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DanRETwin: A Digital Twin Solution for Optimal Energy Retrofit Decision-Making and Decarbonization of the Danish Building Stock

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Abstract: The current trend in renovating existing buildings is to perform retrofits on a case-by-case basis without a systematic assessment, using static tools with broad assumptions and generic inputs. As a result, only about 1% of the building stock undergoes energy renovations each year. To address this issue, new approaches and modern tools are necessary to enhance and expedite energy retrofits in Danish buildings. While there were a few initiatives and projects exploring the implementation of digital twins in building applications, the focus is primarily on newly constructed, highly energy-efficient buildings with integrated building information models (BIM). Conversely, existing and older buildings often lack any form of digital modeling, making it challenging to implement digital twins in those contexts. This paper presents an innovative digital twin solution, 'DanRETwin', which will provide decision-making support, retro-commissioning, and data-driven performance optimization for non-residential existing buildings. The proposed solution will utilize building operational data, employing machine learning and artificial intelligence techniques to develop scalable data-driven models of building energy. Additionally, clamp-on IoT sensors will be used for data collection, enabling a fully automated and flexible solution. By utilizing DanRETwin, building owners will enjoy higher energy efficiency and improved comfort in their retrofitted buildings; facility managers will have an advanced monitoring solution that enables systematic retro-commissioning of their newly retrofitted buildings, eliminating faults and reducing losses; consultants will have a potential solution to retrofit, enhance, and optimize their clients' building performance, allowing them to make informed, data-driven decisions and interventions; and city planners will have an effective, scalable, and adaptable tool to expand retrofit efforts and evaluate various scenarios.

Keywords: digital twins; smart buildings; energy retrofitting; data modeling; IoT sensors; energy efficiency

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1. Introduction

In the European Union (EU), buildings consume approximately 40% of total energy and are responsible for around 36% of CO_2 emissions [1,2]. Recognizing the need to achieve its ambitious energy and climate goals for 2030 and 2050, the EU identified the building sector as a key priority due to its significant potential for cost-effective energy savings and a corresponding reduction in greenhouse gas emissions [3]. The revised Energy Efficiency Directive (EU) 2018 [4] established a major energy efficiency target of at least 32.5% for the EU by 2030, compared to projected energy use for that year. Furthermore, the EU Commission proposed in the Climate Target Plan 2030 [5] to reduce net greenhouse gas emissions in the EU by at least 55% by 2030, compared to 1990 levels. Energy efficiency is regarded as a crucial element of these efforts, with a particular emphasis on scaling up and accelerating actions in the building sector. To achieve the 55% emissions reduction target, the EU plans to decrease greenhouse gas emissions from buildings by 60%, reduce final energy consumption by 14%, and lower energy consumption for heating and cooling by 18% by 2030.

Denmark is no exception to these challenges, as the building sector accounts for a significant 40% share of the overall energy consumption and corresponding greenhouse gas emissions [6]. Consequently, the Danish building regulations, known as 'Danish BR' [7], underwent continuous enhancements in recent decades, primarily focused on newly constructed buildings. These standards encompass strict regulations for building design, operation, thermal comfort, and air quality, as well as the building envelope, components, and specifications. Figure 1 illustrates the progress made in terms of the maximum allowed primary energy use for a typical 150 m^2 newly constructed Danish residential building, highlighting the evolution and development of different building regulations ('BR') [8]. Notably, the permissible primary energy use for a newly built structure decreased by 95%, from approximately 350 kWh/m^2 per year for buildings constructed in 1961 to just 20 kWh/m^2 in 2020. This clearly demonstrates the significant potential not only for constructing energy-efficient new buildings, but also for enhancing the overall performance of existing buildings, particularly those built before the 1980s, through systematic retrofit processes and activities.

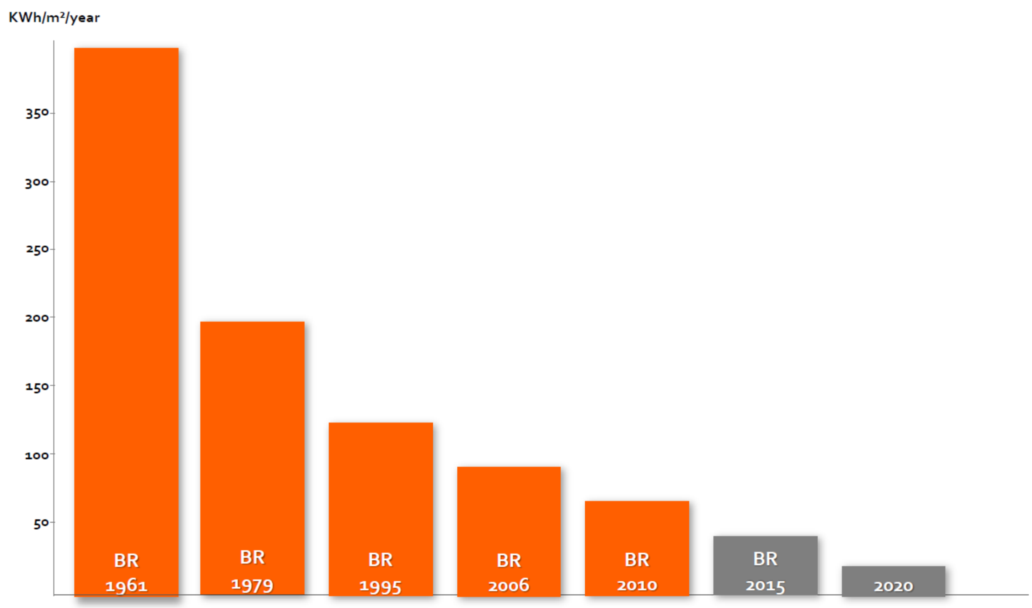

Figure 1. The maximum allowed annual primary energy usage in connection to the progressive building regulations for a 150 m^2 Danish residential building [8].

Building energy retrofitting is a proven and widely implemented technique that demonstrated positive impacts in technical, economic, and societal aspects. However, the annual energy renovation rate in the EU remains low, at only around 1% of the building stock per year [1]. At this pace, achieving carbon neutrality and decarbonizing the building stock would take centuries. Therefore, it is crucial to take action and scale up efforts and innovations. Over the past decade, numerous Danish, European, and international initiatives and strategies emerged, calling for widespread implementation of building energy retrofitting projects, improvement of existing buildings, and reduction in carbon emissions. In response to these ambitious initiatives, this work presents a timely and urgently needed intervention. Its goal is to design, develop, and demonstrate the first-of-its-kind digital twin solution called 'DanRETwin', which will facilitate optimal decision-making, retro-commissioning, and performance optimization of non-residential existing buildings. This work represents the first Danish initiative to leverage digitalization and data capabilities to enhance and accelerate energy retrofitting projects. The digital twin solution integrates real-time data collected from building energy meters and innovative clamp-on IoT sensors with dynamic building energy models to offer a robust and flexible platform. It provides the following services:

1. Acquisition, storage, integration, management, and exchange of building data from various sensors, meters, and IoT devices.
2. Decision-making support for energy retrofits, allowing testing and simulation of different options, scenarios, and system integrations.
3. Post-retrofit retro-commissioning of energy systems and automation and control systems.
4. Data-driven performance optimization platform for building control and management.

