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Proceedings of Technical Papers

CESB25 – Central Europe towards Sustainable Building 2025

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CESB25 conference is organized under the auspices of international conveners CIB, iiSBE, UNEP-SBCI, FIDIC and GABC, and belongs to the Sustainable Built Environment regional conference series.

Editors

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Foreword

Twenty years ago, in 2005, the Czech Society for Sustainable Construction was founded and since then, six international CESB conferences have been organized as a part of a series of SBE conferences. This year's CESB25 conference is the seventh in a row and continues the tradition of conferences on sustainable building.

Twenty years is a long enough time to evaluate how the tasks leading to the sustainability of society and particularly to the sustainable construction of buildings are being met. Is this development sufficient? Is this development fast enough? What can we do to make it more efficient and faster to achieve the necessary goals?

Sustainability is about survival of humans on the Earth. According to the Intergovernmental Panel on Climate Change (IPCC), global warming needs to be kept to a maximum of 1.5 °C above pre-industrial levels. The key to this is achievement of carbon neutrality by 2050. This goal was also set by the Paris Agreement adopted at COP21 signed by 195 countries around the world.

However, in the recent summary of the 62nd Session of the IPCC organized in February 2025 is stated: *"As the planet continues to break warming records and communities around the world contend with unprecedented floods, fires, and droughts, the need for immediate and impactful action on climate change is clear. However, collective ambition to tackle climate change seems to have lost its way: in many countries, governments and corporations are backtracking on their emission reduction commitments and reinvesting in fossil fuels."*

It is necessary to continue the process of transforming the whole society towards a sustainable pattern of behavior. And it is the construction of buildings and the entire built environment that plays a key role in this process. The objectives, tasks and proposed solutions leading to sustainability should be widely discussed in an international group of experts, considering the global scale of the problem and subsequently at the regional levels. This conference CESB25 is a platform for the exchange of ideas, and its aim is to contribute to the intensive search for suitable and effective solutions.

The main conference topics are:

- Net zero-carbon buildings and district
- Sustainable and resilient urban development
- Circular economy, resilience and sustainability in building design
- Decision-support tools, assessment, and modelling for building design
- Healthy and comfortable indoor environment
- Sustainable refurbishment of cultural and industrial heritage
- Sustainability – innovative approaches, technologies and systems
- New materials and elements for sustainable buildings
- Digital building logbook technology

We would like to express our thanks to all authors for presentation of their achievements and sharing their ideas within our community. All abstracts and papers were carefully blind reviewed thanks to active participation of members of the Scientific Committee.

We also thank to the Czech Technical University in Prague, University Centre for Energy Efficient Buildings, Faculty of Civil Engineering, and international conveners iiSBE, UNEP, CIB and FIDIC for their kind support. We thank also to all supporting organizations that provided their auspices, to our media partners who helped us to spread the word, and last but not least, to our commercial partners and exhibitors.

A special thanks are addressed to all members of organizing committee, especially Martin Volf, Kateřina Sojková, Petr Hejtmánek, Rudolf Kinc, Petra Zahrádková, Tereza Valentová and Juan Chiachío for their efforts in organizing this event. All help and support were needed for successful organization of the conference and all satellite events. Without help and kind support of all these people and organizations, the CESB25 conference would not be possible.

We hope that the CESB25 conference will contribute to the enhancement of knowledge in the field of sustainable buildings and built environment, considering changing natural, as well as socio-economic situation in the world.

In Prague in August 2025

Petr Hájek
Jan Tywoniak
Antonín Lupíšek

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From Research to Practice: Utilizing GIS Models to Identify and Quantify Residential Development Opportunities in Salzburg

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Abstract. To promote sustainable development, the use of Geographic Information Systems (GIS) has become crucial. One significant application is by identifying potentials for inner development in land use planning, thereby minimizing land consumption and promoting efficient use of existing building spaces. This paper presents the successful implementation of a set of prototypical GIS models, originally developed in the Scale-Up research project , into real-world practice. In collaboration with SAGIS, Salzburg's state-run geospatial information system, the models are applied using official spatial data to analyse residential building potential. The automated analysis assesses existing building stock, evaluates the structural usability of individual parcels, and estimates the optimal utilization for residential development. This analysis is regularly updated to reflect changes in the residential land dataset, ensuring up-to-date information. The results are made accessible via web map service to Land-Invest, a state-owned company dedicated to securing and developing affordable land for residential construction. Through this collaboration, undeveloped land can be monitored and identified, thus supporting the state of Salzburg and its municipalities in the practical implementation of their spatial planning objectives.

1. Background and Introduction

Residential development in the State of Salzburg faces significant challenges such as revitalizing urban centres, ensuring affordable housing, and limiting excessive land consumption. Small and medium-sized towns struggle with declining economic activity, insufficient residential density, and inconsistent urban renewal procedures (Netsch, 2024). Meanwhile, the expansion of residential areas to remote locations with limited public transport accessibility increases land consumption, the dependence on motorized individual transport (Cadus, 2014) and raises environmental concerns. Focusing on inner development, which promotes the efficient use of existing urban spaces and infrastructure, could mitigate these issues (Rahimi, 2016; Reiß-Schmidt, 2018; Scholl, 2007). To achieve sustainable residential development, innovative planning tools and approaches are needed to balance growth with efficient land use and infrastructure planning. In this context, GIS-based methods offer valuable tools to analyse spatial structures (Ogrodnik and Kolendo, 2021), identify redevelopment potential (Cabrera-Jara, Orellana and Hermida, 2017; Eggimann et al., 2021), and support data-driven decision-making for land use planning (Bojórquez-Tapia, Diaz-Mondragón and Ezcurra, 2001).

According to the Austrian Federal Constitutional Law, the responsibilities of local spatial planning are reserved for the municipalities within their own sphere of activity. In exercising this competence, municipalities are bound by the spatial planning regulations of the state of Salzburg and are subject to supervisory controls by the Salzburg State Government, which is professionally supported by the Department of Building and Housing of the Office of the Salzburg State Government. To ensure that local development aligns with broader regional and national planning objectives while promoting sustainable and orderly growth, three key planning instruments are utilized: the Spatial Development Concept (Räumliches Entwicklungskonzept), the Land Use Plan (Flächenwidmungsplan), and the Development Plan (Bebauungsplan) (Land salzburg, 2025b). Despite these instruments, challenges remain. Development information is often fragmented, existing separately within municipalities—frequently in paper format—and is further complicated by changes over time. As a result, the Salzburg State Government lacks a unified and up-to-date dataset that provides an overview of residential development potential across the region.

To address this critical gap, the subproject, conducted as part of the broader Scale-Up project, aims to provide an automated method utilizing a set of GIS models that produces a comprehensive, standardized dataset for the estimation of construction potential in residential areas. This dataset will integrate local planning information, offering a centralized and current overview of residential development potential, enabling data-driven decisions for sustainable spatial planning. This method is designed to streamline the data update process and ensure the dataset remains current and relevant. The result dataset will be directly utilized by Land Salzburg and Land-Invest (Land Salzburg, 2025a) to effectively address current challenges in location and municipal development. Furthermore, the system is designed for integration into the Salzburg Geographical Information System (SAGIS), with the scalability to incorporate additional data sources. A key aspect of the project is jointly coordinating and defining the model's input parameters and data interface with SAGIS. In the end, a fully prepared and operational GIS model and the resulting dataset based on current data are provided to the client, ensuring its long-term utility. In this paper, we will first introduce the automated GIS analysis model, including its required input data and its conceptual framework . Next, we will present the resulting dataset and its applications for the target user groups. Finally, we will discuss the accuracy of the model and its potential for supporting sustainable spatial planning.

2. Automated GIS Analysis Model

To set the context, we first define the concept of construction potential, which is based on the difference between the optimal utilization of building density and the existing building stock. The optimal utilization of building density refers to the maximum possible gross floor area that can be mathematically realized while adhering to the local density standards and legal distance requirements. The automated model utilized this definition to identify and quantify residential development opportunities. Its framework consists of seven key parameters that follow a logical progression but are not strictly sequential (see Figure 1). These adaptable parameters are executed within sub-models and integrated into the main automated model, enabling a flexible analysis of each residential area's buildability and optimal utilization. The model requires specific input data, which was provided by the Department 7/06 – Geodata Infrastructure for the state of Salzburg in 2024. These data was delivered in ESRI File Geodatabase or Shapefile format and were directly integrated into the GIS model without further manipulation. The input data include cadastral parcels, land use areas, land registry ownership, building dimensions (Götzlich et al., 2021; Spitzer et al., 2021) and zoning data.

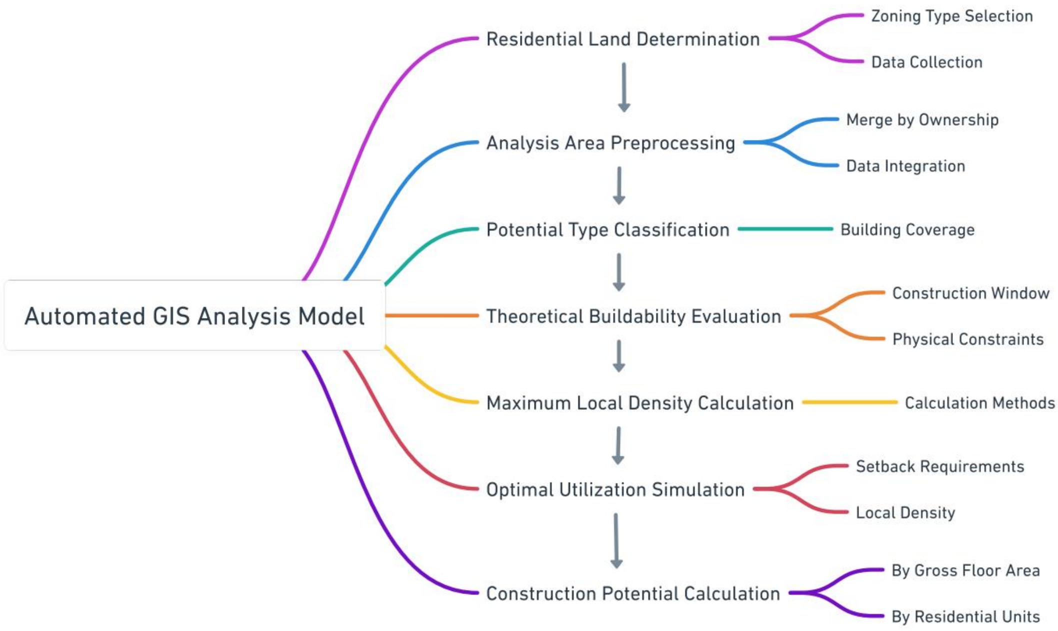

Figure 1. Mind map illustrating key parameters of the automated GIS model for identifying and quantifying residential development opportunities.

The first parameter in the model is the definition of residential land, which select the zoning types that can be used for residential development. The following classes are selected (original German abbreviations retained for accuracy): BARW (Reine Wohngebiete – Pure Residential Areas), BAEW (Erweiterte Wohngebiete – Extended Residential Areas), BAFW (Förderbarer Wohnbau – Subsidized Residential Housing), BAKG (Kerngebiete – Core Areas), BALK (Ländliche Kerngebiete – Rural Core Areas), BADG (Dorfgebiete – Village Areas), BAZG (Zweitwohnungsgebiete – Secondary Residence Areas), and VOFW (Vorbehaltsfläche für förderbarer Wohnbau – Reserved Areas for Subsidized Housing). Once this is defined, the land parcel for analysis is selected. And for a cleaner uniformed input, parcels with the same owners are merged and then intersected with the zoning plan to deduct the part that is not defined as residential land by the first parameter. Next, analysis areas are classified based on their development status and to create the corresponding data field "Potential Type". The categorization is determined by the building coverage (building footprint area) of an analysis area. Areas with a building coverage of $0m^2$ are classified as Type 1, representing undeveloped areas. Those with a building coverage greater than $0m^2$ but less than $12m^2$ are classified as Type 2, indicating areas developed only with ancillary buildings. Finally, areas with a building coverage of $12m^2$ or more are classified as Type 3, representing densification areas. This is followed by the evaluation of the theoretical buildability of the area, determining whether it is suitable for development based on the minimum requirements for size and shape to form a theoretical construction window. An analysis area is considered theoretically buildable if the area can satisfy the requirement for the statutory minimum setbacks (4 meters) from the boundaries, the minimum area size of 100m^2 and minimum width of 10 meters. The model then calculates the maximum local density of the analysis area, considering the surrounding development patterns and regulations that may influence density. Following indexes are used to represent the density: Ground Space Index, Floor Area Ratio, Cubic Index, and Ridge Height (see Table 1). For each analysis parcel, its construction density is calculated. The second-highest construction density is derived for each analysis area from the nearest surrounding eight analysis areas that have already been built on and stored as the maximum local construction density.

Table 1. Indexes Used to Represent Local Construction Density

Index	Abbreviation	Definition
Ground Space Index	GSI	The ratio of the building footprint (ground floor area) to the total plot area.
Floor Area Ratio	FAR	The ratio of the total usable floor area of all building stories to the total plot area.
Cubic Index	CI	The ratio of the total building volume (in cubic meters) to the total plot area (in square meters).
Ridge Height	RH	The maximum height of a building, typically measured from ground level to the ridge of the roof.

Using this maximum local density and applicable distance requirements, the model determines the optimal utilization of the analysis area. This parameter represents the maximum possible Gross Floor Area (GFA) for each site while ensuring compliance with setback requirements and local density standards (Spitzer et al., 2022). This process involves two main steps. First, potential building volumes are simulated by adhering to legal setback requirements (a minimum of 3/4 of the eave height, or at least 4 meters). These simulations include a range of possible volumes, considering setback distances up to 75 meters, eave heights up to 100 meters, and a maximum of 33 floors, with each floor assumed to have a height of 3 meters. To optimize model performance, smaller volumes are analysed with finer precision (1-meter increments), while larger volumes are assessed with coarser steps (5 meters). Each simulated building footprint must have a minimum width of 5 meters. This process is illustrated in Figure 2. Second, from the set of simulated volumes, the one with the highest GFA that adheres to local density limits is selected as the optimal solution. For the selected building volume, the following data fields are generated and stored in the output dataset: optimal base area (m^2), gross floor area (m^2), building mass (m^3), and ridge height (m). Finally, the model calculates the construction potential of the analysis area by subtracting the GFA of the existing building from the optimal utilization. This potential is then expressed as additional residential units, calculated by dividing the potential GFA by 85 m^2 per unit, based on the assumption of 85 m^2 per residential unit. Throughout the development of the model, all of these parameters are discussed with the SAGIS team to ensure that the analysis reflects the most accurate and current data and standards, thereby ensuring that the final output is useable and meaningful for future decision-making in land development.

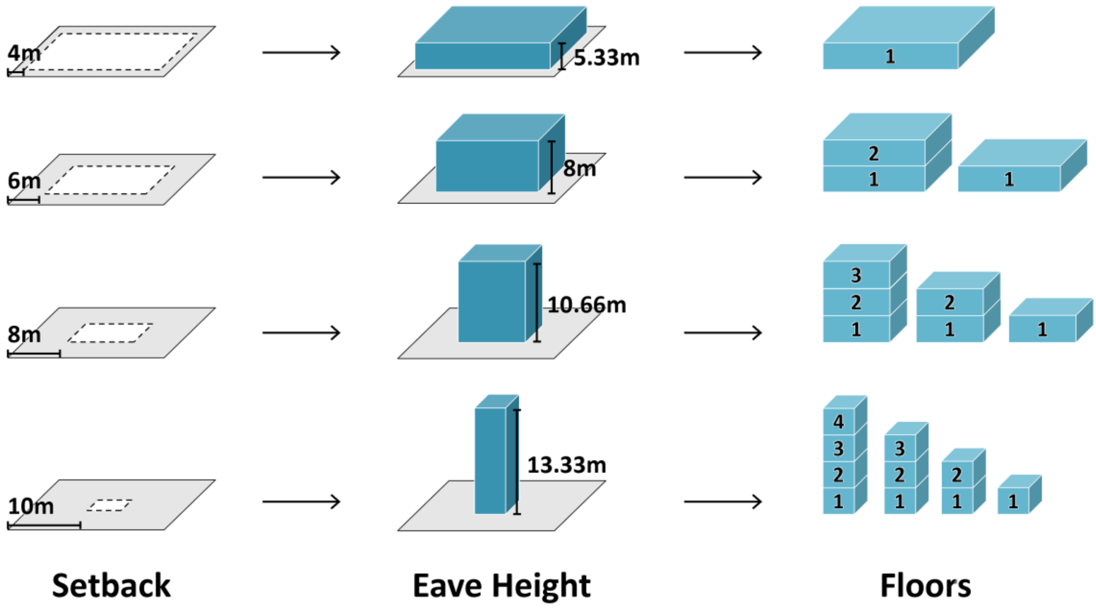

Figure 2. Illustration of how setback distances influence eave heights and the number of floors in the building volume simulation process.

3. Results and Model Handover

The automated method was developed using ArcGIS Model Builder and is stored within a toolbox. This toolbox consists of a main model and several interconnected sub-models, each representing a specific analysis step. These sub-models are integrated within the main model, allowing users to define and easily manage input data. Importantly, if updates are required, users only need to replace the input data file in the main model, streamlining the update process without the need for extensive modifications to the model itself. The analysis outputs are automatically stored in a geodatabase for efficient data management. As part of the handover process, SAGIS will export the model into Python, enabling its integration into their existing data processing workflows. The resulting output data will also be incorporated into their data portal for internal usage within the city administration departments, enhancing accessibility and decision-making capabilities.

The resulting dataset from the automated GIS model contains detailed information about each analysed residential area, structured into key fields that describe zoning classifications, ownership details, buildability, existing structures, and potential development. Each field in the dataset is designed to support comprehensive spatial planning, with clear links to the key parameters we described in the previous chapter. For existing structures, it captures metrics such as building ground area, gross floor area, building mass, building height, ground space index, floor area ratio, and cubic index. For potential development, the dataset provides metrics regarding the maximum local density and optimal usage values, including optimal building ground area, gross floor area, building mass, and building height. It also quantifies the development potential by measuring the additional gross floor area and residential units achievable beyond the existing structures. All values are calculated according to standardized models, ensuring consistency in the analysis.

The outcome of the model are also made accessible through a web map service “Construction Potential Radar”(Figure 3) tailored to non-GIS experts, such as Land-Invest —a state-owned company that plays a key role in securing and developing affordable land for residential construction. As one of the stakeholders, Land-Invest supports municipalities in achieving their spatial planning objectives while making land available for affordable housing. Acting as a land development agency, the company works to secure land through trust-based acquisitions, prepare it for development and offer it to local communities, private builders, and housing developers. In this map, residential land is classified to meet the needs of the target users. Land without construction potential is excluded, while land with potential is categorized as follows: undeveloped land, undeveloped land of 1,500 m^2 or larger (a primary focus for Land-Invest), developed land with potential to provide an additional 1–9 residential units, and developed land with potential to provide 10 or more additional residential units (another key focus for Land - Invest). Users can easily query detailed attributes of specific parcels by clicking directly on the map.

