to foster digitalization in construction.

Additionally, the project is in line with the Danish strategy for digital construction, which aims to enhance the use of digital tools, promote open standards, and foster the development of digital competencies across the construction value chain. The DT platform addresses all five focus areas of the strategy, contributing to more sustainable construction through digitalization.

8- Contributions to Research and Education

In terms of the involvement of PhD students, Mr. Jakob Bjørnskov, PhD student at SDU Center for Energy Informatics, have been involved in the project since day 1, with his PhD entitled 'Digital Twins for Building Applications'. He has contributed majorly in WP3, in terms of the Development of Building Energy Models for Digital Twin Applications, and in WP6 with the demonstration of the solutions in OUH building. Additionally, PhD student Andres Sebastian Cespedes Cubides took part in WP3 with the development of data-driven energy models and in the demonstration of the solution in the OU44 building at SDU. The two PhD students have also been in direct contact and collaboration with the project commercial partners, which was crucial and key for their PhD studies, providing practical and industrial perspectives in addition to the academic and research aspects.

The project methodology has also been integrated into two courses within the Energy Technology education program at SDU: "Building Energy Modeling and Simulation" and "Smart Buildings." This has provided students with practical exposure to cutting-edge technologies and tools, ensuring that the next generation of energy professionals is equipped with the necessary skills and knowledge.

7. Project conclusion and perspective

The project has achieved several key milestones, contributing to advancements in building energy efficiency through the development of a sophisticated Digital Twin (DT) platform. Overall, the project has progressed smoothly throughout the project life, despite that it started after a hard time with negative impacts of COVID 19 on various domains and on every single organization in the project. The collaboration between the different partners was very fruitful, where various expertise has been blended to develop and demonstrate the proposed solution. The project findings were very well reported and disseminated in a large number of publications and in various national meetings and workshops and international conferences. The following detailed conclusions encapsulate the project's impact:

1. **Integration of Smart Data Ontologies and Flexible Models**:

Smart Data Ontologies: The project successfully integrated smart data ontologies, such as SAREF and its extensions, to enhance semantic interoperability. This approach enabled seamless data exchange and integration across different systems and components within the building.

Flexible Energy Models: The development of Grey-Box Energy Models combined the predictive accuracy of white-box models with the operational efficiency of black-box models. This hybrid approach provided a balanced method for managing and optimizing building performance, addressing limitations found in traditional modeling techniques.

2. **Holistic Digital Twin Platform**:

Building Context Information Model: The platform's Building Context Information Model consolidated data from various sources, including historical, real-time, and forecast data. This integration facilitated a comprehensive understanding of building dynamics, improving decision-making and operational efficiency.

Grey-Box Energy Models: The incorporation of Grey-Box models allowed for more accurate energy predictions and real-time performance assessments, enhancing the platform's ability to adapt to changing conditions and operational needs.

3. **Pilot Testing and Real-World Impact**:

Case Studies: The implementation in diverse case study buildings demonstrated the platform's versatility. In the SDU Teaching Building, real-time performance monitoring and anomaly detection led to potential energy savings of 30%. AT OU44 building, the platform was capable to save 45% on the power capacity and 28% on the energy consumption of the ventilation system by suggesting a smart control strategy. At Nyt OUH, improvements in indoor comfort by 85% were achieved through optimized heating configurations.

Practical Applications: The successful demonstration of the platform's capabilities in real-world settings underscored its practical value and readiness for broader deployment. These case studies highlighted the potential for significant improvements in energy efficiency and user comfort.

4. **Technical and Commercial Milestones**:

Technical Achievements: The project advanced the technology from TRL 4 to TRL 6-7, marking a significant step towards commercialization. Key achievements included the development of the Twin4Build Python package and the integration of building energy models and data platforms.

Commercial Viability: The strong industry partnerships with KMD and COWI, along with early real-world applications, demonstrated the commercial potential of the solution. These partnerships facilitated the development of a market-ready product with a clear path to commercialization.

5. **Next Steps for Developed Technology**

A. **Extended Testing and Validation**:

Broader Deployment: To ensure the platform's effectiveness across various building types, additional testing is needed. This includes applying the technology in different environments such as office buildings, healthcare facilities, and other commercial and residential settings.

Performance Metrics: Developing comprehensive performance metrics and benchmarks will be crucial for assessing the platform's versatility and effectiveness in diverse scenarios.

B. **Refinement and Enhancement**:

Optimization: Continuous refinement of data integration methods, predictive modeling capabilities, and user interfaces will be necessary to address any limitations and enhance the platform's performance.

User Feedback: Gathering feedback from end-users and stakeholders will provide valuable insights for further improvements and customization.

C. **Commercialization and Market Deployment**:

Market Introduction: The solution is expected to be market-ready within a year, with initial deployment in Denmark followed by global commercialization. This phased approach will allow for iterative improvements based on market feedback.

Marketing Strategy: KMD and COWI will leverage various marketing channels, including articles, social media, and video presentations, to promote the solution. Highlighting successful pilot studies and real-world benefits will be key to gaining market traction.