Digital twin solutions were already successfully implemented in various sectors, such as the manufacturing and automotive industries, and their market is expected to grow rapidly in the coming years. However, their adoption in the building and construction sectors is still in its early stages, with limited focus on existing buildings or highly energy-efficient structures. Considering that existing buildings make up over 97% of the overall building stock, this work represents the first initiative in Denmark to harness the potential of digital twins to optimize retrofit processes, increase renovation rates, improve overall performance, and decarbonize the existing Danish building stock.

Although there were several initiatives and projects investigating the incorporation of digital twins in the realm of building applications, the primary focus is mainly on newly constructed buildings and facilities that boast high energy efficiency. These buildings are equipped with integrated building information models (BIM). Conversely, pre-existing and older buildings often lack any semblance of digital representations, posing a challenge for the implementation of digital twins in such contexts. This research introduces an innovative digital twin solution for existing building applications called "DanRETwin." This solution aims to offer support for decision-making, retro-commissioning, and data-driven performance enhancement specifically for non-residential existing buildings. The proposed approach will harness operational data from buildings and leverage machine learning and artificial intelligence techniques to construct scalable data-centric models for building energy. Additionally, the utilization of clamp-on IoT sensors will facilitate data collection, resulting in a completely automated and versatile solution. Through the adoption of DanRETwin, building owners can expect heightened energy efficiency and increased comfort in their retrofitted structures. Facility managers will gain access to an advanced monitoring system that streamlines the systematic retro-commissioning of recently upgraded buildings, mitigating issues and curbing losses. Consultants will be presented with a potential avenue for retrofitting, augmenting, and optimizing their clients' building performance, empowering them to make informed decisions and data-backed interventions. Simultaneously, urban planners will possess an efficient, adaptable tool that supports the expansion of retrofit endeavors and the assessment of diverse scenarios.

2. Building Energy Retrofitting

2.1. Current Status

Despite significant efforts by most countries to promote the decarbonization of buildings, the global implementation of energy efficiency measures in existing buildings is lacking and falls far short of the necessary actions to achieve net-zero carbon dioxide emissions by 2050. This is evident from the fact that existing buildings still make up the majority, accounting for over 97% of the building stock [9]. The EU's building stock, for instance, consists of more than 220 million units, with 85% of them constructed before 2001. It is projected that around 85–95% of these buildings will still be in existence by 2050 [10]. The majority of these buildings are energy inefficient, relying on fossil fuels for heating and cooling and employing outdated technologies and wasteful appliances. Therefore, it is advisable to focus on the existing building stock by implementing comprehensive energy efficiency improvements through well-planned renovation and retrofit processes. These actions should consider the specific characteristics, specifications, and various economic, technical, and functional limitations associated with each building.

Building energy renovation refers to a comprehensive process aimed at improving the energy efficiency and indoor thermal comfort of existing buildings. This is achieved by implementing cost-effective measures and techniques that target various building components, including energy production and supply systems, building envelope and constructions, building management and control strategies, as well as renewable and alternative energy units. Building energy retrofitting is a well-established and widely adopted approach that is proven to have positive technical, economic, and societal impacts.

In addition to reducing energy consumption, energy losses, and carbon emissions, building energy retrofits also contribute to better indoor air quality, improved thermal comfort, increased productivity, enhanced asset value, and an overall better quality of life [11,12]. Despite these favorable outcomes, the annual rate of energy renovation in the EU is currently low, accounting for only around 1% of the building stock per year. When it comes to deep energy renovations, the average annual rate is even lower at 0.2% in the EU [1]. At this pace, achieving carbon neutrality and decarbonizing the building stock would take centuries. To meet the EU's 2030 climate target and achieve climate neutrality by 2050, there is an urgent need to significantly increase these renovation rates by a factor of 15. Specifically, the annual rate should reach 3% by 2030 and be sustained until 2050 [13]. Therefore, it is crucial to take action and scale up efforts and innovations in this area.

In line with this objective, the EU Commission introduced a strategy to initiate a Renovation Wave for Europe [14]. The aim is to at least double the annual energy renovation rate for both residential and non-residential buildings by 2030 and promote deep energy renovations. By pursuing these goals, it is projected that 35 million building units will be renovated by 2030.

Over the past two decades, Denmark witnessed significant activity in energy retrofitting and renovation of its existing building stock, particularly considering that more than 75% of the current buildings were constructed before 1980. The Danish government implemented an extensive buildings renovation strategy as part of the 2012 energy agreement, titled "Strategy for the energy renovation of the existing building stock" [15]. This strategy comprises 21 initiatives aimed at accelerating energy-efficient and cost-effective renovation projects in Denmark, with a target of achieving a 35% reduction in heating demand by 2050. Furthermore, Denmark, in line with its ambitious goal of reducing emissions by 70% by 2030, committed to new energy-saving measures for government-owned buildings through a circular letter that came into effect on 1 January 2021 [16]. Under this agreement, energy consumption in government-owned buildings that are owned and utilized by the administration must be reduced by a minimum of 42,480 MWh compared to the energy consumption in 2020. This equates to renovating 3% of the total floor area in these buildings on an annual basis. By meeting these requirements, Denmark ensures compliance with the EU's Energy Efficiency Directive, which set a target of at least 32.5% energy efficiency by 2030. Additionally, other government-owned buildings such as colleges, universities, and museums are obligated to achieve at least a 10% reduction in energy consumption over the next 10 years, amounting to approximately 173,000 MWh from 2021 to 2030.

In existing building renovation projects, there is a prevailing trend in Denmark where retrofitting occurs as needed, often disregarding the functionality of installations and the lifespan of building materials and components. Consequently, energy-efficient measures and cost-benefit analyses are overlooked during the decision-making process [8]. Moreover, the Danish building industry currently lacks systematic design and assessment tools for building energy retrofits. Instead, it heavily relies on static tabulated approaches that involve significant assumptions, as well as simplistic one-to-one static calculations and estimations to evaluate the impact of various renovation measures [17]. In response to these challenges, the project team at the SDU Center for Energy Informatics dedicated their efforts over the past few years to engaging in multiple projects and collaborations with the industry. Their focus is on designing, developing, demonstrating, and establishing an alternative approach that utilizes dynamic energy models as a foundation to support and optimize decision-making processes for efficient and effective retrofit applications [18].

2.2. Building Energy Models and Tools for Retrofit Applications

The process of enhancing building energy efficiency and making decisions regarding energy retrofitting involves an optimization method aimed at selecting technically advantageous and cost-effective measures. In this decision-making process, the building energy model plays a crucial role in accurately characterizing the actual building and simulating various alternatives, scenarios, and improvement measures in a robust and flexible manner. Different modeling approaches can be categorized as white-box, grey-box, and black-box. These approaches vary in terms of the level of physical relationships incorporated into the models. White-box models are fully physics-based, where every detail of the building is known [19]. They are predictive models that can be clearly explained in terms of their internal mechanisms. In building applications, white-box models are widely used in the form of simulation software such as EnergyPlus, eQUEST, DOE-2, ESP-r, BLAST, and TRNSYS, among others. These models are highly detailed and comprehensive, providing a flexible approach to assessing the retrofit potential of building systems or technologies.

White-box models rely on building physics, whereas black-box models are data-driven and utilize data collected from various building meters and sensors [20]. Black-box models are systems that are analyzed based on their inputs and outputs without any knowledge of their internal workings. These models were extensively used in the building domain for fault detection, diagnosis, and building system control, leveraging their classification and prediction capabilities. Successful applications include timely detection and prediction of faults in heating/cooling cycles, appliances, lighting energy use, and changes in indoor environmental conditions [21].