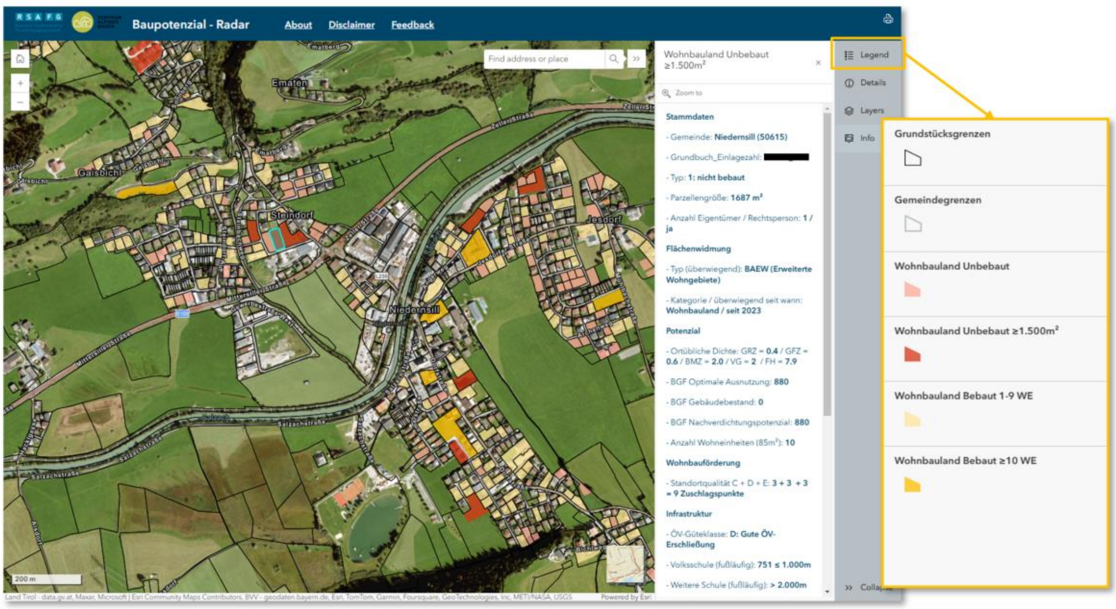

Figure 3. Web map service "Construction Potential Radar," displaying a selected developed land parcel alongside a screenshot of the legend window on the right.

4. Discussion and Conclusion

This paper presented the automated GIS model designed to produce a comprehensive and standardized dataset for estimating construction potential in residential areas. Initially designed as part of a broader research initiative, the model has been refined in collaboration with SAGIS to meet real-world requirements and is now actively utilized to support spatial planning in the state of Salzburg. And the collaboration with stakeholder such as Land-Invest highlights the practical application of research, as the web map service ensures that the results of the model are easily accessible and interpretable for non-expert stakeholders, enabling them to make informed decisions without requiring specialized GIS knowledge. This transition shows the successful application of research outcomes in addressing practical challenges. A key achievement of this project is the seamless integration of the model into SAGIS, enabling efficient incorporation into their existing workflows. By centralizing local planning information, the system provides a sustainable and adaptable solution that allows stakeholders to respond effectively to evolving needs. Its straightforward update process—enabled by simply replacing input datasets—ensures outputs remain current and relevant, reducing the resources required for maintenance and enhancing long-term usability.

Since the model is designed to provide an overall estimation of construction potential rather than precise prediction for individual parcels, some parameters are set to reflect broader spatial patterns. Given the limited availability of dataset for evaluation, assessing the model's accuracy at a detailed parcel level is challenging. Instead, the model prioritizes estimating development potential across the entire region to support strategic planning. It was developed in collaboration with planning experts and is calibrated for the entire Salzburg region, covering parcels of various types and sizes, while factors such as open space ratio (e.g., green spaces) are not considered. As a result, the identified potentials are often perceived as overestimated, as the model reflects the maximum possible building volume. Nevertheless, comparisons with selected residential developments intended for sale—where companies typically aim to maximize built volume—indicated that the model produced fairly accurate results in these cases. Future developments could focus on up-scaling the model by incorporating additional data sources where available to support diverse planning objectives across broader regions and domains, while also exploring calibration methods to enhance its applicability given the challenges in accuracy assessment.

In conclusion, this project demonstrates how collaborative efforts between research and practice can produce innovative, practical solutions. The improved GIS model provides a robust framework for identifying and quantifying residential development opportunities, ensuring its long-term utility and impact on sustainable planning in the state of Salzburg.

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Intelligent and Expandable Framework for Cost-Effective Maintenance of Photovoltaic System in Highly Dense Cities

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Abstract. The rapid expansion of photovoltaic (PV) systems necessitates effective monitoring and maintenance strategies to sustain optimal performance. This study proposes an innovative, cost-effective, and scalable framework for PV system performance monitoring and anomaly detection, capable of addressing the unique challenges of dense environments by utilizing existing data and network infrastructure. Through the comprehensive design and evaluation of various AI models, a tailored Gated Recurrent Unit (GRU) model for PV energy generation prediction was developed. The study successfully identified the key prediction timeframe, input features, and model architecture, achieving a high accuracy level with a weekly Peak Absolute Percentage Error (PAPE) of 1.93%, which is 55.27% lower than that reported in similar research. Focusing on real-life implementation, two alarm-setting approaches were reviewed to identify discrepancies in energy generation and demonstrated the capability to detect real system faults, such as inverter instability, months earlier than scheduled maintenance, resulting in significant power restoration. The framework's generalizability was validated using PV systems in Australia, demonstrating its transferability to other regions. This study lays a solid foundation for cost-effective PV system maintenance, supporting the global shift to sustainable energy.

1. Introduction

1.1 Increasing number of PV in Hong Kong

Climate change remains one of the most critical global challenges, necessitating urgent action. HK has also committed to combating climate change through its Climate Action Plan 2050 [1]. The plan sets a clear roadmap for reducing carbon emissions, one of the targets include increasing the renewable energy share around 15 times in 2050. Solar energy is expected to grow substantially. Introduced in April 2017, the Feed-in Tariff Scheme [2] allows public to sell renewable energy to power companies at premium rates, significantly increasing interest in PV installations. Furthermore, the government has actively installed additional PV systems, contributing to the growing adoption of PV technology across the region.

1.2 Need for Maintenance of PV System

PV are subjected to degradation, external damage, and other factors that can significantly impact power output. Studies have identified numerous faults in PV panels, including power degradation, corrosion, cell breakage, delamination, color changes, snail trails, and diode failure [3] [4] [5].

External factors such as shading, soiling, bird droppings, and rooftop slope can also cause defects, leading to hotspots and overheating, which may result in severe damage like fires. The IEA has reviewed a variety of internal faults that affect the I-V curve of PV panels [6]. Research indicates that over 40% of users report performance degradation, with studies estimating energy losses of around 10% [7] [8]. These findings emphasize the need for effective monitoring.

1.3 Existing Operation and Maintenance Approach in HK and problem

HK's small, distributed PV systems hinder centralized monitoring, leaving many owners unable to track performance effectively. Current systems only focus on electrical components, neglecting PV-specific metrics. Labor-intensive methods like infrared and electroluminescence imaging are rarely used, leading to undetected panel degradation and reduced output. Proprietary tools fail to address HK's unique challenges due to the geographical challenge in HK and high cost of the system. Hence, a cost-effective, tailored solutions are needed for PV systems in HK to enhance the maintenance and optimize energy output.

2. Literature of Advance Maintenance Approach

Various approaches have been proposed to address challenges in PV system performance evaluation and maintenance. A recent review categorizes these into three dimensions: Electrical Parameter Monitoring, Visual Analysis, and Power Generation Comparison.

2.1 Electrical Parameter Monitoring and Visual Analysis

Electrical parameter monitoring analyzes data to identify issues like module or connection failures. Though effective for instant problems, its high-cost limits use in smaller installations and overlooks long-term degradation. Notable study introduced a real-time predictive fault diagnosis method by analyzing Voc-Isc curves, enabling early fault detection, low-cost technology integration, and automatic disconnection to prevent severe failures [9].

2.2 Visual Analysis

Visual analysis uses image processing to detect physical PV defects, like cracks or hotspots, often missed by electrical monitoring. Thermal imaging, for instance, effectively identifies such faults. [10]. Visual analysis relies on time-consuming site visits. Advanced techniques integrate UAVs with video analytics for automated image and video analysis, addressing this limitation [4].

2.3 Power Generation Comparison

The power generation comparison method uses historical power data, weather conditions, and system specifications to estimate expected PV system output. Deviations between predicted and actual output are analyzed to assess performance. It is comparatively cost-effective and both capital and operational cost. Deep learning such as ANN and LSTM models are widely used for this purpose. ANN excel at learning complex patterns, with applications like daily power output prediction [11]. LSTM, which capture long-term dependencies in time-series data, have been applied for the prediction using clustering techniques [12] and edge-computing at city levels [13].

3. Proposed Framework

In HK, unique challenges such as high-rise buildings and partial shading require tailored solutions for accurate power estimation making it less attention. This research aims to develop a unique power generation comparison model, leveraging advanced machine learning techniques to capture complex relationships between historical data, weather conditions, and other variables.

The proposed framework detailed the steps on how to perform data preparation, model development, enhancement and evaluation, alarm threshold design. By following the step illustrated in Figure 1, a scalable, efficient, and cost-effective solution can be developed.

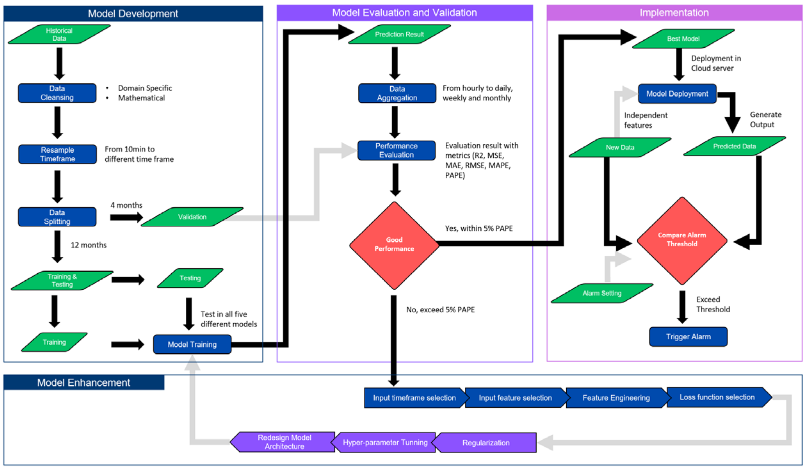

Figure 1. Proposed Framework Cost-Effective Maintenance of Photovoltaic System

4 Data for Study

4.1 Data Collection and Preprocessing

The Electrical and Mechanical Services Department in HK oversees the maintenance of government buildings. Currently, PV systems in remote and major buildings are connected to the Regional Digital Control Centre (RDCC) via existing infrastructure. With data from over 30 buildings and approximately 1,000 panels, the system will be expanded to over 140 buildings with over 5,000 panels.

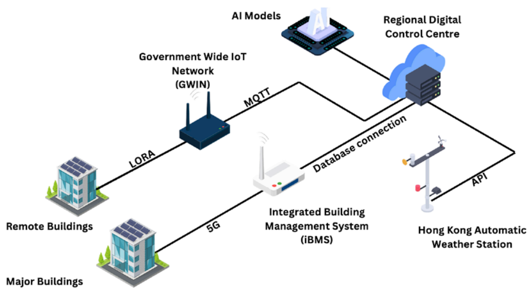

Figure 2 Existing EMSD infrastructure for Intelligent PV Maintenance System

A specific PV system was selected for detailed investigation due to its comprehensive maintenance and data availability. The system includes three strings of 10 Silicon Mono-crystaline panels, each with 19.4% module efficiency at STC and connected to inverter. The overall rated output is 9750W. Physically, the panels are arranged in four rows with a uniform tilt angle. Details are shown in Figure 3.


Figure 3. Site photo of the PV system and the related sensors

4.2 Additional public meteorological data

In addition to PV system, data, research indicates that meteorological data correlates with the energy generation. This study incorporates data from the HK Observatory (HKO) to evaluate potential improvements in model performance and possible mass deployment. There are 50 automatic weather stations in HK, with a density of 22.29 stations per km2 [14]. Overall, the data collected from the PV system is power generation and panel temperature. The weather data collected from the is rainfall, pressure, ambient temperature, wind speed and local irradiance.

4.3 Data Preparation and Exploration

Domain-specific and mathematical methods are used to identify abnormalities, with 0.2043% of the data exhibiting issues. Missing data is addressed through interpolation to maintain continuity, while abrupt zeros or spikes in time-series data are corrected. A domain-specific feature, System Efficiency, is introduced and checked against maximum panel efficiency. The dataset is normalized using Min-Max scaling. Feature distributions are analyzed, and a correlation heatmap is generated, showing solar irradiation as the most influential factor on power output, with a correlation coefficient of 0.98 which aligns with previous studies [15].

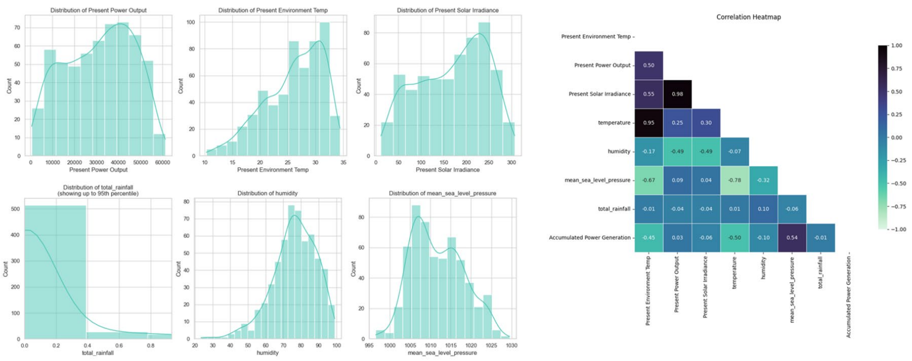

Figure 4. Scatter Plot and Correlation Heatmap of power output with other data

5 Model Development

5. 1 Baseline Model and Selection of model for development

The baseline model for comparison is based on a recent research study [16]. This model utilizes weather data through a deep learning approach known as the Hybrid Model of Recurrent and Shallow Neural Networks. This baseline model achieved an MSE of 0.03, MAE of 0.09, and an R^2 of 0.96 which will be served as base line model for comparison in later session. To better align with real-world applications, a additional metric, PAPE, was introduced.

Five models commonly used in time-related forecasting are selected for further development. Random Forest (RF) handles high-dimensional data, captures non-linear relationships, and provides feature importance rankings [17]. Gradient Boosting (GB) reduces bias and variance, achieving high predictive accuracy for complex datasets [18]. Long Short-Term Memory (LSTM) [19] and GRU [20], both types of recurrent neural networks, are effective for capturing temporal dependencies, with GRU offering a more efficient structure. Artificial Neural Networks (ANN) excel at learning complex patterns through their hierarchical structure [21].

5.2 Data for the study and Selection of Prediction Time Frame

The study utilized 12 months of historical data (April 22 to April 23), split into 80% for training and 20% for testing. Additionally, 4 months of unseen data were reserved for independent validation, and 2 months were set aside for real-life application testing. Model predictions were compared with actual daily, weekly, and monthly power generation metrics.

The analysis of the data time frame aimed to determine the optimal duration for generating alarms and the minimum sensor sampling frequency. The original dataset, collected at 1-minute intervals, was resampled at 10-minute, 1-hour, and 1-day intervals. During the training stage, the 10-minute interval outperformed the 1-hour interval in R^2, MSE, and MAE by 0.21%, 14.01%, and 6.26%, respectively. However, in the validation stage, the 1-hour interval significantly outperformed the 10-minute interval, improving R^2, MSE, and MAE by 4.12%, 34.20%, and 1.05%, respectively, suggesting the finer granularity caused overfitting. The 1-day interval performed the worst, as its low temporal granularity hindered the model's ability to capture short-term fluctuations.

5.3 Feature Engineering and Selection

Feature engineering and selection were employed to enhance model performance by identifying the most influential input features. Over ten combinations of input features were systematically tested to benchmark performance on unseen data. The optimal combination, local solar irradiation and regional rainfall data, improved performance by 5.56% compared to solar irradiation alone and by 42.91% compared to the combination of solar irradiation and panel temperature. This finding challenges the assumption that solar irradiation and panel temperature are the most critical variables, likely due to the inability of a single reference sensor to represent all panel conditions, whereas regional rainfall captures broader environmental factors. Additionally, the feature selection process improved predictive accuracy while reducing computational demands, enhancing the model's practicality for real-world implementation.

Table 1. Performance result of different combination of features

Rank	Local Data		Regional Data					Average weekly MAPE (%)
	Temp	Irrad.	Rainfall	Temp.	Humid.	Press.	Irrad.	
1		o	o					7.65
2		o						8.10
3	o	o						13.40
4	o	o	o	o	o	o	o	13.75

Remarks: Selected 4 out of 10 combinations are shown. The worst performing is using all the regional data except irradiance.

5.4 Loss Function

MSE is ideal for minimizing significant deviations, as it penalizes large errors more heavily. MAE is robust to outliers, treating all errors uniformly, and is better suited for tasks where absolute differences. Two additional loss functions were proposed. Peak Absolute Percentage Error (PAPE), the exact metric used for validation, and a tailored loss function. Based on the results in the following table, MAE demonstrated more consistent and superior performance in terms of Weekly PAPE across all five models and is therefore recommended for adoption.

Table 2. Performance result of different Loss Functions

Loss Function	Weekly PAPE (%)					
	RF	GB	LSTM	ANN	GRU	Average
MSE	11.26	10.66	10.61	10.37	8.93	10.36
MAE	11.26	10.66	7.40	6.06	6.42	8.36
PAPE	22.49	19.16	16.56	14.85	31.05	20.82
0.4xMSE + 0.3xMAE+0.3xPAPE	22.49	19.16	20.73	37.87	39.87	28.02

5.5 Regularization

Deep learning models are susceptible to overfitting. Regularization was applied to enhance generalization and preserve accuracy. The analysis showed varying degrees of improvement across models, with L1 and L2 significantly boosting performance in the ANN and GRU models during validation, achieving improvements of 57.35% and 61.78%, respectively. The findings confirm that properly regularization improves model performance and should be implemented.

Table 3. Performance result of different regularizer and value setting

Regularizer	Value	Weekly PAPE (%)		
		LSTM	ANN	GRU
None	-	7.40	6.05	6.41
L1	0.01	7.91	2.59	9.68
L2	0.01	7.91	2.58	3.59
L1 & L2	0.1	99.24	99.12	99.12
L1 & L2	0.01	10.97	5.22	2.45

5.6 Result of Hyperparameter Tuning and other improvement

Optuna and Random search were employed for ML and DL models respectively. The tuning systematically explored combinations of optimal configuration, such as units, dropout rates, and regularizers. Notably, the tuning resulted in significant reductions in weekly PAPE for the DL models: GRU (3.09%), ANN (4.47%), and LSTM (3.26%) compared to their untuned versions.

Among the models, GRU performed best achieving the weekly PAPE of 3.09% which is sufficient for practical use. Further enhancements, such as adding hour and season features, adjusting input sequences, and applying temporal K-fold, showed no performance improvement. However, modifying the GRU structure and filtering data with solar irradiance below 3 W/m^2 significantly improved results. The final GRU model achieved remarkably low errors, with a weekly MAPE of 1.02% and a PAPE of 1.93%. This result also outperforms the R^2 of the baseline model by 3.9%. Additionally, when compared to other similar study [22] with a relative error of 4.316%, this model further reduced the error by 55.28%, showing significant improvement.

6 Implementation in real life

Two approaches to alarm setting are being reviewed. The first approach is to use the weekly PAPE as a reference and include an offset of 50% as safety margin and setting is ±2.78%. This approach is simple but has some delay in generating the alarm, especially when the fault occurs in the middle of late of the weekly window. Another more systematic approach is to offset from the 25th and 75th percentiles and the settings are -1.26% and +2.96%. These settings were tested on unseen 2-month data, including a control fault case with the loss of output from 1 panel on November 2. The 1st approach triggered an alarm on November 12, one week after the fault, while the 2nd approach trigged the alarm on within same week. The results confirm the model's effectiveness in predicting PV power output. Its practicality was validated by detecting a real-world fault, proving its value for PV system monitoring and diagnostics.