D. **Research and Development**:

Further Research: Investigating the optimal amount of data required for continuous commissioning, fault detection, and performance optimization will be crucial. Collaboration with academic institutions, such as SDU, will support this research.

Innovation: Ongoing research will focus on developing innovative solutions to emerging challenges and enhancing the platform's capabilities.

E. **Standardization and Guidelines**:

Standards Development: Contributing to the development of standardized guidelines for Digital Twin applications will help streamline the adoption process and ensure interoperability across different systems and platforms.

Best Practices: Establishing best practices for integrating BIM, energy models, and context models will facilitate smoother transitions and improve overall efficiency.

6. Future Development Perspective

A. **Advancement of Smart Buildings**:

Digitalization: Future smart buildings will increasingly leverage digitalization to optimize efficiency, security, and comfort. The integration of extensive sensor networks and comprehensive data models will enable proactive responses to environmental changes and seamless connections with other infrastructure elements.

Proactive Building Management: The DT platform will play a crucial role in this evolution by providing a foundation for proactive building management and data-driven decision-making.

B. **Impact on Industry Practices**:

Adoption of Technologies: The project's success in integrating real-time data and flexible energy models is likely to influence industry practices, promoting the adoption of similar technologies and approaches in building energy management.

Innovation: By addressing key challenges and offering practical solutions, the platform sets a precedent for future innovations in smart building technologies.

C. **Influence on Policy and Standards**:

Policy Development: The project aligns with national energy strategies and digital construction goals, potentially influencing policy development and industry standards.

Standards Formation: The project's outcomes can inform the creation of guidelines and best practices for Digital Twin applications, supporting wider adoption and standardization.

D. **Commercial Opportunities and Market Expansion**:

Versatility: The modular and scalable nature of the platform provides commercial flexibility, allowing for deployment as a comprehensive Digital Twin package or as individual applications tailored to specific needs.

Market Traction: Continued marketing efforts and field testing post-project will help expand the technology's influence in the smart building and energy management sectors.

E. **Educational and Research Contributions**:

Workforce Development: Integrating project findings into SDU's Energy Technology curriculum supports the development of a skilled workforce in advanced technologies.

Research Contributions: The project's research and technical advancements contribute to the broader field of building energy management, fostering further innovation and development.

In conclusion, the project represents a major advancement in smart building technology, with promising implications for future development, commercial success, and industry impact. Continued research, refinement, and strategic commercialization efforts will be essential for realizing the full potential of the Digital Twin platform and driving further innovation in building energy management.

8. Appendices

The list of appendices included along this final project report are as follows:

1- Gantt Diagram as of September 2024

2- A report on the energy modeling requirements for Digital Twins applications.

3- A report on the data modeling requirements for Digital Twins applications.

4- A feedback report summarizing the key findings of the field interviews with owners and clients

5- Twin4Build Digital Twin Architecture

6- Digital Twin demonstration in OU44 building room

7- Published Article in HVAC Magsinet: Digitale tvillinger I byggeriet

8- Published Paper in Journal of Building Engineering: Component-level re commissioning of a newly retrofitted Danish healthcare building

9- Published Paper in the Proceedings of BSO-VI 2022- Sixth Building Simulation and Optimisation Virtual Conference: A Modular Thermal Space Coupling Approach for Indoor Temperature Forecasting Using Artificial Neural Networks

10- Published Paper in the Proceedings of Building Simulation Applications BSA 2022: A Fully Automated and Scalable Approach for Indoor Temperature Forecasting in Buildings Using Artificial Neural Networks

11- Published Paper in the Proceedings of IEEE ACTEA 2023 conference: A Digital Twin Platform for Energy Efficient and Smart Buildings Applications.

12- Published Paper in the Proceedings of Building Simulation Conference BS 2023: Adaptable and Scalable Energy Modeling of Ventilation Systems as Part of Building Digital Twins.

13- Published Paper in the Proceedings of Building Simulation Conference BS 2023: Implementation and demonstration of an automated energy modeling framework for scalable and adaptable building digital twins based on the SAREF ontology.

14- Published Paper in the Proceedings of Building Simulation Applications Conference BSA 2024: Data-driven digital twining of ventilation systems for performance optimization: A university building case study.

15- Published Paper in the Proceedings of the International Conference on Sustainable Energy Technologies (SET23): Using Digital Twins to investigate the need for active cooling systems in Danish public buildings.

16- Published Paper in Energy and Buildings Journal: An Ontology-Based Innovative Energy Modeling Framework for Scalable and Adaptable Building Digital Twins.

17- Published Paper in the Proceedings of the Sixth International Conference on Efficient Building Design: Systematic Commissioning and Performance Testing of Next Generation Building Management Systems.

18- Submitted Paper to the International Journal of Building Simulation: Development and Demonstration of a Digital Twin Platform Leveraging Ontologies and Data-driven Simulation Models.

19- Submitted Paper to Energy and building Journal: Automated Model Generation and Parameter Estimation of Building Energy Models Using an Ontology-based Framework.

20- Submitted Paper to Applied Energy Journal: Large-scale Field Demonstration of an Interoperable and Ontology-Based Energy Modeling Framework for Building Digital Twins.