On the other hand, grey-box models offer a balanced hybrid approach to building energy modeling. These models incorporate physics equations to represent building behavior, but the equations are simpler compared to those used in white-box models [22]. As a result, grey-box models can be simulated more quickly. They combine a partial theoretical structure with measured data to complete the model, aiming to closely represent the thermal behavior of a building. However, the simplified physics in grey-box models result in a loss of accuracy, which is compensated for by calibrating the model with data, similar to the black-box modeling approach.

Various countries, both in the public and private sectors, developed a wide range of decision-making tools for energy retrofit applications. These tools aim to facilitate investments in energy efficiency measures by offering information on suitable energy improvement solutions tailored to specific cases. Examples of such tools include the online tool called 1 2 3 Réno [23], which was developed as part of the European project MARIE. This tool enables the assessment of energy improvement packages based on different renovation objectives and various types of homes in the Mediterranean and alpine regions of France.

Another tool, the Quickscan tool [24], was created as part of the European-funded Interreg NWE ACE-Retrofitting project. It provides an initial overview of retrofit measures that could be implemented in each building. The Home Energy Check (HEC) [25], developed as part of the Request2Action project, allows Greek homeowners to simulate the energy performance, rating, and CO_2 emissions of their homes.

In the United States, different tools were developed, such as the Home Energy Yardstick [26] and MyHomeEQ [27]. These tools aim to motivate and inspire homeowners by enabling them to compare their home's energy usage with similar homes in their region and providing information on energy improvement possibilities.

Denmark has its own tools as well, such as Totalkredit's energy calculator [28], developed in collaboration with the Danish Energy Agency. This calculator suggests potential energy improvements based on user-provided addresses and evaluates them in terms of investment cost, annual energy savings, and carbon reduction. Energihjem.dk [29], developed by AB Gruppen AS, also utilizes the user's address to indicate recommended energy improvements from the Energy Performance Certificate (EPC) report, providing estimates of annual savings and investment costs. Recently, DanRETRO, a decision-making tool for the energy retrofit design and assessment of Danish buildings, was developed by SDU CEI as part of the COORDICY project funded by the innovation foundation [30]. DanRETRO [31] utilizes a database containing a large number of simulations conducted in EnergyPlus, considering various types, sizes, and ages of Danish buildings. The tool offers recommendations on energy performance improvement measures for each specific case. Figure 2 depicts the DanRETRO user interface with the different inputs and outputs, as well as the energy renovation measures implemented and the assessment scores.

Input Type	Input Value	Unit
Building Type	Residential 2-story	[Type]
Year of construction	1992	[Year]
Building Area	300	[m2]
Electricity Price	0.33	[EUR/kWh]
Heating Price	0.09	[EUR/kWh]

Baseline Model Values		
Residential 2-story - 1992		
Information	Value	Unit
Electricity Consumption	34.32	[kWh/m2]
Heat Consumption	89.95	[kWh/m2]
Total Energy Consumption	124.27	[kWh/m2]
Primary Energy Consumption	134.75	[kWh/m2]
Baseline Energy Label	D	[A-G]

Energy Label Scale	Primary Energy Thresholds [kWh/m2]
A2020	27.00
A2015	33.33
A2010	58.00
B	77.33
C	120.67
D	164.00
E	207.33
F	261.67
G	261.67

DanRETRO

Building Renovation Measure Type: Residential 2-story Year: 1992	Electricity Savings [kWh/m2]	Heat Savings [kWh/m2]	Electricity Savings [%]	Heat Savings [%]	Total Energy Savings [kWh]	Total Economic Savings [EUR]	Total Environmental Savings [kg CO2]	Primary Energy Consumption [kWh/m2]	Energy Label [A2020-G]
1) Roof Insulation	0.05	3.68	0.16	4.09	1120.13	104.71	86.47	130.94	D
2) Walls Insulation	0.04	2.91	0.11	3.24	884.74	82.22	67.83	131.75	D
3) Floor Insulation	0.11	5.28	0.32	5.87	1615.26	153.17	126.81	129.21	D
4) Windows Upgrade	0.23	11.49	0.68	12.77	3517.32	333.44	276.05	122.68	D
5) Daylight Sensors Installation	2.75	-0.81	8.02	-0.90	581.71	250.41	236.20	128.69	D
6) Motion Sensors Installation	1.78	-0.47	5.18	-0.52	392.32	163.23	153.78	130.78	D
7) Indoor Lighting Upgrade	1.70	-0.45	4.94	-0.50	373.38	155.68	146.68	130.97	D
8) Electrical Equipment Upgrade	4.90	-1.76	14.27	-1.96	941.56	437.34	413.56	124.27	D
9) Solar Cells [10% of the Roof]	9.81	0.01	28.59	0.01	2946.43	971.67	906.87	110.21	C
10) Ventilation Heat Exchanger Installation	0.17	58.31	0.50	64.82	17543.30	1591.24	1306.73	76.02	B
11) Demand Controlled Ventilation	0.21	35.70	0.60	39.68	10771.11	984.34	809.48	98.54	C
12) Ventilation Fan Upgrade	1.15	-0.30	3.34	-0.33	254.33	105.36	99.24	132.19	D
13) Ventilation Preheating	2.73	19.16	7.96	21.31	6569.27	787.99	676.81	108.76	C
14) CO2-Based Ventilation	0.12	7.12	0.34	7.91	2169.92	203.73	168.38	127.34	D
15) Temperature-Based Ventilation	0.90	10.00	2.63	11.12	3271.11	359.33	304.77	122.50	D
16) Heat Setpoint Management	0.15	10.20	0.45	11.34	3106.06	290.58	240.00	124.17	D
17) Heating Circulation Pump Upgrade	0.30	-0.24	0.87	-0.27	16.23	22.89	22.11	134.25	D
18) Adaptive Heating Implementation	-0.02	40.59	-0.05	45.13	12172.63	1094.24	897.07	94.21	C
Package 1) Building Envelope (Walls, Roof)	0.11	7.84	0.32	8.71	2383.66	222.32	183.52	126.65	D
Package 2) Building Envelope (Walls, Roof, Floor, Windows)	0.41	24.86	1.18	27.64	7581.17	711.53	588.00	108.87	C
Package 3) Electrical Systems Upgrade	17.93	-2.64	52.25	-2.94	4586.04	1703.65	1598.16	92.57	C
Package 4) Ventilation System Upgrade	4.16	81.95	12.12	91.11	25833.35	2624.35	2198.62	42.41	A2010
Package 5) Heating System Upgrade	0.32	44.83	0.95	49.84	13547.09	1242.61	1022.59	89.11	C
Package 6) Energy Management Package	4.46	57.69	13.01	64.14	18647.20	1999.68	1689.82	65.90	B

Figure 2. DanRETRO building energy retrofitting tool with inputs, outputs, energy retrofit measures, and evaluation results [31].

In general, most of these tools rely on pre-simulated data, energy certificates, or fixed assumptions. Furthermore, these tools primarily focus on energy retrofitting in residential buildings, with limited initiatives addressing retrofit applications in non-residential buildings, especially in Denmark. Additionally, none of the tools available in the Danish market currently offer the capability to scale up and expedite the rate of retrofit applications while maintaining the accuracy and quality of decision-making.