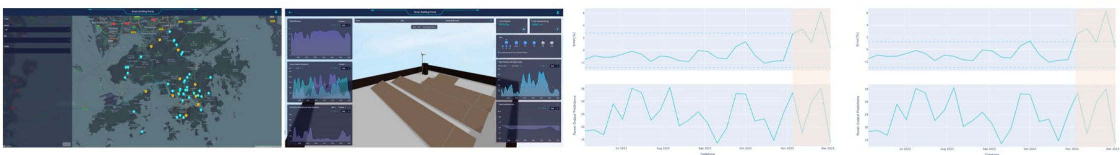

Figure 5. Deployed PV monitoring system and alarm generation from the two approaches

7 Generalizability to other PV systems

Further studies were conducted to test the framework on PV systems with different climates to check the generalizability. Data from three PV plants in Austria were analyzed [23], and the results showed a very similar level of accuracy, as summarized in the table below. The system successfully triggered an alarm at Site 12 upon detecting an intermittent inverter issue requiring replacement. This detection occurred five months earlier than the scheduled annual maintenance, resulting in a possible 13.74% power restoration.

Table 4. Parameter and Data Collection of the selected Site

Weekly Metrics	Site 12	Site 31	Site 37
MAPE(%)	2.02	1.80	1.72
PAPE (%)	3.53	4.20	3.09

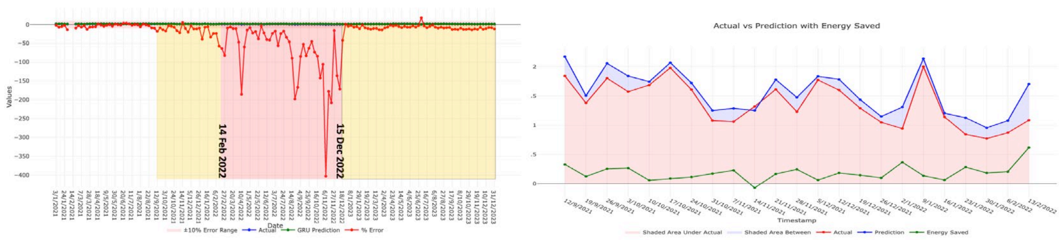

Figure 6. Actual and Predicted Energy output of PV system and the possible energy saving

8. Conclusion

This study presents a robust framework for monitoring and maintaining PV system performance, addressing challenges in decentralized urban PV systems like those in HK. Leveraging existing infrastructure and GRU-based machine learning, it enables timely fault detection and reduces energy losses. Alarm-setting methods enhance proactive maintenance and reliability. Real-world tests demonstrated its effectiveness, detecting inverter faults five months earlier than scheduled maintenance. Its transferability was validated with high accuracy across diverse infrastructures and climates, including Austria. Scalable and cost-effective, the framework optimizes green energy production and supports global carbon neutrality efforts, offering a practical solution for improving PV system operations worldwide.

8. 1 Limitation and Future Work

The model encounters challenges in accurately predicting PV system performance without local solar irradiation sensors, a common limitation in cost-constrained residential systems. Future work will address this through two approaches. The first involves developing a compact, cost-effective device that integrates the algorithm directly into PV systems, enabling broader accessibility and improved usability. The second focuses on incorporating external regional weather data to estimate localized conditions, enhancing accuracy in the absence of direct sensor measurements. These efforts aim to improve the model's adaptability and precision, expanding its applicability to a wider range of PV systems.

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Piloting of new EE Services in the Czech Republic

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Abstract. The energy sector is currently undergoing structural changes due to the running decarbonisation of energy production, decentralising energy sources and achieving climate neutrality by 2050, reflected in national and European initiatives such as the Green Deal and Fit-for-55. These trends require innovative approaches to Energy Efficiency and the integration of advanced technologies and energy systems in buildings, including electricity generation, energy storage, sharing and real-time demand response within the distribution network, including e-mobility services. This paper aims at introducing solutions for development of the integrated package of new smart Energy Efficiency Services and its key aspects. We use methods as a Business Model canvas and validation through the pilot installations, as a set of recommended technology solutions and a business model for future energy efficiency services. Our activities will lead to creation of a comprehensive solution for the market players that facilitates the integration of various technologies for electricity use, heating and cooling, focusing primarily on single family and residential buildings. Finally, the text addresses the identification of both market and technical barriers that currently limit the full development potential of EES. It highlights analytical options for efficient energy management in buildings and proposing methods to reward and financially incentivise prosumers. The text presents current findings from the Czech pilot project, which serve as a basis for assessing the practical implementation of smart energy services and identifying necessary modifications to the Smart EES model. These modifications are essential to ensure compatibility with real-world conditions, user behaviour, and infrastructure limitations. The results confirm that, despite existing challenges, energy flexibility is a key instrument for optimising the use of available energy. It holds substantial potential to support the integration of renewable energy sources and to contribute to the broader objectives of decarbonisation and decentralisation of energy production.

1. The Basics of Decarbonization and Climate Neutrality in Europe

The European energy sector is undergoing a fundamental transformation driven by the goals of decarbonization, decentralization, and achieving climate neutrality by 2050. These ambitions are enshrined in key European Union strategies, such as the European Green Deal [1] and the Fit-for-55 package [2], which set the framework for legislative measures and innovations in energy efficiency. The Czech Republic reflects these goals in its national strategies, such as the National Energy and Climate Plan [3] and in legislative changes, such as the amendment to the Energy

Management Act [4], [5], which implements the requirements of the revised Energy Efficiency Directive [6] and the Renewable Energy Directive [7].

1.1 Context and Importance of New Energy Services
The growing share of renewable sources [8], the development of energy communities [9], and the digitalization of networks require new approaches to Smart Energy Services. These services include the integration of electricity generation, energy storage, real-time demand sharing, and management. A significant role in this area is played by flexibility services [10]. which enable the optimization of consumption and production of energy in buildings and strengthen the stability and resilience of the electricity distribution system [11].

Supporting the prosumer model, which involves active consumers engaged in energy production, requires not only technical innovations but also suitable economic and legislative conditions, such as reward mechanisms for providing flexibility, storage or sharing [12] surplus energy. Existing analyses confirm that smart energy services contribute to more efficient use of renewable resources and decarbonization, thereby supporting sustainable development and the stability of the European energy system [13]. BungEES also builds on the market expertise and technical capabilities of its project partner Voltalis, which operates and manages over 1,500,000 devices for flexible energy management across France.

1.2 The Need and Development of Energy Flexibility
As the use of renewable energy sources (RES) increases, the instability of energy production also rises. Fluctuations in production may lead to a mismatch between energy supply and demand [14], which may result in overloading or underutilization of the electrical grid. This threatens the reliability of energy systems [15], will possibly lead to power outages, and ultimately disrupts the daily lives of individuals as well as the operations of businesses. Therefore, stable and predictable energy production is crucial for ensuring the efficient and sustainable functioning of modern society and is necessary for achieving the established goals of the European Union [16].

2. Goals of New Energy Efficient Services

The new model of energy-efficient services being developed within the BungEES LIFE project focuses on supporting European goals through the advancement of services in energy efficiency, energy flexibility, and the promotion of renewable energy sources.

The aim is to develop and validate smart energy services through pilot projects that will enable the optimization of energy production and consumption in real-time, while also ensuring user needs, thermal comfort, and a healthy indoor environment. At the same time, the development of energy storage technologies will be supported to help balance fluctuations in renewable energy production.

The service model being created will be based on customizable service packages that will be provided according to customer preferences and the technical and technological capabilities of the specific facility. This division into packages will allow for a more comprehensive coverage of needs, greater variability, and the ability to respond to different conditions in individual countries.

3. Methods Used for the Development of the new EES Model

3.1 Application of the Business Model Canvas and Service Model Canvas
The principle of the Business Model Canvas (BMC) [17] was utilized in the development of the EE service model as a strategic management tool that serves as a visual framework for describing,

analysing, and designing business models. As a strategic management framework, the BMC enables the systematic representation and analysis of core business architecture elements, including value propositions, customer segments, key activities, resources, and revenue mechanisms.

In the process of creating the model, the BMC was used to identify and analyse the key elements of the Smart EES business model. This allowed for mapping how the individual components relate to each other and how they contribute to the overall strategy. The visual nature of the BMC facilitates communication and collaboration among team members, stakeholders, and investors, which is particularly important during the development and implementation of new services. Additionally, the BMC fosters creativity and innovation by enabling entrepreneurs to explore new ideas and experiment with different business models. This was reached via focus group meetings of the expert team of six countries and via collection of business cases available. The focus group consisted of aggregator, DSO, ESCOs and energy efficiency experts.

This framework has proven to be a valuable tool for strategic decision-making and innovation in business models, contributing to the overall assessment and design of Smart EES services.

3.2 Pilot Projects and Validation of the Proposed Model

To validate the proposed service model, pilot projects have been launched in the Czech Republic, Spain, and Portugal. These pilots aim to test the applicability of the selected technologies, verify their performance under local conditions, and collect data necessary for tailoring and refining the model to fit the specific needs of each market. The pilot activities focus on:

- Verifying the technical and operational suitability of proposed technologies and procedures.
- Identifying potential barriers to real-world deployment of energy efficiency services.
- Analysing end-user behaviour and willingness to engage with new service models.
- Assessing the impact of different regulatory and market environments across participating countries.

Emphasis is placed on understanding user preferences and behavioural patterns, as this insight is essential for scaling services effectively and ensuring broader adoption of energy flexibility solutions. Pilot sites were selected to match the typology of the residential building stock and the technologies in use, with the goal of maximizing the relevance and replicability of results. This approach allows for a comprehensive assessment of energy flexibility scenarios and supports the development of scalable and transferable service models.

The Czech pilot project is currently in its initial phase. Preliminary findings are included in this report, while final results and comprehensive data are expected in the second half of 2025.

4. Model of the New Smart Energy-Efficient Service

The Energy Efficiency Service (EES) model was chosen based on an aggregator approach, due to the potential to create an entity that would consolidate flexibility and energy savings from various customers while also acting as an intermediary between end users and the energy market or energy system operators. One of the main goals is to optimize energy consumption management so that customers can benefit from savings while also providing a service for grid stabilization or reducing peak demand for energy.

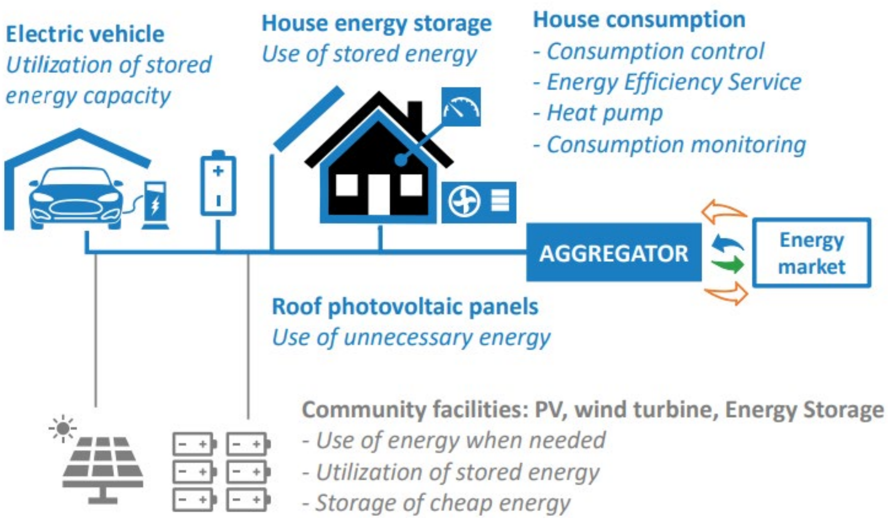

Figure 1. Diagram of the new energy efficiency service model being developed in the BungEES project.

The aggregator, as a key player in the energy sector, communicates with various entities that play an important role in ensuring the stability and efficiency of the energy market. This communication occurs at multiple levels and involves different types of entities that contribute to the overall functioning of the energy ecosystem.

4.1 EES packages and integrated services

Since it is not possible to meet the needs of a wide range of customers with a single fixed offering—each having specific requirements for consumption, production, and flexibility, as well as offering different options for energy flexibility—it was decided to create a system of energy service packages. This system allows customers to assemble a group of services according to their own needs and preferences, thereby ensuring optimal utilization of their flexibility while maximizing benefits for the entire energy system.

The modular structure of the service packages enables customization based on user profiles, building types, and available technologies. Each package may include services such as energy monitoring and analytics, demand response participation, energy storage integration, or self-consumption optimization. The system design supports both individual household use and aggregated services for multi-unit buildings or community energy systems.

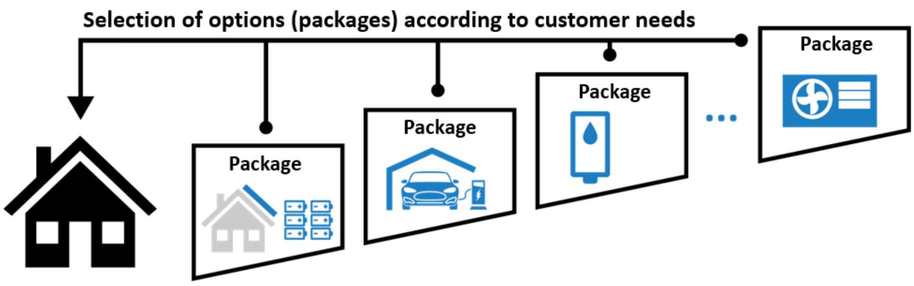

Figure 2. Scheme of EES service packages

An individualized approach is essential, as customer capabilities vary. Households may manage appliances, while large enterprises can regulate full operations. Flexible service packages allow customers to start small and expand as needed, integrating new technologies like EVs. Each user sets their flexibility level to balance comfort and savings. The service offering ranges from technology sales and installation to full operation, covering a broad spectrum of needs.

5. Czech Pilot Project

As part of the BungEES project, three pilot projects have been launched. The pilot project focuses on verifying the use of technologies that are commonly utilized in Czech households, with the aim of ensuring easy replicability of findings in other projects and offered services. The selection of technologies reflects the needs of the Czech market and the technical limitations of typical installations. The following technologies have been included in the pilot project:

- Heat Pumps – One of the key elements in modernizing heating systems with a high potential for energy savings. In the Czech environment, subsidy programs for replacing old heat sources with heat pumps are regularly announced;
- Water Heaters;
- Storage Stoves.

Unlike the pilot projects implemented in other European countries, air conditioning systems were not tested in the Czech Republic. This decision is based on the lower usage of these devices in Czech households and the limited potential for broader application within energy flexible services.

The selection of suitable locations and communication with property owners took place from August to December 2024. The pilot installations were carried out in Prague and its surroundings, where there is a high concentration of residential buildings and suitable technical conditions.

- Total number of contacted owners/institutions: 10+;
- Declined participation: only 1 owner;
- Currently implemented installations: 5.

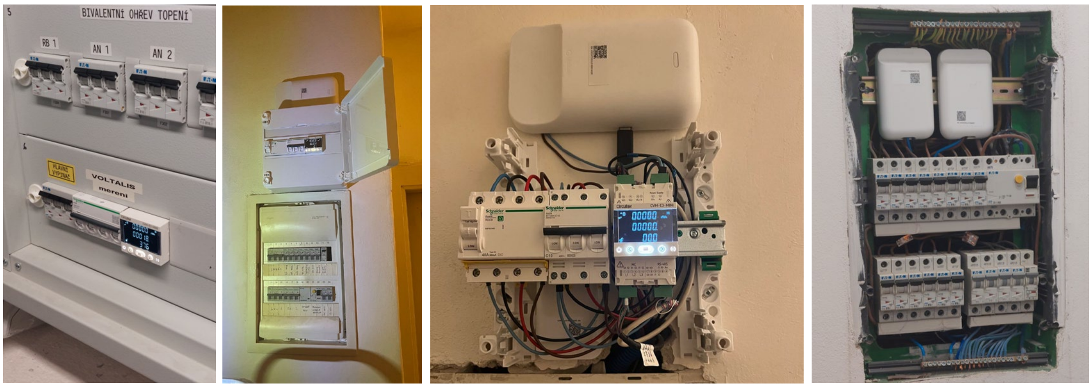

Figure 3. Examples of electrical distribution cabinets; installation of Voltalis units

The implementation is taking place throughout February 2025. During the installation, very important data and new insights are being collected for model adjustments. The final evaluation of the data will occur between April and May 2025. The pilot project had to consider several technical limitations that influenced the selection of sites and the feasibility of installations:

- Minimum power consumption of appliances above 1 kW;

- Requirement for three-wire electrical installations;
- Availability of electrical installation diagrams and spatial constraints for equipment placement;
- Design and implementation of a new distribution board for each site.

The pilot project was carried out in five buildings in different types: 2 single-family houses; 2 apartment buildings; and 1 hotel.

5.2 Key Activities and Expected Outcomes

The pilot project includes functional installations at several locations in the Czech Republic, which allow the testing and optimization of smart energy services. Key activities focus on the implementation of modern technologies for measuring, managing, and monitoring energy consumption, ensuring the efficient use of installed devices and providing users with greater control over their consumption.

The project includes the installation of smart metering with remote communication via GSM technology, which enables detailed real-time monitoring of energy consumption and ensure data transmission for remote control of devices. The pilot installations tests the possibility of remotely switching appliances on and off, allowing for their automatic or manual control from a distance. This opens up opportunities for optimizing consumption based on dynamic electricity prices or the availability of renewable resources.

In addition to appliance management, the project includes remote monitoring of consumption, allowing for detailed analysis of the energy usage of individual devices and their impact on the overall energy balance of the building. Users receives alerts about inefficient energy use or unusual consumption patterns.

A key tool for user interaction is a mobile and web application that offers access to detailed consumption data and optimization options. The application allows users to set preferences and automated control scenarios for appliances, thereby encouraging active user engagement in managing their own consumption.

The project validates technologies and the business model in real world conditions, enabling the assessment of the effectiveness of implementing smart energy services in the real conditions of the Czech market. It contributes to increasing consumption flexibility by testing management options with regard to cost optimization and reducing peak loads on the distribution network. An important aspect is the involvement of users in actively managing their consumption, enabling them to monitor and adjust their energy usage through digital tools. The pilot installations also help identify technical and regulatory barriers that could affect the broader implementation of similar services and lay the groundwork for scaling to other locations and customer segments.

6. Experiences from the Pilot Project

The Czech pilot project has already identified some partial data that can be interpreted and used to draw conclusions, recommendations and requirements for modifying the model. The experience from the pilot also provides a deeper understanding of the real conditions in residential environments, including limitations in infrastructure, variability in installed technologies, and behavioural aspects influencing demand-side flexibility. The following subsections summarize key observations made during the early stages of the Czech pilot project. These findings are critical for informing adjustments to the service model and technical specifications, and for identifying which household technologies show the greatest potential for integration into flexibility schemes.

6.1 Technical Constraints in Existing Electrical Infrastructure - Lack of Space in the Switchboard
During the initial surveys, it became clear that many switchboards are utilized to their maximum capacity, significantly limiting the possibility of integrating additional devices needed for energy consumption management. It can be assumed that this problem will be particularly pronounced in older family homes and apartment units, where the distribution boards were not designed to accommodate the additional space requirements brought about by smart technologies. Therefore, construction modifications are necessary to ensure the expansion of the distribution cabinet or to make it usable.

6.2 Challenges with Smart Heat Pumps
The majority of heat pump installations in the Czech Republic have occurred within the last two decades, meaning they often involve modern units equipped with advanced control systems. While this increases heating efficiency, it simultaneously complicates their integration into pilot projects focused on flexible consumption management. Older, less "intelligent" units are better suited for testing various control strategies. Modulations may also influence lifespan of heat pumps as it increasing number of on-off cycles. Therefore, it is useful reduce number of modulations.

6.3 High Flexibility Potential of Boilers for Water Heating
Unlike heat pumps, electric or gas boilers are a widely used technology in the Czech Republic, making them ideal candidates for controlled consumption and optimization of electricity use. Properly managed water heaters can contribute not only to energy savings but also to increased utilization of electricity from renewable sources if their operation is adapted to the needs of the electrical grid and current supply.

6.4 User Behaviour and Well-Balanced Heating
One of the unexpected findings was that some users already have their heating systems very well set up and optimize their consumption. This factor significantly reduces the potential for further energy savings and limits the use of smart consumption management systems. This indicates varying levels of household readiness for the implementation of smart energy services – while some households may benefit from automation, others have already achieved high efficiency through self-help. A solution may be to focus on differentiated management strategies, where technology is adapted to the individual needs of households. It is also advisable to consider connections with other aspects of flexibility, such as demand management in combination with photovoltaics or battery storage.

6.5 User Acceptance of new technologies
As demonstrated by the pilot projects, the success of energy flexibility services in the residential sector also depends on users' attitudes and their willingness to adopt and actively engage with these services. The initial phase of the pilot revealed several key factors that influence the level of acceptance among households. Users primarily expect financial savings or tangible benefits for the household, such as improved comfort or the use of renewable energy sources. At the same time, there are concerns about disruptions to daily routines—particularly the loss of control over heating systems, often associated with the fear of reduced thermal comfort.

However, users also recognize the benefits of modern technologies, particularly in terms of automation and reduced need for manual intervention. This suggests that end-users welcome smart systems, but they also prefer to maintain a certain level of control over their operation. To build trust, it is essential to provide ongoing information about how the system functions, including a clear and user-friendly interface and notifications that help users stay informed and engaged.

6.6 Additional Challenges and Obstacles

In the Czech Republic, there is a considerable delay in the development of legislation. The implementation of the legal framework for accumulation, aggregation, and flexibility should have been completed in 2021. However, the process has only recently moved forward, partly under pressure from the European Union, which threatened to cut subsidies from the modernization fund if the measures were not implemented by the end of 2024. The amendment to the Energy Act, lex RES III, introduces the concepts of accumulation, aggregation, and flexibility into Czech legislation [18].

Insufficient capacity of the distribution network: The current infrastructure is not ready to integrate a larger share of renewables and flexible services. Connection applicants often face limited grid capacity, which limits the possibilities for developing energy flexibility.

The current infrastructure has limited capacity to adapt quickly to changes in renewable energy supply, which is variable and weather dependent. Many parts of the grid were not designed to cope with the high share of decentralised sources such as solar or wind. This causes problems with congestion and ensuring grid stability.

Projects to upgrade or extend the distribution network often take several years to be approved, delaying the implementation of the necessary modifications. Despite the existence of support programmes, the scale of investment in infrastructure remains below what is needed [19]. In some regions of the country (e.g. South Moravia or South Bohemia) a "stop condition" has been declared for the connection of new renewable energy sources because the distribution network is not able to handle the additional generation. The process of connecting new installations, such as photovoltaic plants, is often very lengthy.

7. Current Results and Potential from the Czech Pilot Data

The pilot implementation in the Czech Republic has demonstrated strong technical performance. Activation data confirm high operational stability, with clean switching, no rebound effects, and consistent system response. These outcomes indicate the technical reliability and readiness of the solution for real-world deployment. The vertical axis shows the relative consumption and horizontal axis shows 5-minute intervals as columns. Blue columns correspond to normal operation and red columns correspond to modulated state (switched off mode).

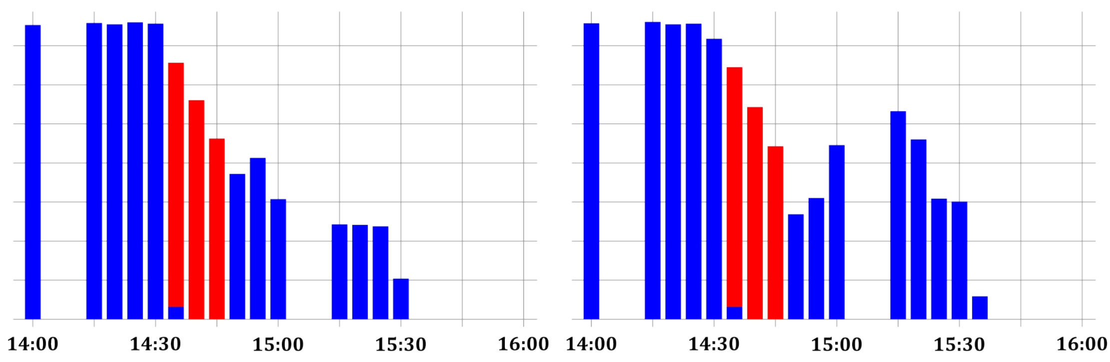

Figure 4. Example modulation for an IR AC

However, the Czech energy market presents several contextual challenges that affect the broader applicability of flexibility services. A considerable portion of households remains connected to existing HDO (ripple control) systems operated by electricity providers. This legacy infrastructure reduces the perceived added value of alternative flexibility technologies and may limit user willingness to adopt new solutions.

Additionally, due to limited awareness of the advanced functionalities of the tested system, restrictions were placed on modulation scenarios during the pilot. These limitations reduced the opportunity to demonstrate the full flexibility potential of the solution, particularly in terms of responsiveness and frequency of activation.

Table 1. Most representative Winter Day – Energy Consumption [kWh/day]

Column heading	Scenario 1	Scenario 2
Total - Day	172.0	142.0
Winter / Heating season		
Total HP consumption [kWh]	14,222.1	11,889.3

Based on the data collected in Spain—where the volume and frequency of activations were higher—it is also possible to estimate the energy savings potential. Under Scenario 2, which involves controlled switching of the ventilation and heating system, savings of up to 16% on heating-related electricity consumption during the winter months were recorded when compared to Scenario 1, representing the current baseline without active flexibility control. These findings underline the added value that demand-side flexibility can bring, both in terms of cost savings for end users and in contributing to the overall efficiency and stability of the energy system.

8. Conclusion

The introduction of new energy services represents a highly complex process, characterized by a wide spectrum of possible solutions and considerable contextual variability. The use of the Business Model Canvas, combined with the collection and analysis of current business cases, has proven to be an effective methodology for identifying country-specific solutions and tailoring service designs to national conditions. The suitability and design of energy service packages depend on multiple factors, including climatic conditions, the regulatory environment, market maturity and user experience with various technologies and technical specifics for each technology and each device.

Integration of energy flexibility into the service package opens new opportunities for both service providers and end-users. However, technical implementation is far from straightforward. Even the installation of the gateway requires skilled professionals due to non-standardized systems and varying technical setups. Operating flexibility depends on high number of data not only collected vi network, we have to collect also data from the household such as indoor temperature or data on thermal stability of the building.

Nationally we found number of legal obstacles such missing regulation for independent aggregators and slow development of smart metering in the Czech Republic. In case of fostering of the legislation. the number of services offered would increase significantly, because increased energy prices increase potential for new energy efficiency services.

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Sustainability – innovative approaches, technologies and systems

Modelling Urban Transformation: A 3D Visualization Tool for Development Scenarios in Salzburg's Schallmoos

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Abstract. Sustainable spatial development with affordable housing is a major challenge for the future of Central European cities like Salzburg, requiring urban spaces to be designed with both complexity and resilience in mind. This paper, set within the context of the "Trans|formator:in" research project—which aims to accelerate and optimize the redesign of public spaces to encourage active mobility and thus improve the quality of urban life—explores strategies for promoting diverse, people-centred spatial uses, contributing to sustainable urban development. Among this project's seven pilot regions, the Schallmoos district in Salzburg faces significant challenges, including segregated residential and commercial areas, high car dependency and large commuter population. However, Schallmoos offers substantial potential for restructuring and revitalization. To support the redesign process, this paper presents a 3D visualization web tool to model various development scenarios, including the design of axis for active mobility within the district serving as transport corridors. This innovative tool utilizes geoinformation to simulate and visualize different urban development scenarios, including the current situation, two theoretical densification models and a mixed-use scenario proposed by urban planners. It also offers statistics on housing and employment space metrics at the block level, enabling urban planners, decision-makers and stakeholders to effectively evaluate and refine the planning models. The tool is designed to assist in creating a space- and traffic-efficient spatial utilization plan that integrates urban planning, design and social considerations, contributing to the project's broader goal of fostering sustainable mobility and urban transformation.

1. Introduction

Urban transformation refers to the process of reshaping urban areas to meet the evolving societal, environmental and economic demands. A successful transformation often integrates diverse, people-centred mixed spatial uses and environmentally friendly mobility systems, as these elements collectively address the challenges such as spatial segregation, car dependency and housing shortage. Using the synergy of these element amplify the benefits of urban transformation. Diverse, mixed-use urban planning fosters dynamic and inclusive environments by combining residential, commercial and recreational spaces in close proximity. Such setting encourages social interaction within communities, reduces the need for long commutes and enhances accessibility for all demographics (Hoppenbrouwer and Louw, 2005; Iannillo and

Fasolino, 2021). Shorter commute distance encourages active forms of mobility (Song, Merlin and Rodriguez, 2013). Cities that prioritize active mobility have shown that offering cycling and pedestrian-friendly infrastructure within mixed-use developments strengthen the establishment of more liveable, connected and resilient communities (Chau et al., 2022; Geller, 2003). Integrating technologies such as GIS, 3D modelling and visualization, as well as dynamic simulations provides innovative approaches for scenario planning and decision-making in urban development. Such tools have potential in enhancing stakeholder engagement, optimizing urban planning strategies and fostering sustainable growth (Isaacs, Blackwood, Gilmour and Falconer, 2013; Koziatek and Dragićević, 2017; Trubka and Glackin, 2016; Xu and Coors, 2012).

The “Trans|formator:in” research project aims to accelerate and optimize the redesign of public spaces to encourage sustainable and active mobility and thus improve the quality of urban life throughout Austria. One task of the project is to explore, develop and demonstrate innovative strategies and solutions in pilot regions for promoting diverse, people-centred spatial uses, contributing to sustainable urban development. By involving local communities, authorities and stakeholders, the project ensures that the transformation of public mobility spaces aligns with the needs and preferences of those directly affected. There are seven pilot regions in Austria: Vienna, Graz, Langenlois, Deutschkreutz, St. Gallenkirch, St. Pölten and the city of Salzburg. The Schallmoos district is considered as a focus area of Salzburg. It is a predominantly commercial urban district located northeast of Salzburg’s historic city centre. It is characterized by relatively low quality of living and faces significant challenges, including segregated residential and commercial areas, high car dependency, a large commuter population and unappealing open spaces. To address these issues, within the project, following goals have been set for this area: strengthening climate-friendly mobility; creating a prototypical transferable digital dataset and planning basis to support structural spatial analysis and urban planning simulations; identifying transformation possibilities of public spaces towards a land-use concept that reduces traffic and promotes active mobility; and aligning with the strategic development goals of the City of Salzburg, such as the Smart City Master Plan, Green Grid and Climate Change Adaptation strategies.

In this paper, we focus on the development of the 3D visualization web tool designed to simulate different development scenarios, including the design of active mobility axis within the district. The paper begins with an analysis of the existing condition of target area, followed by GIS modelled planning scenarios for sustainable spatial development. Finally, the paper introduces the 3D tool, which is developed based on the analysis and scenarios, along with its technical implementation. This tool enables targeted user groups to explore and better understand the modelled scenarios and their potential effects.

2. Study Area Identification

Located between the railway tracks, the Schallmoos area is relatively isolated despite its proximity to Salzburg’s historic city centre. Regardless of a certain degree of heterogeneity, the area is characterised by large industry area and high volumes of motorized traffic. The underutilized and uninviting open spaces along with partially vacant commercial areas, show great potential for restructuring and revitalization. Meanwhile, hardly any pedestrian- or bike-friendly infrastructures, as well as green elements are present in this area. Additionally, local amenities are sometimes difficult for residents to access, and the area’s cultural identity is barely recognizable.

GIS-based analyses based on structural data--such as land parcels, mapping of existing buildings and building regulations--prove and quantify the densification potential existing in the area. Figure 1 shows the theoretically achievable infill potential in terms of gross floor area for residential area or cubic meters of building mass for commercial areas per property in Schallmoos. The choice to use gross floor area for residential areas and cubic meters of building mass for commercial areas aligns with the planning concept established by the City of Salzburg, which differentiates between these parameters based on land use type. Specifically, the existing buildings on the partially spacious commercial areas can be densified, in some cases by over 10,000 m^3 per property. However, such potential barely exists in the residential area. Additionally, the potential for upzoning at the scale of building blocks is analysed. These quantified indexes are used for the establishment of the GIS modelled planning scenarios.

The City of Salzburg plans to create an axis for pedestrian and biking to break up the isolated island-like location setting of Schallmoos, by connecting it with neighbouring districts of Itzling and Gnigl and to serve as a transport corridor that will offer better access to public transport networks while promoting active mobility. With the support of the GIS analysis result mentioned above, in collaboration with the city administration, the location of the mobility axis and its connecting building blocks were selected as key focus area (also see Figure 1), where the development scenarios are modelled and visualized in the tool.

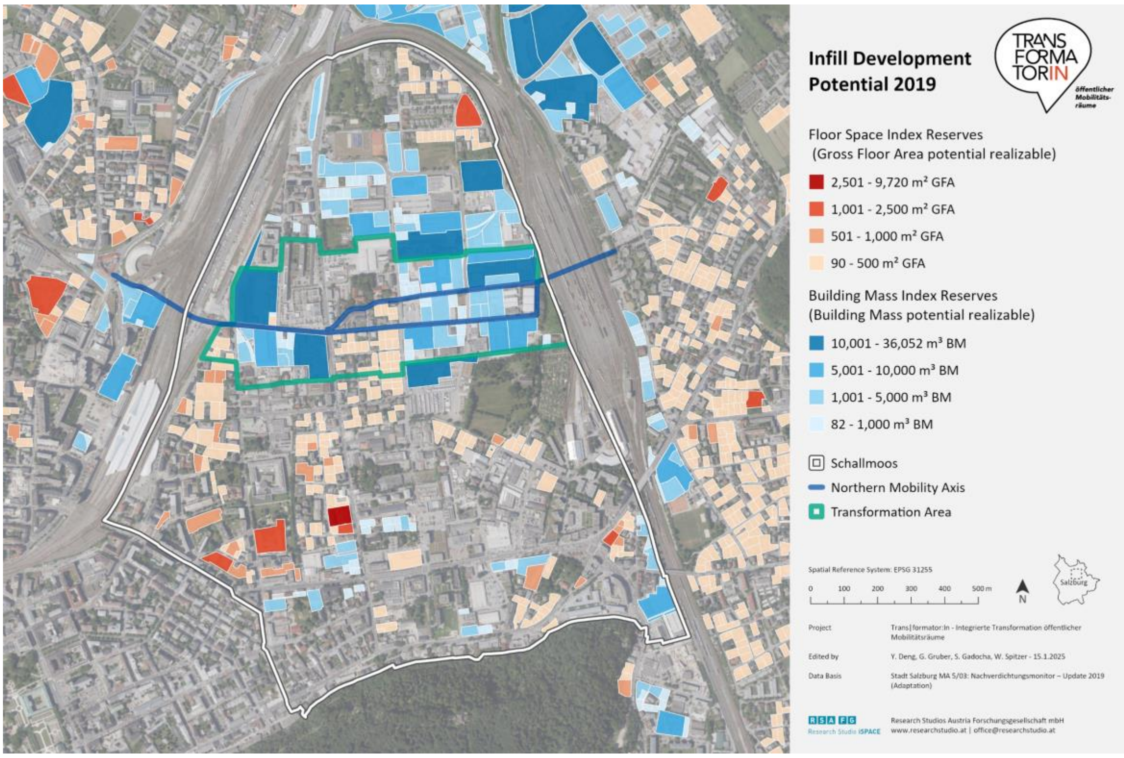

Figure 1. Potential for infill development in the study area Schallmoos, with mobility axis and transformation area marked.

3. GIS Modelled Planning Scenarios

For the focus area identified in the Schallmoos area, four development scenarios were modelled, and their information is stored in a GIS-based geodatabase. Figure 2 provides an overview of the scenarios. The baseline scenario, referred to as Scenario 0, represents the existing building stock based on a detailed building survey conducted by the city of Salzburg in April 2021. This survey includes information about the number of floors, basements, attics, floor layouts, uses of the buildings and the proportions of each use. For densification Scenario 1 and Scenario 2, the maximum building volume is calculated. It considers factors such as land parcels, legal setback distances, building lines and construction boundaries (Spitzer, Reithofer and Prinz, 2017). Both scenarios assess opportunities for restructuring but differ in how strictly they adhere to existing rules. Scenario 1 focuses on infill development, assuming the demolition and reconstruction of buildings while following current development regulations from 2023 (Stadt Salzburg, 2023). Scenario 2 reflects the potential of upzoning, which assumes demolition and reconstruction based on the maximum building volume that can be achieved based on the configuration of the land parcels without following the development regulations. For Scenario 3, experts from MA 5/03 (Office for Urban Planning and Transport of the State Capital of Salzburg)(Stadt Salzburg, n.d.) developed urban planning concepts for short-, mid- and long-term development scenarios, reflecting a more realistic progression. This interdisciplinary collaboration allows the representation of the scenario, unlike the above scenarios, not only focusing on the building elements but also their adjacent open spaces. It include features such as cross-sections of the street (e.g. lane widths and parking bays), greenery elements and bridge for pedestrians and bikes. Regarding buildings, flexible perimeter blocks with a mix of uses are proposed here. The buildings are designed to be five storeys tall, accommodating a mixture of industry and residential functions. This proposed design benefits from proximity to the walkable streets with adjacent open green spaces and in the meanwhile ensures ample natural light for the buildings, which is also supposed to result in energy efficiency as supported by studies on optimized perimeter block layouts (Kim, 2016). Private green spaces are enclosed by the buildings, offering quieter outdoor space dedicated to recreation function that can benefit the occupants of the block. These elements together create synergies, where the joint effect leads to a harmonious setting of the built-up areas and open spaces, fostering a balance between the urban functionality and environmental sustainability. This is crucial for the transformation of the area toward active mobility and improved quality of life for the block occupants.

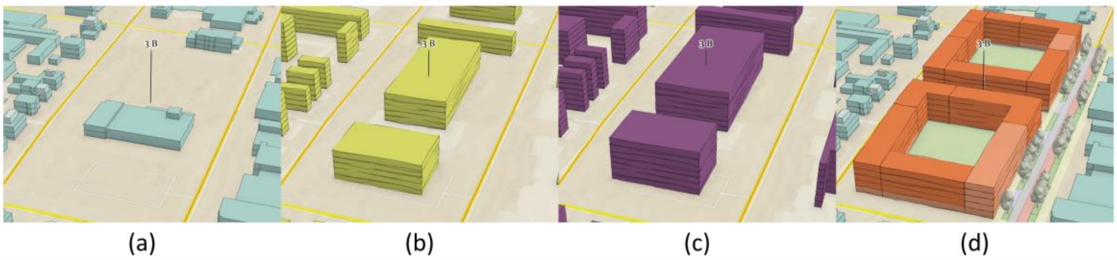

Figure 2. Urban planning scenarios for the focus area in Schallmoos, Salzburg, with a zoomed-in view of block 3B: (a) current development (b) infill development (3) upzoning development (4) urban planning concept.