2.3. Building Retro-Commissioning Process

Commissioning is a crucial process typically conducted towards the completion of building construction. At this stage, the building was fully constructed, and all the necessary subsystems were installed. The commissioning process involves a series of performance tests designed to ensure that the building and its systems meet the requirements specified during the design phase. These tests encompass various aspects, such as verifying the functionality of the subsystems and assessing the overall construction quality of the building. Given the increasing significance of energy efficiency and environmental considerations, building commissioning and performance testing became even more essential and urgent. In many developed countries, building regulations mandate manual performance testing and initial commissioning prior to the building handover. The benefits of conducting commissioning at the end of the construction stage are significant, including a smoother building start-up and improved comfort for occupants. Both building owners and managers stand to gain numerous advantages from the commissioning process [32], including:

- The building is ready for immediate use.
- The indoor environment meets the desired standards.
- Operating costs are optimized, predictable, and manageable within the budget.
- The building is adaptable and resilient.
- The operations staff can efficiently operate the building.
- The documentation aligns with the tools utilized by the operations team.
- Achieving an energy-efficient building with satisfied occupants.
- Well-documented services and consumption data.
- Maximizing the potential for increasing the value of the buildings.

Furthermore, commissioning provides contractors and consultants with the following benefits: (1) ensuring the delivery of the correct building on the first attempt; (2) meeting project deadlines; (3) documenting services and maintaining quality standards; (4) minimizing defects; and (5) reducing the number of warranty claims.

In general, the initial commissioning of newly constructed buildings in Denmark is now considered a standard quality assurance procedure in construction projects. The Danish standard DS 3090 [33] establishes the minimum requirements for ensuring quality and proper work processes during the commissioning phase. This includes conducting performance tests on key building systems such as ventilation, cooling, heating, lighting, elevators, and other services.

However, there is less emphasis on commissioning existing buildings after retrofitting. During retrofit projects, significant modifications are made to the building, particularly in terms of the physical envelope, energy services, energy generation and supply systems, and the building automation system. Due to the involvement of multiple teams and the multidisciplinary nature of retrofit activities, combined with inaccurate calculations and suboptimal decision-making, many retrofitted buildings often contain undetected faults and malfunctioning systems and components that become apparent only after the building is put back into operation.

As a result, there is a lack of systematic retro-commissioning for retrofitted buildings, with insufficient post-retrofit performance monitoring and evaluation. This leads to errors, faults, and malfunctions at various levels, resulting in a performance gap between the predicted energy performance promised to customers and the actual measured energy data on-site. Recent reports on Danish buildings indicate an average gap of around 30% between estimated and actual energy consumption data [34].

3. Building Digital Twins

3.1. Digital Twin Concept and Role

Digitalization plays a crucial role in enabling smart buildings to effectively interact with users and understand the internal and external environment. Central to establishing this interaction is the abundance of data available. Just two decades ago, building managers only needed to connect a few dozen data points within a building. However, this landscape drastically changed, and today we are dealing with tens of thousands, and sometimes even hundreds of thousands, of data points in some facilities. Consequently, smart buildings now generate vast amounts of data from various building services, components, and levels within the built environment.

In buildings equipped with advanced devices such as Internet of Things (IoT) devices, the number of sensors, meters, and devices significantly increased, leading to a greater need for efficient, automated, and user-friendly platforms for data storage, management, and sharing. The primary advantage lies in the immediate access to data, which provides a comprehensive view of a building's performance. This empowers owners and operators to manage assets and facilities more effectively in a timely manner, leading to enhanced operational efficiency.

The concept of 'digital twin' is a fundamental aspect and a key element of digitalization. It refers to a digital representation of physical assets, systems, devices, or processes that serves various purposes. A digital twin goes beyond being a mere digital model of a component or system; instead, it is a dynamic operational model where real-time data are integrated with the virtual replica to create a comprehensive digital twin. This integration enables continuous monitoring of the actual state of the system and facilitates informed decision-making for future states and applications.

In recent years, the scope of digital twin applications expanded, and successful implementations were witnessed across different industries and stages, including design, production, manufacturing, and maintenance. These applications are proven to be particularly valuable in areas such as understanding customer needs, predicting weaknesses and faults, optimizing processes to adapt to dynamic changes, and providing timely maintenance alerts to prevent failures.

Conceptually, a digital twin consists of three main components: (A) the physical component, representing the real-world component in physical space, (B) the virtual component, representing the digital counterpart in virtual space, and (C) data and information, which act as the bridge between the physical and virtual components. As illustrated in Figure 3, the connection and exchange of information between the physical component and the virtual replica are facilitated through data in various forms and at different levels.

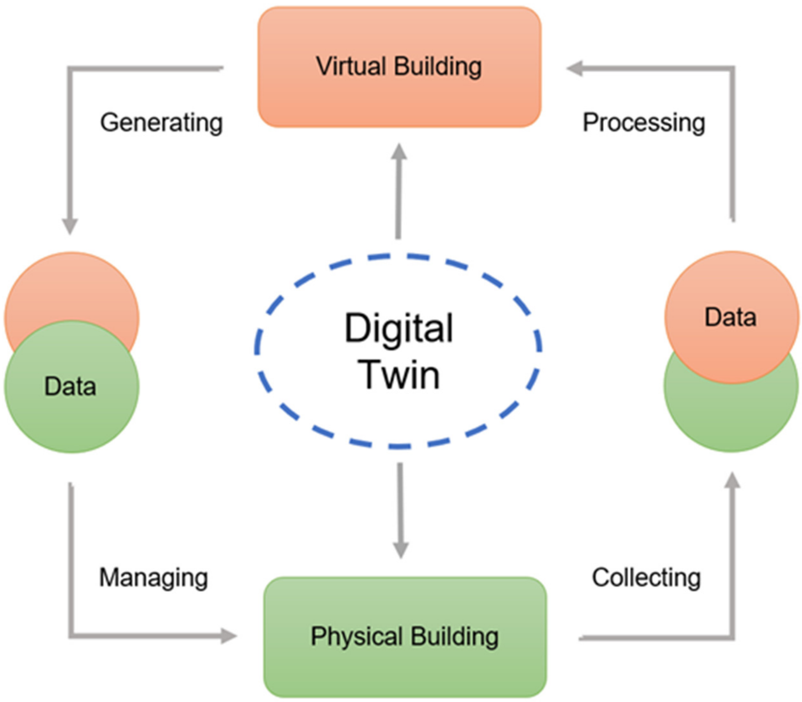

Figure 3. The main components of a standard digital twin.

The successful implementation of digital twin solutions in the manufacturing and production sectors paved the way for exploring their application at the building and facility levels. A building digital twin offers a holistic view of the operational building, bridging the physical and digital realms. It combines a virtual model of the building with real-time data collected from meters, sensors, and IoT devices to analyze, optimize, and inform decision-making throughout the building's life cycle. Consequently, a digital twin holds value at every stage of the building value chain, including conception, design, construction, commissioning, operation, and maintenance.

As more data are integrated into the digital twin, it opens up opportunities for scenario planning and what-if analyses using intelligent algorithms. By leveraging organized data, a digital twin provides real-time insights into the building's performance, enabling immediate adjustments to optimize performance at various levels. This leads to more energy-efficient, cost-effective, and sustainable smart buildings and facilities.