4. Digital Twin for Urban Simulation and Impact Indicators

The scenarios described in the previous chapter were translated into geodata to be integrated into an interactive web map ("digital twin"). This digital representation allows for the visualization and communication of urban planning scenarios and their quantifiable effects. The application interface, as shown in figure 3, allows users to switch between different scenarios, such as current aeriel imagery with building block information overlay, the current state, densification, upzoning or planning stages (Figure 3 - 1). Underneath the scenario toggle, the time slider allows users to toggle between short-term, mid-term and long-term planning scenarios (Figure 3 - 2). It enables dynamic exploration of the development timeline. Given the current situation in the development area, achieving the planned development goals in a single step is impractical, therefore the phased visualization offered by the time slider is a more accurate reflection of the likely development process.

Indicators, including gross floor area (total, residential and workspaces), residential units, population and employment figures can be selected and visualized in the bar chart for detailed analysis and comparison across above-mentioned scenarios (Figure 3 - 3). Users can click on specific building blocks to focus on the area in the map and corresponding data in the bar chart or click outside the transformation area for an overview (Figure 3 - 4). The map navigation is intuitive, allowing users to zoom using the scroll wheel, pan with the left mouse button and rotate or tilt the map with the right mouse button. Additional navigation buttons are also provided on the left corner of the map for ease of use (Figure 3 - 5). On the right corner of the map (Figure 3 - 6), users can use the layer list widget to toggle 2D information overlays on or off, providing flexibility in customizing visualized data in the map view. Furthermore, the application includes a shadow and daylight simulation widget, which offers users insights into how various development scenarios affect shadows throughout different times of the day and across different date of the year. It helps users to have a more concrete understanding of the spatial and environmental impacts of the selected scenario, supporting more informed evaluations in a 3D context.

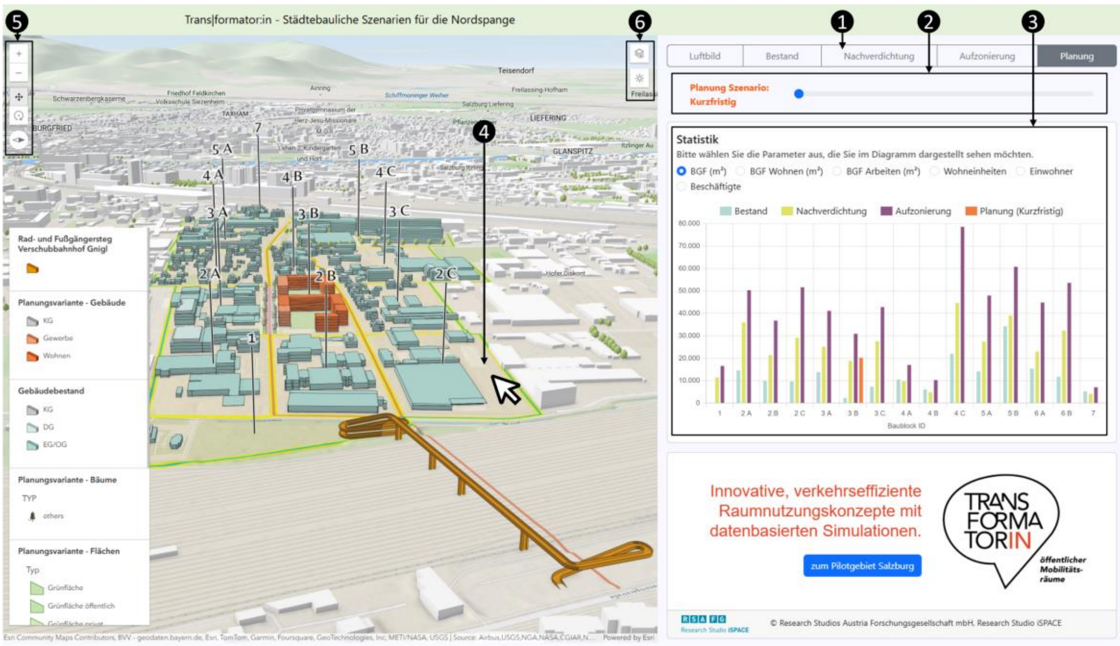

Figure 3. User Interface with the short-term planning scenario selected: scenario toggle (1), time slider (2), statistic bar chart with an indicator selector (3), selectable building blocks in the 3D map (4), navigation buttons (5), layer list widget and shadow & daylight widget (6).

Figure 4 provides a screenshot of this simulation environment, in which the individual scenarios and the construction of the buildings can be tracked over time. In this example, the building block 3B is selected, featuring an urban development scheme specifically designed by experts from MA 5/03. The buildings in the 'Long-term planning' scenario are shown in the foreground. In this scenario, the perimeter block is fully enclosed, forming a complete ring of buildings. The visualization distinguishes individual building storeys and their respective functions, providing a detailed representation of the block's proposed structure and usage. Besides the building elements, the experts also provided us with detailed mapping information for the future design of the neighbouring street, which is divided into open green area, walkways, bike lane, parking zones and lane for motorized individual transport. All this information has been integrated into the 3D environment. Using the included diagrams, key metrics such as the capacity of residential units, gross floor area for housing and workspaces, population and employment figures can be retrieved and compared across all scenarios. As shown in the Figure 4, for the selected building block 3B in the 'Long-term planning' scenario, the capacity for residential units is significantly higher than in the current situation (which is zero), surpasses the theoretical infill development scenario and is slightly lower than the upzoning scenario. Users can hover over the chart for detailed numbers. The comprehensive visualization of the development scenario, combined with the quantifiable impacts, provides concrete indicators for future spatial development, which are intended to serve as planning guidelines and requirements for the tender process and as evidence-based arguments supporting the political mandate.

Figure 4. Screenshot of the application showing building block 3B selected in the "Long-term Planning" scenario, with the indicator "Residential Units" visualized in the statistical bar chart.

5. Technical Implementation

The web map application was developed using Create-React-App (Meta Platforms, n.d.), with 3D mapping functionalities implemented through the ArcGIS Maps SDK for JavaScript (Esri, n.d.-a). The densification models was visualized with usage information for each floor, which was initially stored as polygon layers and then exported as 3D objects before being published as scene layers on ArcGIS Online (Esri, n.d.-b). Proposed usage for open spaces, such as green areas and traffic zones, are represented as 2D feature layers within the 3D scene. Items such as trees are marked as spatial points and visualized in the scene as 3D symbols. Other street furniture in the urban environment, such as benches or bus stations, can also be integrated and displayed in the scene if required. The feasibility of incorporating custom 3D objects imported from 3D modelling software into the ArcGIS scene as scene layer has also been successfully tested and validated. Figure 3 also shows the imported 3D model of the proposed bridge design for the mobility axis that connects the district Schallmoos and the district Gnigl over the railway. However, the design has been deprecated after discussions with the stakeholders. Housing and employment space indicators are derived by making queries to the building block feature layer published on ArcGIS Online and visualized through the interactive bar chart built with the React-Chartjs-2 (Jeremie Coullon and Contributors, n.d.) package. The application is designed to reflect changes in scenarios or usage information in both the charts and the map for real-time interaction. To ensure user-friendliness, React-Bootstrap (React-Bootstrap Contributors, n.d.) was used to create the responsive interface. Moreover, the application was developed with scalability in mind, allowing for future integration of additional features such as distance and area measurement tools, shadow cast tools and the inclusion of other data layers to enhance its functionality on demand.

6. Discussion

We are aware that indicators that reflect the impacts of future development related to green space provision, proximity to local amenities and mobility access are lacking in the current tool. They are planned to be included in the future. These indicators aim to support the evaluation of the development scenarios in alignment with the goal of strengthening the focus area as a corridor for active mobility and improving its connectivity to existing regional public transport networks. They will be complemented by traffic counts and estimations of traffic space usage, including choices of transportation modes, partly conducted by external companies as part of the project evaluation. Including such information is essential for effective communication among planners, stakeholders and municipalities, ensuring that decisions are well-informed and inclusive to ultimately gain political commitment. The tool was also demonstrated during a stakeholder workshop in Salzburg, where it received positive feedback regarding its value for supporting planning discussions. Additionally, it should be noted that even the Scenario 3, devised by the MA 5/03, is a conceptual idea that requires significant refinement and development in different aspects before it can become feasible for implementation in the reality. The goal is to draft a more detailed, legally sound design as the foundation for organizing a competition to select an architectural solution, while ensuring the involvement of local residents. No construction measures are planned within the project and therefore, no specific timeline has been set for implementation. However, the expertise of the project team can be used to design outreach strategies and create participation opportunities for stakeholders. However, a small budget is allocated for testing innovative design ideas to assess public acceptance.

7. Conclusion

In this paper we introduced the 3D visualization web tool designed to model different development scenarios and the configuration of a new mobility axis in the Schallmoos district of City Salzburg. By combining flexible urban design, efficient land use and sustainable transport options, the proposed scenarios set a foundation for a transformation to a vibrant and resilient urban district. The tool utilizes geoinformation to simulate and visualize various urban development scenarios, including the current situation, infill and upzoning development based on the result of GIS analyses, as well as phased mixed-use scenarios envisioned by urban planners. In the phased mixed-user scenarios, concepts for open spaces and traffic spaces design are also integrated into the 3D view. This tool is therefore characterized by the integration of building development, traffic and open space planning into a single platform. Such integration enhances informed decision-making and planning efficiency by conveying transformation concepts through clear visual representations that simplify complex data. Users can test and explore various development scenarios to compare and evaluate their impacts, allowing for the identification of the most feasible options for urban development The interactivity of the tool encourages collaboration among experts, stakeholders, and the broader public, making it accessible to a wider audience. The visualization components and quantifiable metrics can support political approval and funding, for instance, for architectural tendering processes and aid in promoting the project and increasing acceptance among local stakeholders such as business owners and residents. As for the transferability, this tool serves as a prototype for other urban development projects. Similar visualizations and impact indicator calculations can be applied to other planning areas where the required data is available. The densification scenarios (i.e. the infill and upzoning scenarios) can be adapted to incorporate local planning and building regulations as well as community requirements in different urban contexts.

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Improvement of Monolithic Vault Construction Technology Using Tunnel Formwork Systems

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Abstract. This paper provides a detailed analysis of the construction technology for monolithic vaults using tunnel formwork, including the stages of assembly, concreting, dismantling, and repositioning of the formwork system. The study aims to optimize the construction cycle and minimize labor intensity. This article examines the application of tunnel formwork for the construction of monolithic vaults, analyzing the advantages and disadvantages of this method, and comparing leading formwork system manufacturers such as Doka, Ulma, and Peri. Particular attention is paid to technological aspects, including concrete placement rate control, ensuring uniform concrete distribution, and joint sealing. The influence of various factors, such as vault geometry, construction schedules, and budget, on the selection of the optimal formwork supplier is analyzed. The study reveals that despite the high efficiency of tunnel formwork, the concreting process remains the most labor-intensive stage, requiring meticulous planning and control. The conclusion provides recommendations for optimizing the concreting process, including the use of specialized placement ports, plasticizers, and self-consolidating concrete.

1. Introduction

Compared to other structures, monolithic concrete vaults offer significant advantages in strength, stability, and material efficiency. However, traditional prefabricated formwork systems are characterized by high labor intensity and insufficient structural quality.

Existing research indicates that selecting the optimal method for constructing monolithic vaults is a multifactorial task influenced by the geometry of the structure, materials, construction timelines, and budget. Tunnel formwork is widely used in various countries for infrastructure projects, significantly reducing construction time and improving structural quality. However, for broader adoption, further research is needed, particularly on optimizing the assembly and dismantling processes. Despite the variety of design solutions, existing studies often fail to account for factors such as the vault's curvature radius, formwork lifting speed, and fastening methods, which affect the efficiency of tunnel formwork application. The article aims to analyse practical experience and the shortcomings of existing formwork systems for monolithic vault construction to enhance efficiency and reduce costs.

The study evaluates the efficiency of constructing cylindrical vaults using tunnel formwork by analysing four key stages: assembly, concreting, dismantling, and repositioning.

2. Presentation of the Main Research Material

2.1 Advancements in Vault Construction: The Role of Leading Formwork Systems

Leading formwork system manufacturers such as Doka, Ulma, and Peri have significant experience in constructing monolithic vaults using tunnel formwork. They continuously improve their technologies and offer efficient solutions for building structures with variable cross-sections, including vaults. The construction of vaulted structures using tunnel formwork is characterized by high speed since concrete pouring occurs in a single cycle, significantly accelerating the construction process.

Manufacturers highlight several advantages of tunnel formwork, including reduced construction timelines and continuous workflow. However, there are also some drawbacks, such as limitations in structural flexibility, difficulties in transportation and assembly, and the need for a continuous supply of concrete. On sloped vault surfaces, concrete may spread, potentially leading to an uneven vault thickness. Additionally, after pouring concrete, the formwork must remain in place for a specific period before removal.

Despite these challenges, formwork system manufacturers continue to refine monolithic vault construction technologies to make the process more efficient, precise and cost-effective.

2.2 Choosing the Right Formwork: Project Examples and Manufacturer Considerations

One successful example of tunnel formwork application is the construction of an ecoduct near Boljun Field in Croatia. To ensure the safe crossing of wild animals between Učka and Vozilići, a 43-meter-long tunnel was built. PERI engineers developed a special formwork solution that enabled the rapid installation and movement of the tunnel's formwork carriage. The supporting structure for the carriage was designed and built using a scaffolding system. The fully assembled formwork block was placed on steel beams, allowing it to be easily moved on wheels to the next concrete pouring section. [14]

Another example is the construction of a 670-meter-long two-lane tunnel. This project used steel formwork and a movable tunnel formwork carriage. A key feature of this project was the use of PERI's articulated girder system, connected to the formwork to create curved vault surfaces. The structure was modified for optimal load distribution. Thanks to the preassembled formwork carriage from PERI, the final installation took only three weeks. [14]

Formwork manufacturers such as Doka, Ulma, and Peri offer various solutions for constructing monolithic vaults [14, 15, 16]. When choosing formwork, it is essential to consider project-specific factors, including vault geometry, construction timelines, and budget [11]. In addition to tunnel formwork with girder-beam technology, Doka and Peri also provide large-panel formwork, which consists of oversized panels with detachment mechanisms and formwork module movement systems. However, when vaults are built in stages, i.e., in separate sections, ensuring a reliable connection between sections and proper seam sealing becomes a challenge. Peri's formwork system offers greater flexibility due to its wide range of equipment, giving it an advantage in some projects, especially when other companies cannot meet the required work volume. When using continuous concreting technology, it is crucial to control the concrete supply rate and its distribution across the vault surface to prevent defects. However, Peri's prices are generally higher. Ulma offers only girder-beam formwork, which must be assembled manually on-site. Thus, the choice of the optimal formwork supplier depends on the project's specific needs, including its scale, budget, and construction deadlines.

2.3 Methodology and Tunnel Formwork Application

To assess the technological efficiency of tunnel formwork systems for monolithic vault construction, the study employed a mixed-methods approach that included simulation modeling and field testing. Simulation models were used to analyze stress distribution and concrete load behavior across varying vault curvatures and heights. These virtual tests allowed optimization of design variables before implementation.

In parallel**,** practical field trials were conducted using a prototype tunnel formwork system on a test site. Measurements were taken for labor intensity**,** assembly/disassembly time**,** and concrete surface quality**.** This dual approach helped validate manufacturers' claims and fine-tune operational protocols under real-world conditions.

The use of tunnel formwork ensures a cyclic process of raising and lowering the formwork. Its application allows for the simultaneous execution of multiple operations, reducing construction time and ensuring workflow continuity [1]. Tunnel formwork for vaults has specific features related to the need for forming curved surfaces. The use of profiled panels and specialized support systems enables the creation of structures with varying curvature radius.

To evaluate the technological parameters of the tunnel formwork system, a combination of simulation modeling and practical field testing was conducted. In the simulations, structural stress distribution and concrete load behavior were analyzed under various curvature and height configurations. Field trials involved the assembly and operation of a prototype formwork system to measure time, labor intensity, and surface quality in real conditions.

This mixed-method approach helped validate the efficiency claims made by formwork manufacturers and allowed for the fine-tuning of construction protocols.

Let us consider cylindrical vaults and evaluate the efficiency of their construction process. The technological efficiency of formwork systems for vault construction is determined by the effectiveness of the erection process, which consists of four stages: assembly, concreting, dismantling, and formwork movement. These stages are as follows:

Stage 1: Vault Formwork Assembly

This stage (Fig.1) involves assembling the framework at the construction site and then moving it into the design position using rollers and guides. At the concreting site for the first vault section, the inner side of the formwork is installed. Jacking the structure up to the design elevation ensures the necessary vault geometry. [10] Panels adjacent to the concrete body are mounted separately to ensure shape accuracy. The final step before concreting is assembling the outer side of the formwork.

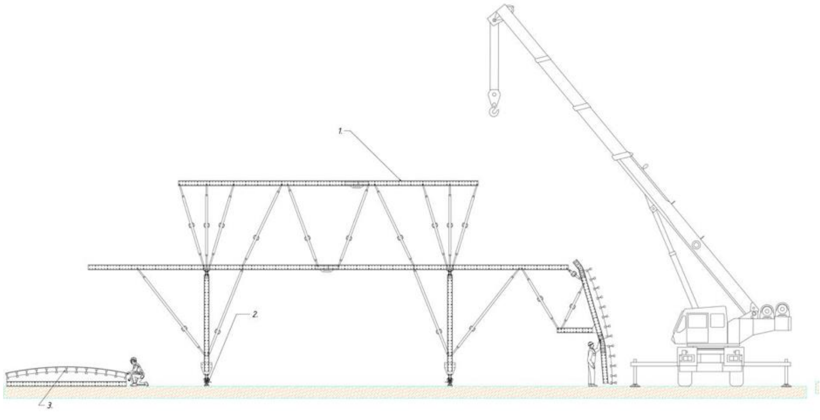

Figure 1. Assembly of the Formwork Structure at the Construction Site.

The first stage involves the assembly of the formwork structure on the construction site, which includes the following processeas:

1. The main framework is assembled in an open area of the construction site.
2. The jacks are shown in a lowered position. Using rollers on guide rails, the formwork structure is moved into its designated position. Once the full structure is formed and positioned, the jacks need to be raised to the specified vault base level.
3. Separately, the installation of panels that will be adjacent to the concrete body of the vault is carried out. These panels are later mounted onto the structure.

Stage 2: Vault Concrete Pouring

The vault is concreted in stages using specially designed sluices, which ensure control over the process and the quality of concrete placement. (Fig.2) The technology involves sequentially connecting the concrete pump hose to an open sluice, ensuring a sealed connection. The concrete mixture is supplied under pressure, controlled by the operator, until the required fill level is reached. Once the necessary level is achieved, the mixture supply is stopped, the sluice is securely sealed, and the hose is disconnected. The hose is then connected to the next sluice, and the process is repeated until the entire vault is filled.

To ensure uniform distribution and compaction of the concrete mixture, additional equipment such as vibrators may be used to achieve a high-quality concrete surface.

A key factor influencing the concreting process is the rate at which the concrete mixture is supplied. As the speed increases, the hydrostatic pressure on the formwork rises, requiring careful calculation of the structure's strength. Since monolithic vaults are typically concreted in a single technological cycle without division into separate height blocks, significant static and dynamic loads occur on the formwork and supporting structures.

This concreting method (see figure 2) allows for precise dosing of the concrete mixture, minimizing material losses and ensuring the formation of a monolithic vault structure with the required characteristics.

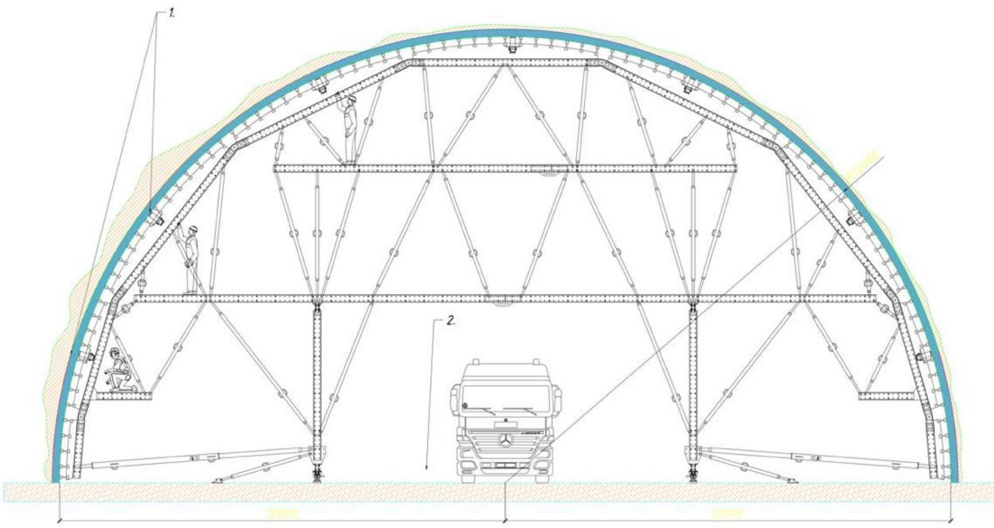

Figure 2. Vault Concreting.

The second stage involves the concreting of the vault on the construction site, which encompasses the following processes:

1. Concreting is carried out in stages through special concreting sluices.
2. Additional passage is provided for construction vehicles, including concrete mixer trucks.

Stage 3: Vault Formwork Dismantling

The dismantling of the vault formwork is performed after the concrete has reached the required strength. (Fig.3) The process begins with the removal of the external formwork using a crane. The internal formwork is dismantled in several steps:

• First, the telescopic brace is unscrewed.

• The lower formwork panel, thanks to a special rotation element, is tilted away from the hardened concrete at an angle of 60-70°, creating space for further lowering of the structure.

• Next, using a hydraulic jack, the entire formwork structure is lowered by 0.5-0.8 meters.

• In the final stage, the formwork is transported to the next section using movement mechanisms (roller wheels) for the next reinforcement and concreting cycle.

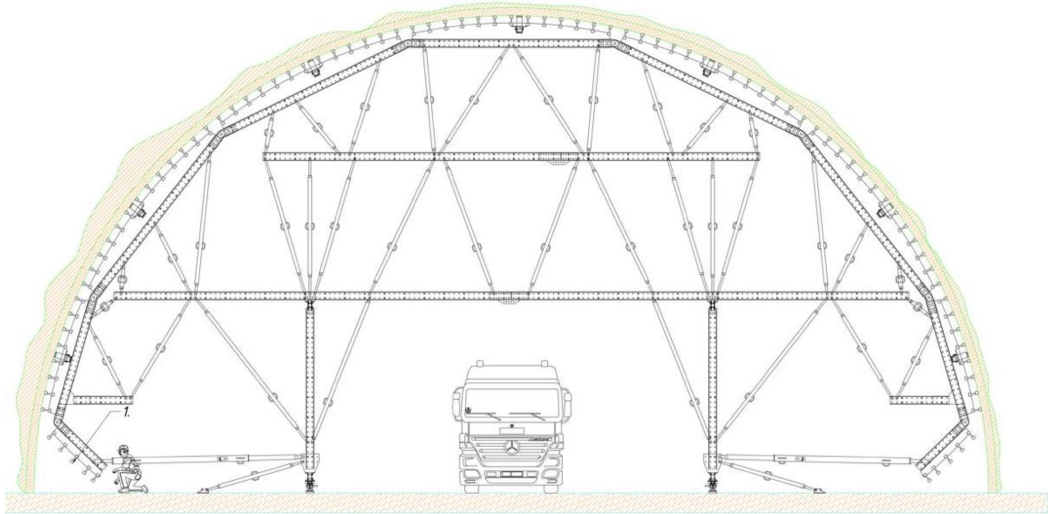

Figure 3. Dismantling of the Formwork Panel.

The third stage involves the dismantling of the formwork panel, which encompasses the following process:

1. The lower panel is dismantled into a bent position to facilitate the further lowering of the structure.

Stage 4: Formwork Relocation

Relocation is carried out by lowering the structure onto rollers using jacks. (Fig.4) The bent position of the panel allows for maneuverability and transportation of the formwork without dismantling the main elements, significantly reducing time and labor intensity.

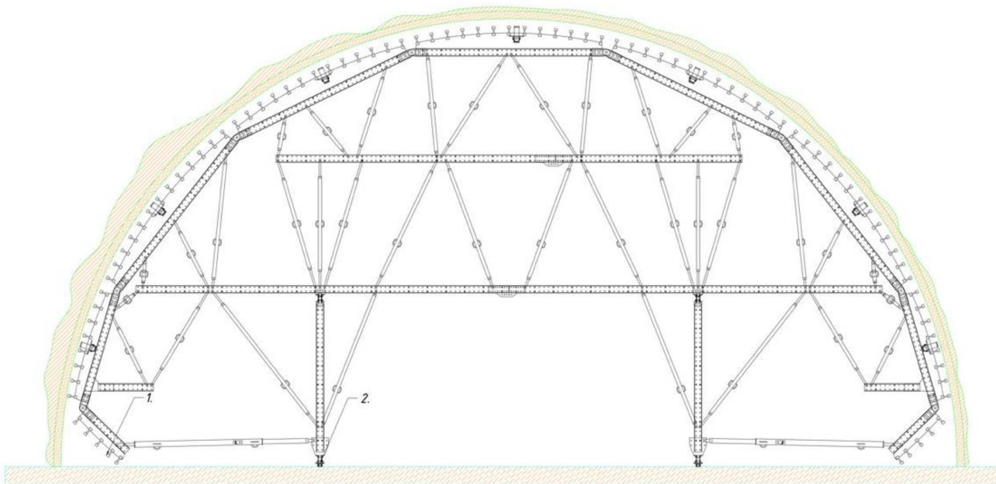

Figure 4. Lowering the Formwork Structure and Moving to the Next Sections

The fourth stage involves lowering the formwork structure and moving it to the next sections, encompassing the following processes:

1. The bent position of the panel allows the structure to be lowered.

2. Using jacks, the entire formwork structure of the vault is lowered onto rollers and moved to the next sections.

Thus, the proposed vault construction technology minimizes labor intensity and increases the efficiency of construction work. [12,13] The high technological advancement of this formwork system helps reduce labor costs and shorten the construction cycle duration with proper concreting.

The tunnel formwork system is more effective for large-scale projects but requires thorough planning and significant initial investment. One of the key indicators characterizing the number of formwork usage cycles is the turnover of formwork systems. The use of universal prefabricated and dismountable formwork systems may increase the breaks between technological processes, leading to higher waterproofing costs compared to tunnel formwork.

Tunnel formwork is an efficient solution for constructing monolithic vaults as it minimizes the number of monolithic joints and ensures continuous concreting. When using tunnel formwork, it is essential to consider the specific requirements for forming curved surfaces and ensuring an even distribution of concrete during pouring.

3. Conclusion

An analysis of the construction process for a cylindrical monolithic vault using tunnel formwork revealed that the most labor-intensive stage is concreting. Despite the use of special sluices and controlled concrete mix supply, this stage requires high precision and coordination. The key challenges include ensuring uniform concrete distribution across the entire vault surface, controlling hydrostatic pressure on the formwork, and achieving proper compaction of the concrete mix.

Moreover, monolithic concreting in a single technological cycle creates significant static and dynamic loads on the formwork, requiring precise strength calculations and continuous monitoring. The supply of concrete mix through formwork sluices under the required pressure helps control concreting speed and uniform distribution of the mix. Additionally, plasticizers, such as self-compacting concrete mixtures, can be used to allow concrete to spread evenly under its own weight, filling all voids and ensuring a high-quality vault surface.

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Healthy and comfortable indoor environment

Overheating Risk Measurements in Retrofitted High-Rise Buildings

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Abstract. Systemic renovation of dwellings is necessary to achieve CO_2 reduction according to climate goals. Industrial renovation concepts were developed to help speed up application. However, summer outdoor temperatures have been rising and additional climate adaption measures in renovation concepts seem necessary. The combination of higher insulation levels and improved air tightness of buildings will also increase indoor temperatures during summer. There is increasing evidence that overheating occurs in buildings during warm weather, while longer periods of higher indoor air temperatures can lead to health issues.
The aim of this study is to compare the indoor air temperature during the summer period in renovated and pre-renovated apartments and map the effect of the renovation. Therefore, two sensors were placed in both renovated and pre-renovated apartments.
Indoor air temperature measurements were conducted in three different Dutch high-rise buildings. The first involved a two-year measurement in ten apartments in a renovated building. In the second and third apartment building, a measurement period of 2-4 weeks in five apartments was studied. Two apartments represent the former situation and three apartments were renovated. The results make it possible to compare the old and new situation to see if in the renovated situation (i) the temperature is higher and if the temperature is higher for a longer period, (ii) the temperature meets the regulations and (iii) the effect of sunscreens on indoor temperature.

1. Introduction

Due to climate change, the Netherlands are increasingly affected by heatwaves. Extreme heat, with temperatures above 35°C, is becoming more common. In cities, it is often even warmer than in the countryside.[1] Heat causes discomfort, health problems, and can even lead to death.[2] The built environment in the Netherlands is not designed for extreme summer conditions. In fact, for a long time, homes were designed to let in as much solar heat as possible. They often have a lot of glass, and effective sunscreens are lacking. The need for solutions to cool homes is increasing.
Housing corporations have delivered homes according to the building standards of that time but are now facing complaints from residents about heat stress. The focus of sustainability projects is strongly on the heating demand of homes in winter, while renovations do not yet sufficiently consider the summer comfort of insulated homes. Taking measures for housing corporations is complex. Residents who find the temperature in their homes unacceptably high are now looking for solutions within their own means to improve their living comfort. For example, the use of

curtains (indoor sunscreens) and open their windows at night, but these measures are less effective than outdoor sunscreens.[3]
Some residents resort to using air conditioning to improve indoor comfort, which, however, leads to higher energy demand and less sustainable solutions.

Systemic renovation of dwellings is necessary to achieve CO_2 reduction according to climate goals as agreed in the Paris accord.[4] Since dwellings were built according to the regulations at the time, they do not meet current standards. For existing buildings less strict regulations apply. This means, among other things, that there are no legal requirements for overheating in existing homes. For new homes, this has been regulated in the Netherlands since January 2021. The absence of requirements for existing buildings is due to the limitations that existing dwellings entail. For example, it is generally not possible to change the orientation, adjust the glass surface, or use overhangs. What often is done is upgrading the insulation and energy label to the level of a newly build dwelling. Additionally, tenants have fewer options for taking measures against overheating. It is the property owner who can make decisions and implement these. For tenants it is usually not allowed to install outdoor sunshades themselves. This means that the tenant is dependent on the owner, for example the housing corporation for this effective measure. Research from the Amsterdam University of Applied Sciences shows that it is most effective to combine multiple measures, and that a single measure is much less effective. This research shows that existing homes are often too warm: the overheating risk regulation, which currently only exists for new buildings, is exceeded in many situations. They researched the effect of four different measurements. However, these measurements only work if you combine the different measures. For example, if a house has sunshades but is not ventilated at night, it can still become too hot. The same applies the other way around. It also makes a big difference whether there are many trees outside or not.[3]

This study specifically investigates the impact of sustainability interventions on indoor summer comfort, building upon previous research. Various indoor measurements and simulations were carried out to compare the situation before and after the renovation.

2. Case-study

The measurements were conducted as part of the ARV research, a European Union-funded project aimed at promoting climate-positive and circular communities in Europe, for example by increasing the pace of housing renovations.
For monitoring purposes, sensors were placed in the living room and bedroom of the apartment. In building 1, the measurements were carried out over two years in 8-10 apartments. The original goal was to monitor the apartments for one year, but due to a relatively cold summer period, it was decided to extend the measurements for a second year. In this situation, measurements were only taken in the renovated state.
In building 2, measurements were conducted in three apartments: two renovated and one pre-renovated apartment. The measurements were carried out simultaneously over three weeks during the summer period, ensuring the same external conditions.
In building 3, measurements were conducted over two weeks in two apartments, one in the renovated state and one in the existing state. Again, the measurements were carried out simultaneously to allow a valid comparison between the two apartments. These initial measurements do provide a basis for more and prolonged research.

Building 1 *Building 2* *Building 3*

Figure 1. Buildings used for measurements

2.1 Deviations

During the measurements, various deviations and problems were identified. In building 3, in the existing situation, a construction scaffold was placed during the measurements. This resulted in an unintended overhang on both sides of the apartment, causing the measured temperature to be lower than it would have been without the scaffold (3.1; building number 3 apartment 1). According to the residents, the temperature was at least 5°C lower than without the scaffold.

In building 2, one of the apartments was unoccupied and the measurements were conducted in a show model apartment. The side wall of this apartment had not yet been insulated, while the renovation of this apartment was not yet complete (2.2; building number 2 apartment 2).

Additionally, the sensors were not always able to transmit the measurement data to the server, resulting in missing data.

In building 1 not all the participants allowed a second year of measurements, resulting in less data for the second year.

3. Methodology

In building 1, measurements were taken over a period of two years, with three sensors per apartment, except in the studio apartments, where one sensor was placed. The table below shows the results of three apartments, one 5-room apartment (1.1), one 4-room apartment (1.2) and a studio apartment (1.3).

The temperature was measured every 10 minutes, allowing for a potential day simulation. For an overall view of the temperature level, these measurements were averaged to an hourly value, achieving higher accuracy.

In buildings 2 and 3, a different type of sensor was used, and the measurement period was shorter. Here, measurements were only conducted during the summer period, for approximately four weeks. The temperature was measured every 5 minutes and averaged to an hourly value.

4. Results (and discussion)

First, the average temperatures in the appartments were examined, as well as how often a temperature above 25 degrees and how often a temperature above 28 degrees occurs. The results are shown in the table below. The first column shows the building number, followed by the apartment number where the measurements were taken.

Building 1 is the first energy-producing apartment building in Europe. The building has been renovated with a high insulation level. After the renovation, the appartments were partially equipped with sunscreens. The building contains various types of apartments. The results for three different types during the summer period are shown in the table. The measurements were carried out in the summer of 2021 and 2022. The results from the summer of 2022 have been included in the table. This was a relatively warm summer, as can be seen from the outdoor temperature. During this period, temperatures above 30 degrees occurred more frequently than in the measurement period at buildings 2 and 3.

Table 1. results measurement and simulation

		indoor						outdoor		
		Orien-tation	Sun-screen	Average Temp	Maximum Temp	% >25°C	% >28°C	Av. °C	% >25°C	% >28°C
1.1	R	NW	Yes	26,7	29,2	88,2	10,6	19,6	6,4	3,9
1.1	R	SE	Yes	25,0	27,5	45,5	0,0			
1.1	R	SE	No	24,1	26,5	18,6	0,0			
1.2	R	NW	Yes	26,2	29,6	72,4	8,2			
1.2	R	SE	Yes	24,5	27,4	38,6	0,0			
1.2	R	SE	No	26,1	28,9	81,1	7,9			
1.3	R	SE	Yes*	29,4	31,9	16,9	83,1			
2.1	N	E	No	25,6	29,4	58,7	4,4	19,5	5,9	3,1
2.1	N	W	No	25,8	30,8	59,6	9,2			
2.2	R	E	No	26,1	30,1	64,4	10,1			
2.2	R	W	No	25,8	30,8	60,0	9,2			
2.3	R	W	No	24,9	30,4	37,9	5,5			
2.3	R	E	No	25,2	30,4	44,0	7,5			
3.1	N	SW	No**	23,7	27,6	15,5	0,0	19,9	6,1	3,7
3.1	N	SW	No**	23,8	28,1	18,1	0,1			
3.2	R	SW	Yes	23,4	28,1	11,1	0,2	19,6	6,6	3,7
3.2	R	NE	Yes	23,7	27,2	18,0	0,0			

R= Renovated ; N = non-renovated

** Studio appartment, one window with sunscreen, other window without*

*** During measurement construction scaffold*

It is clear that in the studio (1.3) the highest temperatures occur in the summer. Because it is a studio apartment, it is more difficult to cool down at night, as the windows are on the same facade. And not all windows are equipped with external sunshades, due to a balcony door. The results show that these kind of apartments have a higher risk for overheating. It also shows the effect of absence of night ventilation.

Building 2 has no sunscreens, both in the existing situation and in the renovated situation. In building 2, it can be seen that the third apartment (2.3), which has been renovated, has a lower indoor temperature than the first apartment (2.1), which has not been renovated. This was not the expectation based on the earlier assumption that a renovated home is warmer than the non-renovated situation. In the third apartment, there were no curtains during the measurements. The residents opened the windows in the evening and night.

The second apartment has also been renovated (2.2), and during the measurements, there were no residents present in this apartment. This apartment was not ventilated during the measurements, and the windows remained closed and there were no curtains present. This may explain the higher temperatures during these measurements. It can be concluded that the behavior of residents can have a significant impact on the indoor temperature.

In apartment 2.1, the residents closed the curtains during the day and opened the windows in the evening. Despite these measures, it still gets warm in the apartment.

In building 3 sunscreens were placed as part of the renovation. This is reflected in the measurement results when comparing building 2 with building 3. In building 3, the temperature almost never exceeds 28 degrees in the same measurement period.

In apartment 3.1, there were no sunshades, but for the upcoming renovation, scaffolding was placed during the measurement period. This naturally results in a lower indoor temperature. According to the tenants, the temperature was at least 5 °C lower than before.

4.1 Analysis

The graphs below show the average temperature, the maximum temperature, and the percentage of time that indoor temperatures exceeded 25°C and 28°C per apartment.

The results clearly indicate that the studio apartment 1.3 NW, with limited ventilation options and only partial external shading, presents the highest risk of overheating. This unit not only recorded the highest average temperature but also exceeded the 28°C threshold far more frequently than any other.

Apartments 3.1 and 3.2 demonstrate the effectiveness of external shading. When combined with night ventilation, this measure proves particularly successful in reducing both average and peak indoor temperatures. These findings highlight the importance of an integrated approach, combining architectural interventions with conscious occupant behavior.