On an overall building level, a digital twin serves as a platform for comparing the actual performance of a building to a dynamic baseline, facilitating commissioning processes, and detecting faults and anomalies. The combination of static building information and dynamic data and predictions within the same platform allows facility managers and building owners to pinpoint malfunctions and errors with high precision and in less time, resulting in optimized predictive maintenance solutions.

At a system level, a digital twin enables operational optimization by utilizing data inputs from sensors and IoT devices to predict and inform control and management strategies. This empowers efficient control and enhances the overall management of building systems.

Having a clear understanding of the role of a digital twin and the context in which data are generated and utilized can reduce the overwhelming volume of raw data that decision makers have to deal with. Instead, it enhances the value of the data and promotes a deeper understanding of the digital realm on which the digital twins are built. This understanding is crucial for optimizing decision-making processes. By effectively integrating, sharing, and utilizing data, a digital twin can provide the following direct benefits:

- Enhanced decision-making through access to more accurate and relevant information.
- Greater appreciation of the value of data and its representation of real-world entities.
- Enablement of a circular economy by understanding dependencies, relationships, and opportunities for reuse.
- Reduced environmental footprint by identifying and addressing inefficiencies.
- Evaluation of the long-term impacts of interventions and improvements in real-world settings.
- Facilitation of innovative business models that leverage the capabilities of digital twins.
- Improved adaptability and compliance with new regulations.
- Increased productivity through optimized processes and resource allocation.
- Secure and resilient data sharing to ensure privacy and the protection of sensitive information.

3.2. Digital Twin Building Solutions in the Market

Although building digital twin technology was available for over a decade, its adoption in the Danish and European markets is still limited. While there were few initiatives and projects exploring the implementation of digital twins in building applications, the focus is primarily on newly constructed, highly energy-efficient buildings. These buildings are seen as ideal candidates for digital twins as they can bring Building Information Models (BIM) to life by integrating real-time data and dynamic information, creating a live and dynamic digital twin that can support the building throughout its life cycle. Conversely, existing and older buildings often lack any form of digital models, making it challenging to implement digital twins in those contexts.

One noteworthy project in this field is the EU Horizon 2020 project called the 'SPHERE: BIM Digital Twin platform.' This ambitious initiative aims to provide a BIM-based digital twin platform that can enhance the energy performance of newly constructed buildings throughout their life cycles. The platform also seeks to reduce time, costs, and the environmental impact associated with the construction process.

Overall, while digital twin technology demonstrated positive impacts in terms of energy savings, cost reduction, and resource optimization, its widespread implementation in the Danish and European markets is still in progress. The current focus is primarily on new, energy-efficient buildings, with the goal of expanding the use of digital twins to existing structures in the future.

Additionally, given the considerable potential demonstrated in utilizing digital twins across various fields, several commercial solutions for digital twins in the building sector emerged in recent years, offered by energy engineering and construction companies. Arup, for instance, introduced 'Neuron' [35], an intelligent digital twin platform for buildings that leverages advanced machine learning and predictive maintenance to assist asset owners in achieving significant energy savings. By utilizing 5G and the Internet of Things, the platform collects real-time data from equipment and systems, referred to as 'sense data.' Furthermore, it employs Building Information Modelling (BIM) to present these intricate datasets through a cloud-based, centralized management console. Arup also employs artificial intelligence and machine learning for the analysis, optimization, and automation of operations. Similarly, Granlund presented a comparable platform known as the 'Granlund Manager's Digital Twin' [36], which offers real-time data visualization on the building's 3D layout drawing, allowing for the monitoring of specific conditions at the building, floor, and unit levels. This digital twin aggregates data from BIMs used during the design phase, as well as from IoT and automation systems and property users. Another noteworthy development is Autodesk's 'Autodesk Tendem' [37], a cloud-based digital twin technology platform designed for buildings and facilities applications. The Tendem platform enables projects to initiate and maintain a digital presence, utilizing BIM data to generate valuable business intelligence. Through the utilization of Autodesk Tendem, construction and engineering companies can create and transfer a digital replica of a building to owners and operators, incorporating accessible, contextually relevant, and insightful data to support operational efficiency. The Tandem platform assists AEC firms in leveraging BIM data throughout the entire project lifecycle, facilitating the creation and transfer of a digital twin. This platform also helps building owners connect operational systems to the digital twin, consolidating fragmented data into actionable business intelligence.

Similarly, Siemens introduced a digital twin solution called 'Building Twin' [38], which provides real-time insights into a building's performance and allows immediate adjustments to optimize efficiency. This solution also offers data to enhance the design of future buildings, resulting in more cost-effective, streamlined, and sustainable smart buildings. It enables improved understanding of a building's performance, real-time issue identification and resolution, and optimal space utilization.

Furthermore, Bosch recently developed its 'Connecting Building Services' [39] offering and deployed Azure Digital Twins, enabling contextual solutions that create a digital representation of assets, environments, and business systems, including buildings and facilities. This allows customers to apply forecasts and predictive insights to make informed decisions for improving building performance and reducing carbon footprints.

Additionally, Catenda developed a digital platform solution called 'Bimsync Arena' [40] specifically designed to support building digital twins. This solution enhances design collaboration, reduces errors, saves time, and improves the quality of deliverables through an open BIM collaboration platform. Bimsync facilitates the integration of information and data into the virtual asset, resulting in the development of a comprehensive building digital twin throughout the entire process.

3.3. Major Challenges

Considering the state of the art and major current practices and developments, the main challenges that need to be addressed as a key condition to accelerating building energy retrofit rates in Denmark and meeting the energy and environmental goals are:

1. The majority of the current energy retrofit support tools are based on pre-simulated data or static assumptions, which fail to capture the true specific dynamics of the building components and systems operation, resulting in a major gap between promised impacts before retrofitting and real results attained post-retrofitting.
2. In terms of energy modeling, both white-box models and grey-box models have the potential to assess retrofit options in a specific building case when data and parameters are available and documented. However, this is rarely the case, and thus innovative energy modeling techniques are needed to scale up and accelerate retrofitting rates.
3. Due to inaccurate calculations and poor decision-making, the majority of retrofitted buildings will often contain faults and malfunctioning systems and components that were not discovered before re-operating the building. Thus, there is an overall

need of systematic retrofitted buildings retro-commissioning, allowing performance monitoring and evaluation post retrofit process.

4. While digitalization and employing data from various building sensors, smart meters, and IoT devices demonstrated positive impacts in improving building operation on different levels, such sensing and metering devices are generally not available in existing buildings, and their integration is expensive and complicated. Thus, alternative and temporary means of collecting and integrating information and data in such buildings are needed.

The challenges listed above, among others, in addition to economic and socio-cultural factors, hindered scaling up the rate of energy retrofitting and deep energy renovations of the Danish existing building stock. Thus, new approaches are needed, and novel up-to-date tools must be introduced to scale up the efforts and aid an optimized and accelerated energy retrofitting of the Danish existing building stock. For instance, in the recent Danish National Strategy for Sustainable Construction in 2021 [41], it was explicitly stated that: 'What is needed now is a digital support for energy renovation efforts, which should, for example, identify savings opportunities and potentials for building owners by collecting data on buildings.'

4. Proposed DanRETwin Solution

Figure 4 presents the overall research design and process in the design, development, and demonstration of the proposed DanRETwin digital twin solution in this study. As highlighted in the figure, the digital twin requirements are first identified. Then, data collected from various meters and sensors in the living lab building are used to develop and train the data-driven energy models. Both data and models are used to design and develop the digital twin platform. The platform is then implemented in real case study buildings. Finally, a comprehensive technical, economic, social, and environmental evaluation is carried out.

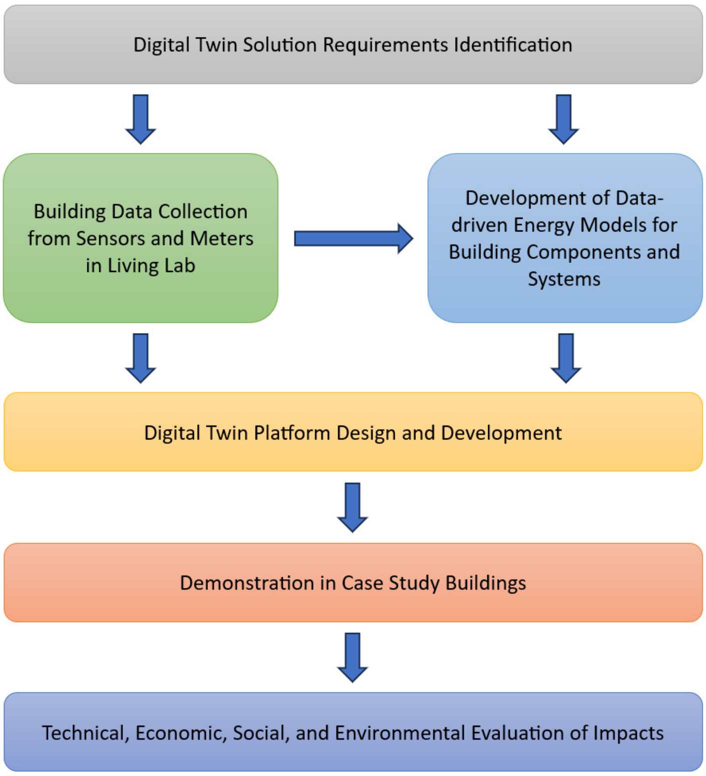

Figure 4. DanRETwin research design and process.

4.1. Overall Framework

Considering the current status of digital twin applications in the building sector as well as the current solutions developed and implemented in the market, it is noted that most of the mentioned initiatives and commercial solutions focus on newly constructed buildings and utilize Building Information Models (BIM) to develop and implement digital twins. Our current project is driven by the fact that existing buildings generally lack BIMs and are not as well-equipped as newly built ones. Therefore, we propose the innovative 'DanRETwin' digital twin solution, which will be the first of its kind, specifically designed for making informed decisions on optimal energy retrofits, retro-commissioning, and data-driven performance optimization of non-residential existing buildings. These kinds of solutions are yet to be developed and made available in the existing building sector, presenting an opportunity to create a Danish tool and platform that can not only support the scaling of Danish energy retrofit processes, but also contribute to European and global retrofit initiatives.

This initiative aligns with the Danish digital construction strategy (published in 2019), which aims to foster development and enhance digitalization in the construction industry. In this context, we propose a groundbreaking digital twin solution called 'DanRETwin'. Its purpose is to facilitate informed decision-making for optimal energy retrofits, retro-commissioning, and data-driven performance optimization of non-residential existing buildings. This project marks a pioneering Danish effort to leverage digitalization and data capabilities in order to streamline and expedite energy retrofitting projects and applications. The digital twin integrates real-time data collected from building energy meters and utilizes innovative patented clamp-on IoT sensor technology. These inputs are combined with adaptable and scalable dynamic building energy models, resulting in a robust and flexible solution.

The major differences between the current state of the art and trends in the majority of building energy retrofitting projects and the proposed DanRETwin solution for optimized retrofitting and renovation processes are shown in Figure 5. As highlighted in the figure, most of the current retrofit activities and projects are conducted based on a building-by-building approach, employing static and tabulated approaches and tools with very large assumptions and generic inputs. This hinders realizing the optimal capacity and added value of the retrofit process. In addition, retrofits are performed as a reactive approach, with changes implemented when needed based on feedback from users. This non-systematic approach to retrofitting led to large performance gaps between promised savings and actual savings after retrofits. Nevertheless, such approaches are expensive and time- and resource-consuming. To address these issues, a digital and scalable solution is proposed in this research that can be easily adapted to multiple cases and buildings with minimal adjustments. The proposed solution is based on data from different seamlessly and wirelessly connected and integrated low-cost, clamp-on IoT sensors and meters. This technology allows the users to effortlessly monitor power, flow, heating, and cooling by simply attaching sensor units to the exterior of the cables and pipes without the need for sophisticated technical expertise or system disconnection. This is attained through the implementation of advanced mathematical AI models, eliminating the need for costly and intricate hardware. Nevertheless, the data from different IoT devices are organized and used to develop robust and adaptable energy models for various systems and components. These models form a library from which various components can be selected to fit various cases and applications, allowing an effective, flexible, and efficient use of time and personnel. On top of that, an optimization approach is integrated with the digital twin solution to select the most efficient and/or cost-effective solution for modification in the specific building.

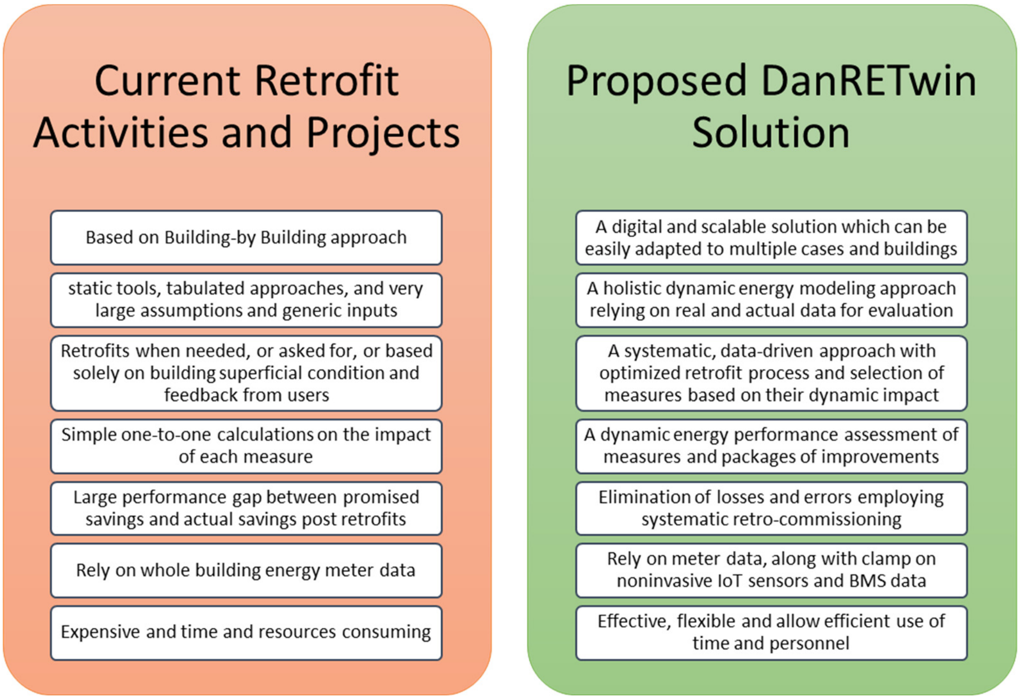

Figure 5. Major differences between the current projects and practice and the proposed DanRETwin solution.