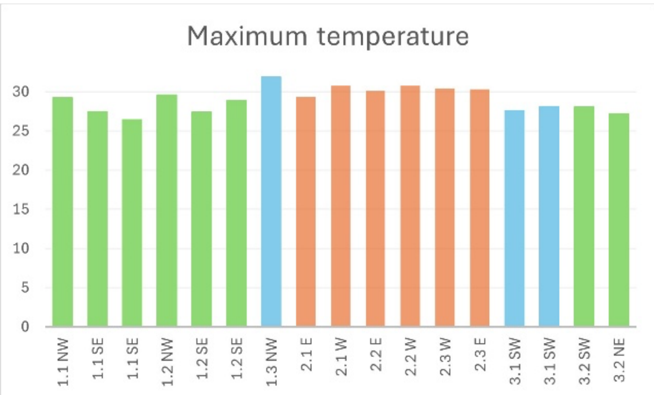

Figure 2. Maximum temperature

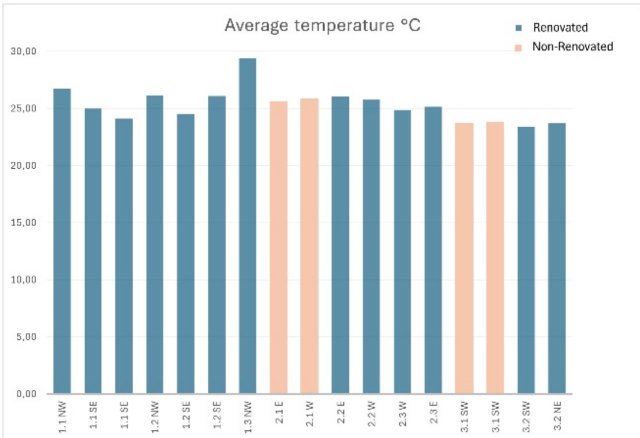

Figure 3. Average temperature

Green = with external shading
Blue = partially external shading or building scaffold
Orange = without external shading

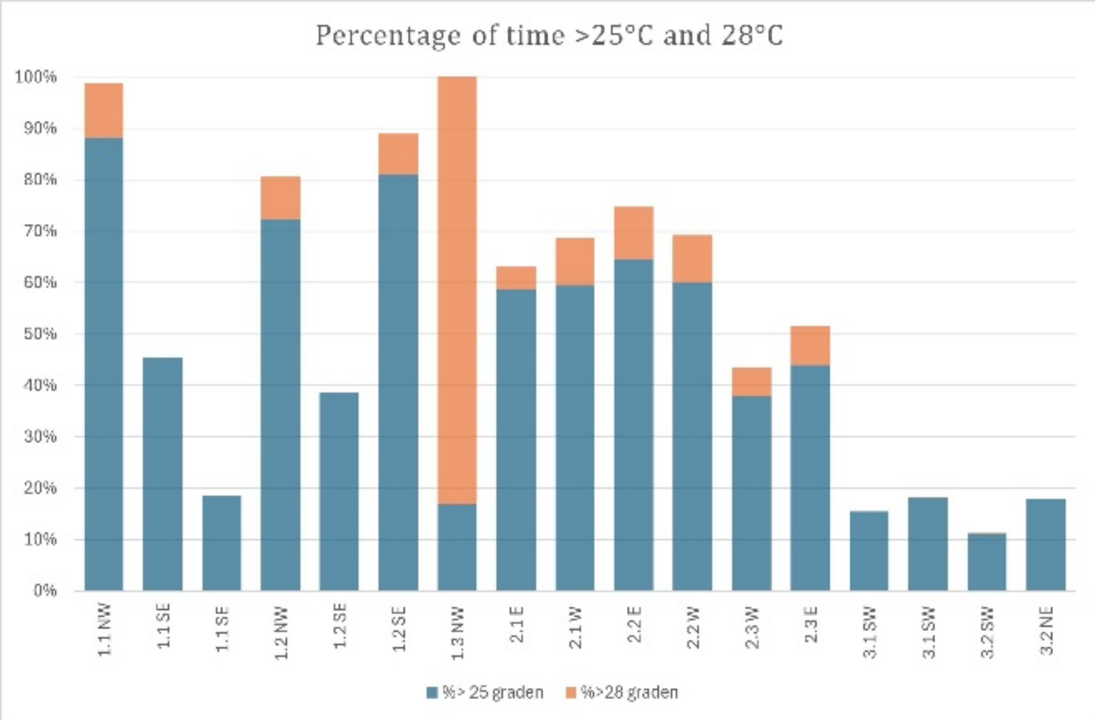

Figure 4. Percentage of time with temperatures above 25 and above 28 degrees

The effect of external shading is clearly visible in the graphs. Apartments equipped with external shading—such as 1.1, 1.2, and 3.2—show lower average and maximum indoor temperatures compared to similar units without shading.
The influence of occupant behavior, including (night) ventilation and the use of curtains, is evident when comparing apartments 2.3 (occupied) and 2.2 (unoccupied). Although both apartments were renovated, 2.3 maintained lower temperatures, highlighting the importance of night ventilation as a behavioral strategy.
Apartments with either external shading or night ventilation remained below 10% in terms of time spent above 28°C. In contrast, southeast-facing apartments without shading experienced significantly higher temperatures than comparable units with shading, emphasizing the role of orientation in overheating risk.

4.2 Impact of Overheating Measures
This section outlines the impact of various measures aimed at reducing overheating in dwellings:

- **External Shading**: Apartments equipped with external shading show a reduction of approximately 5 to 10% in the number of hours during which indoor temperatures exceed 28°C. External shading significantly reduces both average and peak indoor temperatures. Apartments equipped with shading consistently showed lower overheating percentages.

- **Night Ventilation**: Dwellings with operable windows on opposite sides (cross-ventilation) exhibit an average indoor temperature that is 3 to 5°C lower during warm periods. Night ventilation, as practiced by residents in some units, proved effective in reducing indoor heat accumulation, even in renovated dwellings.

- **Orientation**: West-facing apartments without shading experience the highest maximum indoor temperatures, highlighting the importance of shading for this orientation.

- **Studio apartments** with limited façade exposure and partial shading are particularly vulnerable to overheating.

These findings highlight the importance of integrating passive cooling strategies, such as external shading and night ventilation, into retrofit designs, especially for vulnerable apartment types and orientations.

5 Conclusion

For newly build houses, there are already standards in place to limit overheating, but for existing buildings, these standards do not yet exist. Existing homes are usually not designed with possible overheating in mind. Many homes in the Netherlands have been built to let in as much light and warmth from the sun as possible, often resulting in a lot of glass. Additionally, many homes lack effective sunshades. Even in renovation plans, where sustainability and insulation are prioritized, heat measures such as sunshades are often not yet included.

In rented houses, tenants have fewer options to prevent overheating because they usually are not allowed to install sunscreens by the owner. According to Dutch rental price legislation, if the indoor temperature exceeds 26.5 degrees Celsius for more than 300 hours, it can be considered a deficiency. The 300 hours are counted annually and do not need to be consecutive. This standard is derived from the GIW-ISSO 2008 regulations.[5]

There are various sustainable measures that can be taken to prevent overheating in homes, such as ventilating the house, using external sunshades, and greening the neighborhood. For this study, measurements were conducted in several apartments to investigate the effect of a renovation on the indoor temperature during the summer.

This study demonstrates that energy-efficiency renovations, such as improved insulation and airtightness, can increase the risk of overheating in dwellings, particularly during warm summer periods. Measurements conducted in three high-rise buildings revealed that:

- **Renovations without additional overheating mitigation measures** (such as external shading or night ventilation) can result in higher indoor temperatures compared to the pre-renovation state.
- **External shading** proved to be one of the most effective strategies to reduce overheating, especially in apartments with single-sided orientation or large glazed surfaces.
- **Occupant behavior** plays a crucial role: opening windows during the evening and night significantly reduced indoor temperatures, while lack of ventilation led to higher temperatures even in renovated homes.
- **Apartment orientation** influences overheating risk: southeast-facing units without shading experienced the highest peak temperatures.

Based on these findings, the following recommendations can be made for future retrofit projects:

1. **Integrate overheating mitigation measures**—such as external shading and night ventilation—as standard components of renovation strategies.
2. **Provide occupant guidance** on effective behaviors during hot periods, including the use of shading and nighttime ventilation.
3. **Use building simulations during the design phase** to predict overheating risks and select appropriate mitigation strategies.
4. **Consider orientation and layout** when planning renovations, particularly for studio apartments or units with limited ventilation options.

Although conducting measurements in occupied dwellings proved to be complex, the results offer valuable insights for improving indoor thermal comfort in retrofitted homes. Applying these insights can help ensure that future renovations not only reduce energy consumption but also enhance summer comfort and occupant health.

These findings suggest that overheating risk should be assessed early in the retrofit design process, especially for west- and southeast-facing units. Passive cooling strategies should be prioritized in subsidy schemes and renovation guidelines.

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Towards Safer and Sustainable Ventilation Standards for Underground Garages in Slovakia: A Comparative Review

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Abstract. As urban areas continue to densify, underground garages have become an integral component of urban infrastructure, necessitating the implementation of robust and efficient ventilation systems. The design standards for ventilation of such spaces in Slovakia are not without flaws. They are not aligned with the latest technological advancements, nor do they reflect the current requirements for energy efficiency and safety. This paper aims to provide a critical review of the existing documents, including relevant standards, regulations, and guidelines that govern ventilation design in underground parking facilities. By undertaking a comparative analysis of documents from other countries, this paper identifies key areas where Slovak standards are deficient, including the integration of recent technological advancements and methodologies that prioritize energy-efficient systems and ensure a healthy, non-harmful environment for occupants. The study emphasizes the necessity for a comprehensive update to these standards, underscoring the importance of aligning them with contemporary practices to foster safer and more sustainable designs. In addition to identifying weaknesses within these documents, the paper sets recommendations for improving the efficacy of the existing framework, encouraging updates that reflect both technological advancements and best practices observed internationally.

1. Introduction

Parking garages represent an integral part of the urban infrastructure, and ensuring their appropriate internal environment through effective ventilation design is essential. Ventilation of such spaces provide a set of challenges, due to the continuous influx of potentially harmful contaminants. Additionally, in the event of fire, smoke must be controlled properly to ensure safe evacuation of occupants. Ventilation systems of vehicular facilities are therefore designed to fulfil two fundamental functions: the removal of harmful contaminants during non-emergency operation (e.g. CO and NO_x) and the control of smoke and hot gases in the event of a fire [1]. Given that fire ventilation is a highly complex topic, this paper focuses exclusively on ventilation during non-emergency operation.

The health risks associated with carbon monoxide is a well-studied topic. Exposure to its high concentrations can result in severe health issues and, in extreme cases, even death. Whilst the preservation of human health must remain utmost priority, energy efficiency has also become a critical consideration. As garages are typically large spaces, their mechanical ventilation systems can demand a considerable amount of electricity. The relevant ventilation standards in the Slovak

Republic were established more than 30 years ago. Technological capabilities and health-related research have advanced considerably since then. This paper therefore examines whether these standards align with the current health and energy efficiency requirements.

To achieve this goal, the paper undertakes a critical review and comparison of Slovak ventilation standards with those of other countries, alongside with best practices and WHO guidelines. By identifying key deficiencies, the analysis aims to offer recommendations and insights into integrating modern ventilation solutions. The paper proceeds with a description of the research methodology, followed by the comparative analysis, presentation of findings and recommendations, and finally, the conclusion.

2. Methodology

2.1 Comparative Framework

The primary objective of this paper is to identify and examine the deficiencies in valid Slovak standards and other guidelines for parking garages ventilation. Therefore, it is crucial to compare them against equivalent standards from other countries. The comparison begins with an overview of general international guidelines published by recognized organizations which will serve as a baseline. It is followed by a detailed examination of national standards in countries with comparable climatic and geographical conditions but also countries that have comparable cultural, historical and legislative frameworks, which makes their comparison particularly relevant. In addition, standards from other regions are reviewed to provide a broader perspective.

2.2 Data Sources

The primary international guidelines reviewed in this paper include ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers) Handbook and WHO (World Health Organization) Guidelines. ASHRAE is a widely recognized American professional association that shapes the global HVAC industry through research, standards writing, publishing and educational initiatives [2]. WHO is specialized United Nations agency that provides technical assistance to countries, sets international health standards, collects data on global health issues, and serves as a forum for scientific or policy discussions related to health [3, 4].

On a national level, the Czech standards were selected due to the historical and cultural ties that the Czech Republic has with the Slovak Republic. Both countries shared the same legislation and standards under Czechoslovakia. Given these shared origins, the Czech *ČSN 73 6058* serves as a logical first point of comparison.

Additionally, the German standard *VDI 2053* was included in the review because VDI (The Association of German Engineers) is considered as one of the most important standardisation authorities in Germany and their standards reflect the current state of the art.

Finally, to broaden the international perspective, the paper additionally examines the relevant British Standards, specifically *BS 7346-7*.

2.3 Evaluation Criteria

In order to systematically identify deficiencies in the Slovak standard and proposed methodologies, several key comparative parameters were defined. First parameter focuses on occupant health and safety, with attention to the primary pollutants addressed in each compared publication. Pollutant thresholds were compared against limits recommended by WHO. Those limits served as the baseline for evaluating pollutant control requirements.

The second parameter involves the methodology for determining recommended air exchange rates. Various calculations approaches and their respective accuracy levels were analysed to highlight differences and potential areas for improvement.

Lastly each standard was analysed for the presence of energy-efficiency recommendations and its alignment with recent smart control systems or any other recent technological advancements. This factor highlights the extent to which the standards are aligned with today's sustainable design requirements.

2.4 Scope and Limitations

Although fire control measures are an essential aspect of ventilation in underground garages, a detailed evaluation of fire safety provisions lies beyond the scope of this paper. The complexity of fire ventilation design, combined with page limitations for this conference paper, precludes a comprehensive investigation into how each standard integrates fire safety requirements. Future work may address this topic in depth, offering a more complete view of ventilation practices in these settings.

3. Base guidelines

3.1 ASHRAE Guidelines

The 2019 *ASHRAE Handbook* - Heating, Ventilating, and Air-Conditioning Applications devotes an entire chapter to enclosed vehicular facilities, with one section specifically addressing parking garages. The text identifies two primary objectives for ventilation in these environments: controlling pollutant concentrations under normal operating conditions and managing smoke during fire events. From a nonemergency perspective, carbon monoxide (CO) is highlighted as the primary contaminant because of its well-documented health risks, although oil and gasoline fumes, nitrogen oxides (NO_x), and smoke haze from diesel engines also warrant consideration. Notably, the ventilation rate required to dilute CO to acceptable levels typically suffices to manage other pollutants, provided the proportion of diesel vehicles does not exceed 20% [1].

Historically, model codes and standards—including ASHRAE Standard 62.1—recommended a flat exhaust rate of 0.0038 $m^3/(s.m^2)$ or 6 ACH for enclosed parking garages. However, as vehicle emissions have declined, ASHRAE sponsored a study that found significantly lower rates could still maintain acceptable indoor contaminant levels [1,5].

ASHRAE Research Project RP-945 confirmed that several key factors determine the necessary ventilation rate for parking facilities: acceptable contaminant levels, number of cars in operation during peak conditions, the duration of travel within the garage, and the emission rates of typical vehicles under hot- and cold-engine conditions. When these operating conditions are known, a detailed calculation method can be used to ensure ventilation targets are met [1].

In terms of energy-efficiency, the ASHRAE Handbook underscores the advantages of demand-controlled ventilation, which employs CO sensors to modulate fan speed or activation times, thereby reducing energy consumption without compromising indoor air quality. The text also compares two main mechanical strategies: ducted systems, which rely on distributed ductwork for air supply and exhaust, and ductless (jet-fan) systems, which induce airflow through high-velocity fans positioned strategically throughout the space. Both approaches can be effective, but considerations such as clearance height, potential dead zones, and optimal supply/exhaust placement are crucial. In addition, computational fluid dynamics (CFD) analysis is often recommended to refine fan placement, validate smoke-control measures, and ensure overall design efficiency [1].

3.2 WHO Guidelines

The World Health Organization (WHO) Air Quality Guidelines (AQG) offer an evidence-based framework to assist national, regional, and municipal authorities in protecting public health by limiting exposure to harmful pollutants. These guidelines set recommended concentration limits for multiple pollutants relevant to enclosed vehicular facilities such as parking garages including benzene, carbon monoxide, nitrogen dioxide, and particulate matter. Given that carbon monoxide has been identified as the primary contaminant of concern in this analysis, the WHO recommendations for CO exposure are of particular interest [6].

Upon absorption, approximately 80–90% of CO bonds with haemoglobin to form carboxyhaemoglobin (COHb), thereby reducing the blood's capacity to transport oxygen. As a result, tissues with high oxygen demands (such as the brain, heart, skeletal muscles in use, and developing foetuses) are particularly vulnerable to CO-related hypoxia. Severe acute CO poisoning can lead to both short-term neurological symptoms and more serious, sometimes delayed, neurological impairment. Additionally, CO differs from many anthropogenic air pollutants in that extremely elevated concentrations (well above ambient levels) frequently lead to accidental or deliberate fatalities [7].

To mitigate these health risks, the WHO recommends the following limits for carbon monoxide:

- 100 mg/m^3 (90 ppm) for 15 minutes,
- 60 mg/m^3 (50 ppm) for 30 minutes,
- 35 mg/m^3 (30 ppm) for 1 hour,
- 10 mg/m^3 (10 ppm) for 8 hours [7].

4. Comparative Analysis

A review of Slovak regulations indicates that no specific law or decree directly addresses ventilation in underground garages or sets explicit limits for CO concentrations for regular occupants. Existing legislative documents provide only general guidelines. However, *STN 73 6058: Multi-storey and underground garages. Basic principles*, first issued in 1987 and revised in 1988 and 1989, remains a valid technical standard. Although it covers a broad range of topics related to garages such as traffic management, spatial layout, and construction requirements, one section specifically addresses ventilation.

The standard recognizes only natural and mechanical ventilation, allowing the use of natural ventilation for all above ground levels and mechanical ventilation for all cases where natural ventilation is unsuitable [8]. The Czech *ČSN 73 6058* (2011) goes further by distinguishing operational, emergency (for gas-fuelled vehicles) and fire ventilation [9]. Each category has distinct requirements, yet the standard permits combining them into a single system if the specifications for all categories are met. A similar allowance for merging fire and operational ventilation is also described in *BS 7346-7* [10].

4.1 Occupant health and safety

In terms of occupant health and safety, *STN 73 6058* mandates that parking areas and internal roads must be ventilated to prevent the accumulation of unacceptable pollutant concentrations and to inhibit the spread of pollutants to adjacent spaces used for different purposes [8]. By comparison, *VDI 2053* and *ČSN 73 6058* provide a more detailed guidance, differentiating between garages primarily used by transient occupants and those staffed by employees working regular shifts, which therefore must follow legal workplace requirements [9,11]. Both Czech and German standards explicitly reference government regulations specifying permissible CO exposure limits for employees, thereby incorporating these legal requirements directly into the standard. Although equivalent workplace limits, reflecting EU regulations, exist in Slovak legislation, *STN* does not explicitly reference those directives, nor does it stipulate that garages with on-site staff should be treated differently.

VDI also emphasizes the protection of nearby residents who may be exposed to garage exhaust, mandating careful placement of exhaust vents to avoid health impacts on adjacent windows, balconies, and playgrounds. When potential off-site risks are uncertain, the standard recommends using modelling or screening analyses [11].

STN identifies CO as the primary pollutant for setting ventilation rates in garages, consistent with other examined standards [8]. It stipulates a permissible CO concentration of 87 ppm over a 30-minute exposure, which exceeds the 50 ppm recommended by the *WHO* and stated in *ČSN* by approximately 75% for the same interval [8]. The Czech standard specifies that when this 30-minute CO threshold is used to calculate air exchange rates, occupants must be informed of the maximum permissible stay in the garage (i.e., 30 minutes) [9]. Most other standards do not define a 30-minute limit; the British Standard, for example, stipulates a 90 ppm peak for periods not exceeding 15 minutes, while *VDI* sets a 15-minute average limit of 60 ppm [10,11]. *VDI* further notes that, given catalytic converter technologies and the use of CO as a pilot gas for other pollutants, a 100 ppm limit may no longer ensure that other contaminants remain within acceptable ranges [11]. Notably, none of these documents propose limits for pollutants besides CO.

Table 1 presents the permissible CO concentrations for various exposure times as defined by the analysed standards. Due to variations in how each standard frames its CO limits, direct comparisons can be challenging. However, it is apparent that—except for *STN*—none of these standards exceed *WHO's* recommended short-term CO threshold. Conversely, most standards adopt eight-hour exposure limits derived from EU directives, which typically surpass *WHO* guidelines for that duration.

Table 1. Permissible CO concentrations for a given exposure time of occupants in various analysed publications [author].