A simplified illustration of the DanRETwin digital twin solution with the main technology components and connections is shown in Figure 6. On this basis, the proposed DanRETwin digital twin will provide the following services:

1. Building data acquisition, storage, integration, management, and exchange employing a communication-enabling ICT infrastructure preserving privacy, security, and quality. This includes data from sensors, as indoor temperature, CO_2, humidity, PIR, as well as energy meters on various levels, as heating, electricity, and water flow.
2. Energy retrofit decision-making support and the capability of testing and simulating various options, scenarios, and systems integration to optimize the selection and implementation of renovation technologies on the level of the building envelope and the energy generation and supply systems.
3. Post-retrofitting retro-commissioning of the energy systems and the automation and control system to ensure a fault-free and energy efficient restart of the building after the retrofit process and proper integration of various components and units.
4. Data-driven performance optimization platform employing advanced machine learning and artificial intelligence techniques to drive building control and management.

Furthermore, it is expected that the implementation of the proposed digital twin platform will:

- Improve the energy efficiency of existing buildings and allow around a 15% reduction in buildings' energy demand, with an average reduction of 53 kWh/(m^2.y) and energy savings up to 60% in the case of deep energy retrofitting [1].
- Provide comprehensive retro-commissioning and smarter buildings with data-based operational management and generate up to a 20% reduction in a building's maintenance and energy costs [42].
- Allow an average reduction of 18% and up to 35% for deep energy retrofits in CO_2 emissions in buildings after the retrofit process [1].

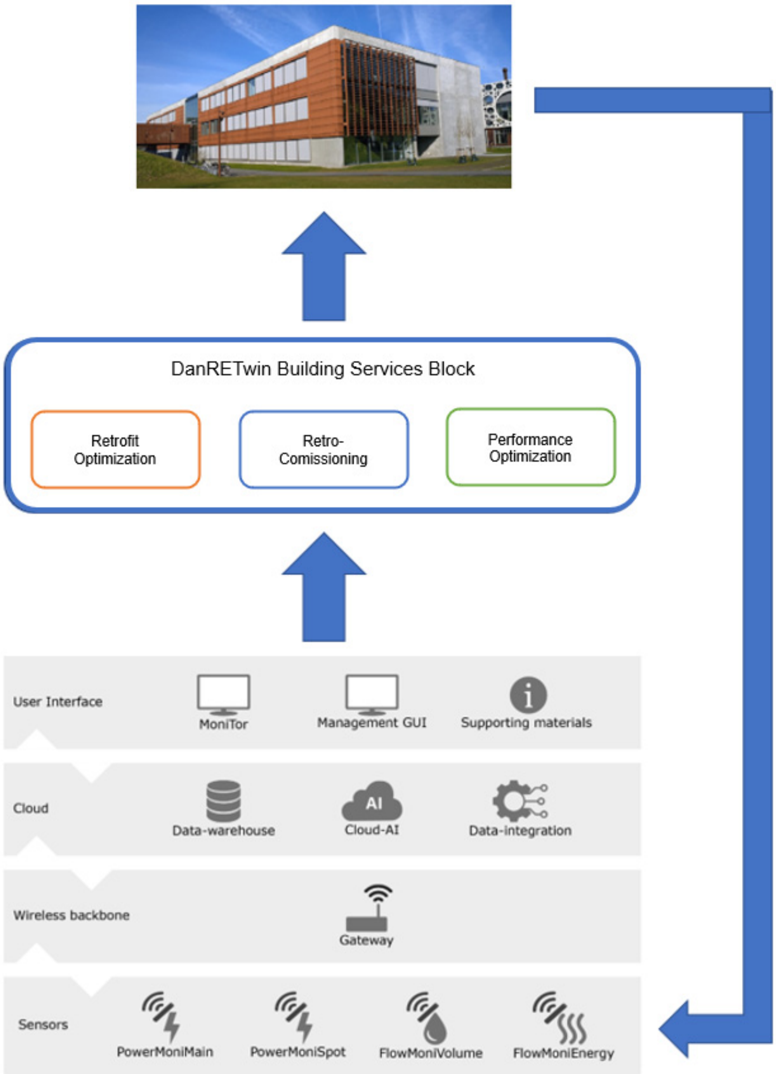

Figure 6. DanRETwin solution illustration with the main technology components and connections.

4.2. Technical Approach

4.2.1. Machine Learning-Based Data-Driven Energy Models

When it comes to renovating older buildings, particularly those that are 50 years old or older, it is often the case that we have limited knowledge about the building itself. This is mainly due to inadequate documentation from the time it was constructed or because the existing documentation was lost over the years. Consequently, renovation teams are forced to make significant assumptions, some of which may be inaccurate or unreliable. As a result, decision-making in the renovation process becomes suboptimal, leading to a significant disparity between the expected outcomes of the retrofitting project and the actual results. In order to address this challenge, data-driven black-box models emerged as a crucial factor in optimizing energy retrofits and expediting the pace and scale of these endeavors. These models rely on simple yet effective algorithms that leverage the power of advanced artificial intelligence to optimize performance indicators and identify data patterns. As a result, data-driven models gained considerable attention in recent years as the preferred modeling technique for shaping the digital future.

In recent years, machine learning (ML) emerged as a widely employed technique for constructing and supporting black-box models of building energy performance. ML refers to computer algorithms that learn from existing data, typically utilizing a large dataset and a relatively small set of input features for the learning process. These ML models function as black boxes, establishing the relationship between selected input building features and the given energy index without requiring extensive information about the building itself. These input features may not necessarily be raw building characteristics or weather data; they can be complex variables derived from basic ones, such as the wall-to-floor ratio or mean daily global radiation. Numerous studies and applications in the field of building energy increasingly utilized machine learning methods in combination with artificial intelligence techniques, particularly for optimizing building energy retrofits, resulting in demonstrated positive impacts. The choice of the ML technique for this work will depend on the specific requirements gathered from end users and feedback on their needs, which will highlight the essential inputs and outputs of the energy model. However, two prominent techniques were recently successfully employed in energy retrofitting and deep energy renovation optimization applications: artificial neural networks and the decision tree algorithm.

4.2.2. Clamp-On IoT Sensors and the ICT Communication Infrastructure

As part of the DanRETwin digital twin platform design, a cloud-based solution, developed by ReMoni, is seamlessly and wirelessly connected and integrated with low-cost, clamp-on IoT sensors and meters. The unique aspect of this technology lies in its sensor system, which allows users to effortlessly monitor power, flow, heating, and cooling by simply attaching sensor units onto cables, pipes, etc., without the need for technical expertise or system disconnection. This is achieved through the implementation of advanced mathematical AI models, eliminating the need for costly and intricate hardware. By utilizing the same IoT sensors for multiple solutions, ReMoni also established a scalable technology that offers cost advantages for individual solutions. In the context of this project, these sensors play a vital role in the developed solution and will undergo further refinement and customization to seamlessly integrate into an interoperable platform. The wireless connectivity ensures seamless two-way communication between the sensors and the internet, enabling online reconfigurations and over-the-air firmware updates. Despite sampling data every second and transmitting every 5 min, the sensors are designed to operate on low power, ensuring a long battery life of over 15 years. The solution developed by ReMoni distinguishes itself from competitors through its comprehensive clamp-on cloud AI solution, which costs only 20% of alternative offerings in the market for a fully integrated solution.

As part of the proposed solution development, a collaborative ICT communication infrastructure will be established to facilitate secure data exchange between the physical building and its digital twin, as well as with cloud systems and models. To achieve this, data acquisition and storage systems will be constructed on the foundation of an existing operational cloud infrastructure within the ReMoni ReCalc Building Energy Analytics tool. The communication infrastructure will have a crucial feature: it will enable both real-time online operation and simulations of the building, with the simulation speed typically being faster than real-time. This flexibility is essential to accommodating the specific requirements of operating a digital twin. The ICT communication infrastructure will leverage the existing ReMoni cloud platform, which provides open APIs, and will be expanded to incorporate integration with existing HVAC sensors, actuators, and other devices. All sensors can be consolidated into a single unit or device, wirelessly transmitting data through a gateway to the cloud. The cloud will host the artificial intelligence (AI) components, user interfaces, and integration with other systems, enabling scalable cloud operation and ensuring the solution's robustness.

4.2.3. AUSTRET Retro-Commissioning Service

Regarding retro-commissioning, there was a recent initiative to establish a systematic and comprehensive approach for existing buildings through the development of an innovative tool called 'AUSTRET'. This tool, previously developed by the authors [43], focuses on automated step response testing for building energy systems and automation and control systems. It assesses how specific systems respond to operational modifications and verifies their ability to achieve the desired outcomes. The tool offers the required input for configuring parameters, selecting building systems, and generating output results for each test conducted. The framework's objective is to control the ventilation, heating, and cooling of rooms, as well as the heating and cooling of water modules within a building. Figure 7 illustrates a screenshot of a heating radiator test conducted with AUSTRET. As shown in the figure, this specific test targets the room space heating system's response to the change in the heating temperature setpoint, which is changed from 17 °C to 21 °C. The test success criteria rely on the evaluated parameter, in this case the room temperature, to attain a stable occurrence with the set success bandwidth, as shown in the dotted line in the figure. The tool offers the required input for configuring parameters, selecting building systems, and generating output results for each test conducted. The framework's objective is to control the ventilation, heating, and cooling of rooms, as well as the heating and cooling of water modules within a building. In the proposed digital twin solution, certain features and services within AUSTRET will be utilized as part of the retro-commissioning framework. This will ensure that the building management system operates and integrates correctly after the retrofitting process and that energy supply systems function effectively.

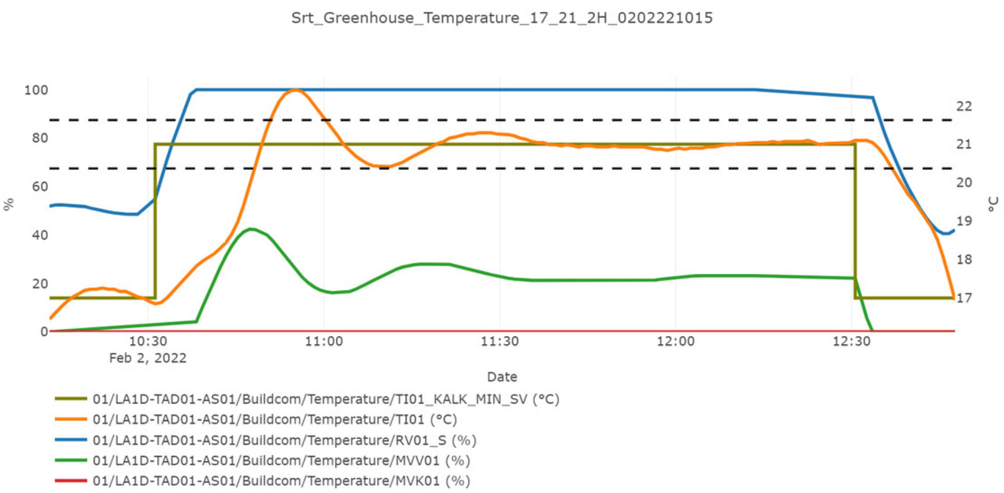

Figure 7. The step response testing results of a heating radiator system using AUSTET tool [44].

5. Conclusions

In future smart communities, buildings are required to possess energy-efficient systems, offer optimal comfort, empower occupants with information, adapt operations based on energy grid conditions, and facilitate strategic maintenance [44]. With the latest transformations and advancements in the building sector, it is anticipated that digital technologies will play a significant role, resulting in intelligent, sustainable, efficient, reliable, and interconnected buildings worldwide. The remarkable progress in the fields of data, analytics, and connectivity is enabling the emergence of various new digital smart applications and devices. Digitalization and the availability of digital information are the primary catalysts that are rapidly permeating different aspects of the building sector and the construction industry.

The majority of ongoing retrofit endeavors and activities follow a per-building strategy, utilizing static and tabulated methods and tools that rely heavily on broad assumptions and generic inputs. This approach obstructs the realization of the retrofit process's optimal potential and added value. Furthermore, retrofits are carried out in a reactive manner, where modifications are made when required based on user feedback. This lack of a systematic retrofitting approach resulted in significant disparities between the projected savings and the actual savings achieved post-retrofit. However, these methods are not only costly but also consume substantial time and resources. To tackle these challenges, this research introduces a digital and scalable solution (DanRETwin) that can be effortlessly tailored to diverse scenarios and structures with minimal adjustments. The suggested approach is founded on data gathered from an array of affordable, clamp-on IoT sensors and meters, which are seamlessly and wirelessly connected and integrated. These sensors allow users to easily monitor parameters such as power, flow, heating, and cooling by attaching sensor units externally to cables and pipes, eliminating the need for intricate technical knowledge or system disconnection. Advanced mathematical AI models are employed, rendering elaborate hardware unnecessary. The data from various IoT devices is then structured and harnessed to construct robust and adaptable energy models for different systems and components. These models constitute a repository from which a variety of components can be chosen to suit diverse scenarios and applications, enabling efficient, adaptable, and effective utilization of time and personnel. Furthermore, the solution incorporates an optimization approach into the digital twin framework to select the most efficient and cost-effective modification solutions for specific building enhancements.

The proposed solution will impact and improve energy efficiency in the building sector and provide added value throughout the entire tool chain.

1. Building owners and clients will have more energy-efficient and comfortable buildings that are optimally retrofitted and well-recommissioned, with better indoor comfort and operational performance from day one and throughout the building life cycle.
2. Facility and building managers will be able to harness DanRETwin's services of advanced monitoring and systematic retro-commissioning on their newly retrofitted buildings and facilities, allowing timely intervention in the case of failures or faults, as well as data-driven performance optimization on different building levels.
3. Designers, energy consultants, and contractors will be employing the services provided by the proposed digital twin as a potential offering to retrofit, enhance, and optimize clients' buildings performance and to inform optimal decisions.
4. City planners, authorities, building agencies, municipalities, and regions will find in the proposed digital twin platform an effective, scalable, and adaptable tool to aid energy-efficient and optimal building energy retrofit planning, design, and implementation.

The developed digital twin is to be demonstrated in multiple case study buildings, and the implementation and added value brought by the different corresponding services are to be evaluated and monitored. On this basis, a techno-economic evaluation will be carried out along with a social and environmental assessment of the digital twin implementation under various conditions and for different uses. This will help optimize future implementations and enhance the expected outcomes.

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