Publication	CO limit for 15 minutes	CO limit for 30 minutes	CO limit for 1 hour	CO limit for 8 hours
WHO Guidelines	90 ppm	50 ppm	30 ppm	10 ppm
ASHRAE Handbook	-	-	35 ppm	25 ppm
STN 73 6058[a]	-	87 ppm	-	20 ppm [e]
ČSN 73 6058[b]	-	50 ppm	-	26 ppm
VDI 2053[c]	60 ppm	-	-	20 ppm [f]
BS 7346-7[d]	90 ppm	-	-	30 ppm

[a] valid Slovak technical standard, [b] valid Czech technical standard, [c] valid German technical standard [d] valid British technical standard, [e] value from government regulation of the Slovak Republic 355/2006 on the protection of employees against risks related to exposure to chemical agents at work, not referred to in the standard [f] value from standard referenced German technical regulation for dangerous substances TGRS 900

4.2 Methodology for determining recommended air exchange rates

Regarding air exchange rates, most of the reviewed standards provide separate methodologies for natural and mechanical ventilation. In natural ventilation, a prescribed minimum free opening area is identified, such as 0.15 m^2 per parking space (*STN* and *VDI*) or 0.025 m^2 per parking space (*ČSN*), with additional guidance on the positioning of these openings [8,9,11]. By contrast, the British Standard requires that the size of a permanent ventilation openings must amount to at least 5% of the floor area on each level, equally divided between opposing walls [10].

Because this paper focuses on underground garages, where *STN* and *ČSN* advise mechanical ventilation, the subsequent analysis centres on mechanical ventilation methodologies. Among the studied documents, the BS guidance on operational ventilation is the least detailed, offering a basic recommendation of six air changes per hour [10]. A simplified approach can be also seen in *STN*, which provides default values of 900 m^3/h per parking space for facilities with peak traffic and 300 m^3/h per parking space for those without [8]. *VDI* presents an alternative simplified method—derived from Federal States' regulations—using an area-based flow rate of 6 $m^3/(h.m^2)$ [11].

Where actual operating conditions are known, *STN*, *ČSN*, and *VDI* all propose more detailed calculation methods. These approaches, however, vary considerably. For instance, *STN* provides the least specificity: it assumes a single CO emission rate of 0.5 m^3/h per vehicle, without distinguishing between idling versus moving, or warm versus cold engine emissions [8]. This value stems from the standard's original development period and now significantly exceeds emissions under current European Euro 6 regulations. *STN* also does not differentiate between diesel- and petrol-powered vehicles. In contrast, *ČSN* and *VDI* account for driving distances, and *VDI* includes corrective factors to address real-world discrepancies from theoretical calculations [9,11].

4.3 Energy-efficiency

When addressing energy-efficiency, *STN* requires that mechanical ventilation systems must be designed to allow airflow to be reduced to one-third of the basic rate, enabling partial-load operation and potentially improving overall energy performance. In these cases, the ventilation operation must be controlled automatically. It also allows the use of hygienic, non-hazardous warm air from other parts of the building for garage ventilation if it is available during the operating hours of the facility [8].

VDI promotes automated ventilation to minimize fan usage, mainly by enabling on/off cycling or variable-speed control based on CO measurements, and by suggesting the subdivision of larger car parks into zones for partial operation where feasible. *VDI* also examines jet fan systems as an alternative to extensive duct networks. While jet fans do not inherently lower the required outside air volume, they enhance mixing, potentially reducing the need for multiple large fans or duct runs. Under certain conditions (e.g., stable temperature differentials), a layer ventilation strategy—where cooler outside air enters at floor level and rises by thermal buoyancy—may cut airflow demands by approximately 15% without sacrificing indoor air quality. In addition, *VDI* provides a more detailed CO surveillance system description compared to *STN* [11].

Finally, *ČSN* explicitly encourages economical (energy-saving) ventilation practices, including intermittent fan operation (activating fans only as needed), variable airflow rates (adjusting volumes according to measured CO or time intervals), and zoned or parallel-unit configurations (allowing partial use in areas with lower occupancy) [9].

5. Findings and Recommendations

The Slovak standard *STN 73 6058* currently provides no guidance on fire or emergency ventilation, unlike other international standards (e.g., the British Standard) that address such topics in detail. To rectify this gap, new provisions should either be created or linked to external documents (e.g., the *ATN* guidelines from the Passive Fire Protection Association of the Slovak Republic). While these guidelines are not yet recognized as Slovak technical standards, they would enhance *STN*'s content, given that fire and emergency ventilation are universally treated as critical aspects of car park design [12].

Moreover, contemporary garages often accommodate more than just diesel and petrol vehicles; there is a need to integrate requirements for gaseous and electric-fuelled cars. Currently, *STN* provides no explicit guidance on the associated ventilation requirements. The only relevant reference in Slovak legislation is a 2021 recommendation from the Presidium of the Fire and Rescue Corps which advocates installing a system to remove heat and combustion products [13]. It recommends either 10 ACH in the case of mechanical ventilation or cross ventilation achieved by openings with a minimum size of 5% of the floor area [13]. To ensure broader applicability, *STN* should incorporate these provisions and, following the examples set by *ČSN* and *BS*, addresses combining multiple types of ventilation (operational, emergency, fire) into a unified system, with specific criteria for each function.

A review of Slovak legislation also reveals insufficient or unclear pollutant thresholds for underground garages. At a minimum, the standard should either reference CO limits (e.g., from WHO guidelines) or update its own permissible values. For garages with long-term employee presence, *STN* should explicitly reference Slovak workplace directives—similar to how *VDI* and *ČSN* mandate compliance with government regulations—ensuring that worker exposures remain within safe limits.

In addition, *STN* should specify clear guidelines for exhaust outlet placement to safeguard both building occupants and neighbouring residents from pollutant exposure, mirroring *VDI*'s recommendation to avoid positioning vents near sensitive locations like windows, balconies, or playgrounds.

From a design standpoint, *STN* provides the least detailed calculation method for determining air exchange rates. Unlike *VDI* and *ČSN*, it does not differentiate between cold and warm engine emissions, idling versus driving, or vehicle travel distances. Incorporating these factors, along with corrective factors for real-world scenarios, would improve accuracy, as demonstrated by *ASHRAE*, *VDI*, and *ČSN*.

Finally, while *STN* does propose the possibility of partial-load operation, its energy-related provisions could be strengthened by explicitly referencing modern control systems, providing a more comprehensive description of CO surveillance, and outlining alternative ventilation methods. The incorporation of guidance on jet fans or mixed duct/jet fan systems, as well as the clarification of measures for system redundancy, would align the *STN* with contemporary global standards.

6. Conclusion

This review demonstrates that Slovak ventilation standards for underground garages—specifically *STN 73 6058*—are not in accordance with international best practices in several critical areas, including fire and emergency ventilation, pollutant thresholds, and design methodologies. On the other hand, in the STN, certain energy-saving provisions – such as partial load operation – have already been included, yet there is scope for further expansion. Given the complexity of this topic and the concise nature of a conference paper, further detailed analysis is recommended. The insights presented here emphasizes the necessity for a comprehensive update and can serve as practical guidance for standardization authorities as they work toward updating *STN 73 6058* in the future.

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Indoor Air Quality in Newly Commissioned School Buildings - A Case Study from the Czech Republic

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Abstract. The paper deals with the indoor air quality in three school classrooms in the Czech Republic soon after commissioning in buildings that have been newly built or renovated. It presents the results of a survey that monitored the concentration of volatile organic compounds, formaldehyde and carbon dioxide in three different types of school classrooms during full operation and at weekends. The monitoring of the aforementioned compounds was initially for building certification purposes with the SBToolCZ certification tool. The results show that concentrations of VOCs and formaldehyde can be problematic in new or newly retrofitted buildings, even if the carbon dioxide concentration meets all limits. At the same time, the influence of occupants and their activities on the overall indoor air quality in the monitored areas was also shown to be significant. The choice of building equipment material as well as the correct ventilation system control settings can be key to maintaining a healthy indoor environment in school facilities.

1. Introduction

Volatile organic compounds (VOCs) are a group of organic chemicals that easily evaporate at room temperature. They are found in many everyday products and materials, including paints, varnishes, cleaning supplies, pesticides, building materials, and office equipment. Short-term exposure to high levels of VOCs can cause symptoms such as eye, nose, and throat irritation, headaches, dizziness, and nausea [1]. Long-term exposure can lead to more serious health issues, including damage to the liver, kidneys, and central nervous system and can cause cancer [2]. TVOC (Total VOCs) represents the total concentration of all VOCs present in the air. TVOC provides a comprehensive measure of the overall level of VOCs in a given space without identifying each specific compound [3]. Formaldehyde is a specific type of VOC, a colourless, flammable gas with a strong odour, commonly used in building materials and household products. Short-term exposure to formaldehyde can cause watery eyes, burning sensations in the eyes, nose, and throat, coughing, wheezing, nausea, and skin irritation. Long-term exposure has been linked to an increased risk of cancer [4]. Children are particularly vulnerable to the effects of VOCs and formaldehyde due to their developing bodies and higher breathing rates relative to their body weight [5]. Building certification tools like SBTool, LEED, BREEAM and WELL are designed to

promote sustainable building practices and ensure healthy indoor environments. These tools often require the monitoring and control of VOCs and formaldehyde concentrations [6] thus play a crucial role in creating healthier indoor environments [7].
The purpose of this paper is to present the results of measurements of TVOCs, formaldehyde and carbon dioxide (CO_2)concentrations in classrooms of three newly commissioned schools in the Czech Republic. These buildings were striving for SBTool CZ certification, which necessitated the mentioned measurements.

2. Methodology

2.1 Monitored schools/classrooms
IAQ was monitored in three classrooms in three different types of schools that were renovated or newly built. All of these schools were commissioned between 2022 and 2024. Measurements were always taken shortly after commissioning so all the equipment of the classrooms was new. The all ventilation systems are during the week days controlled according to the concentration of CO_2 and during weekends the air flow rate is decreased to minimal level in all the buildings. Only school 1 has openable windows, which were not operated during the measurement.The monitored areas are shown in Figure 1.

School 1 The first monitored room is a standard classroom of a high school in Prague. The age of students using this classroom is from 11 to 19. The number and age of the students changes during the day and week.

School 2 The second monitored classroom is the classroom for practical education of the secondary school of horticulture in Prague. The age of students using this classroom is from 16 to 20. Students spend limited time here during the year, only in practical flower arranging courses.

School 3 The third classroom is a regular classroom in the building of the Faculty of Economics of the university in Ostrava. The age of students using this classroom is over 19. Different numbers of students are present during the week classroom operation.

2.2 Boundary conditions for measurement and evaluation of indoor air quality
Measurements were carried out for at least one week in each building to cover periods of normal operation and periods of no operation (weekends). Details of the conditions are given in Table 1. The location of the air intake point for the analysis was preferably in the middle of the room which was possible for the first two classrooms, in the case of the third classroom this point was in the area for the teacher. In each room, the current concentration of TVOC and formaldehyde were measured with a time step of approximately 4 minutes and the average hourly concentration was always calculated for evaluation. The measurements were supplemented by monitoring the carbon dioxide concentration to get a clearer picture of the occupancy and ventilation system management.

Measuring instruments and data evaluation. The Innova photoacoustic gas monitor was used to measure TVOC, formaldehyde and carbon dioxide concentrations. This instrument measures the concentration in ppm and for conversion to $\mu g/m^3$ a molar mass of formaldehyde of 30.026 g/mol and molar mass for the TVOC of 78 g/mol were considered. The carbon dioxide concentration was further measured with a Comet data logger. The Czech regulations in force (at the time of the measurements) were used to evaluate the indoor air quality[8][9]. There is no given limit value for TVOC concentration in the Czech regulations, in this case the limit according to the World

Figure 1. Monitored classrooms from left: school 1, school 2, school 3

Health Organization (WHO) was used. All required limit values are in accordance with SBTool certification requirements. Details are in Table 2.

Table 1. characteristics of the rooms and monitored period

School	Type of the classroom/Volume[m^3]	Monitored period	Measuring point position
School 1 high school	Normal classroom /228	March 6-12, 2023	in the middle of the room near the exhaust air of the ventilation system (at a height of 2.5m)
School 2 horticultural high school	Practical classroom – flower arranging /364	June 11-18, 2024[a]	in the middle of the room, above the desk (at a height of 1.6 m)
School 3 university	Normal classroom /147	October 25 -31, 2024	at the front of the room by the whiteboard (at a height of 1.7 m)

[a] Students present only on 13th and 14th June

Table 2. Measuring instruments, measured quantities, requirements of standards

Instrument	Quantity [measured units]	Recalculation ppm→μg/m³ molar mass [g/mol]	Standard requirement value (according to)
Photoacoustic gas monitor Innova	TVOC concentration [ppm]	78	3000 μg/m³ (WHO)[a]
Photoacoustic gas monitor Innova	Formaldehyde concentration [ppm]	30.26	60 μg/m3 (Decree No. 6/2003 Coll.)[b]
Photoacoustic gas monitor Innova / datalogger Comet	CO_2 concentration [ppm]	-	1200 ppm (Decree No. 146/2024 Coll.)[c]

[a] 1hr concentration, SBTool highest limit, no Czech limit for TVOC concentration

[b] 1hr concentration, Czech Decree for hygienic limits of chemical, physical and biological indicators, SBTool limit

[c] Czech Decree on construction requirements

3. Results

The measured data have been processed and all results can be found in the respective research reports [10][11][12]. For our purposes, the weekly course of all observed variables for each classroom was always used.

3.1 School 1

TVOC concentration In the first classroom (Figure 2) TVOC concentrations always increase during the night due to emissions from interior furnishings, with a decrease in the early morning due to the start of the ventilation system. On some days there is an extreme increase in concentration in the morning hours (limit for TVOC is exceeded), in this case the source of the pollution can be considered to be the occupants (release of TVOC from the furnishings is slow). Increased concentration during the weekend is due to the interior furnishings and reduced air flow rate.

Formadehyde concentration Figure 3 shows the course of the hourly formaldehyde concentration. The concentration is almost always below the required limit during the period of the school's operation. At the weekend, the limit value is exceeded almost twice as much. The chart shows that the school's ventilation system is able to maintain a safe level of formaldehyde when students are present.

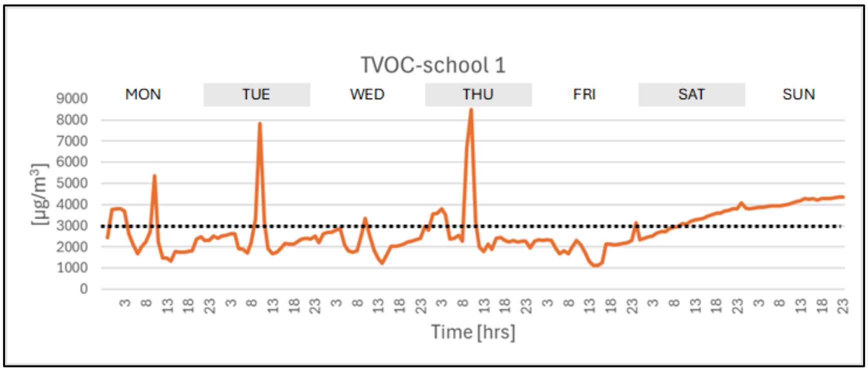

Figure 2. 1 hr concentration profile of TVOC– school 1, dotted line represents the limit value

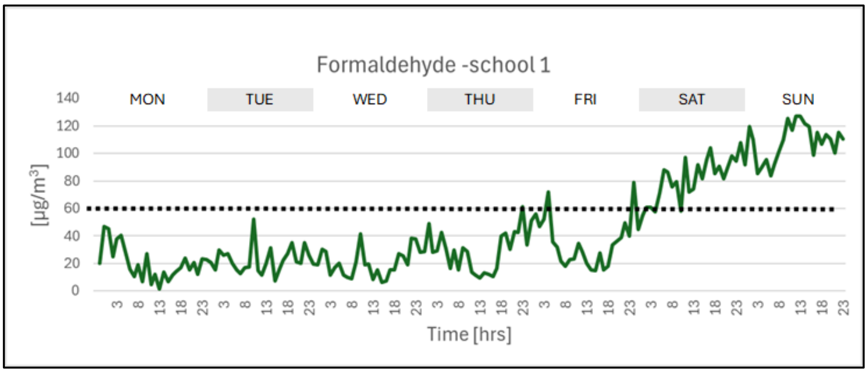

Figure 3. 1 hr concentr. profile of Formaldehyde – school 1, dotted line represents the limit value

The chart of *carbon dioxide concentration* (Figure 4) gives information about the occupancy of the monitored classroom. During the morning hours of the working week the concentration increases, during the afternoon hours it gradually decreases. On some days the concentration limit value was briefly exceeded in the early afternoon.

3.2 School 2

TVOC concentration can be seen in Figure 5. During the absence of people, the concentration is stable around 10000-15000 μg/m³ with the highest values measured in the early morning hours, then the concentration decreases on weekdays due to the start of the ventilation system. The high

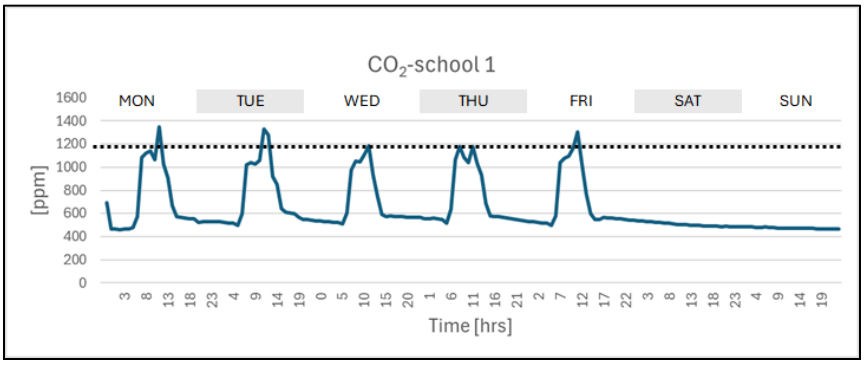

Figure 4. CO_2 concentration profile – school 1, dotted line represents the limit value

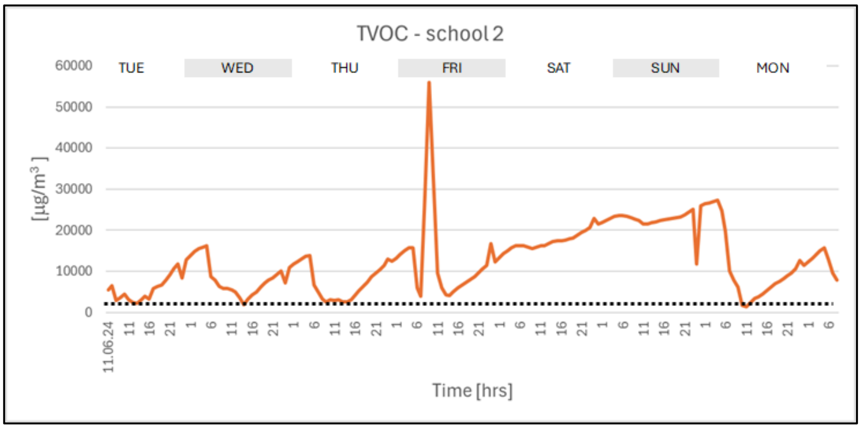

Figure 5. 1 hr concentration profile of TVOC– school 2, dotted line represents the limit value

TVOC concentrations seem to be caused by release of these substances from the interior furnishings and structures. Furthermore elevated values of up to around 55000 μg/m³ occur during the occupancy of persons, when VOCs can be connected to users´ activities. The values are more than ten times higher than the WHO safe level. *Formaldehyde concentrations* shown in Figure 6 are very high on average over the whole period, however, from its course it can be concluded that the production is also linked to the interior furnishings and structures. Concentrations increase during the night and decrease during the day, with the switching on/off the ventilation system on weekdays. At the weekend the concentration increases steadily due to

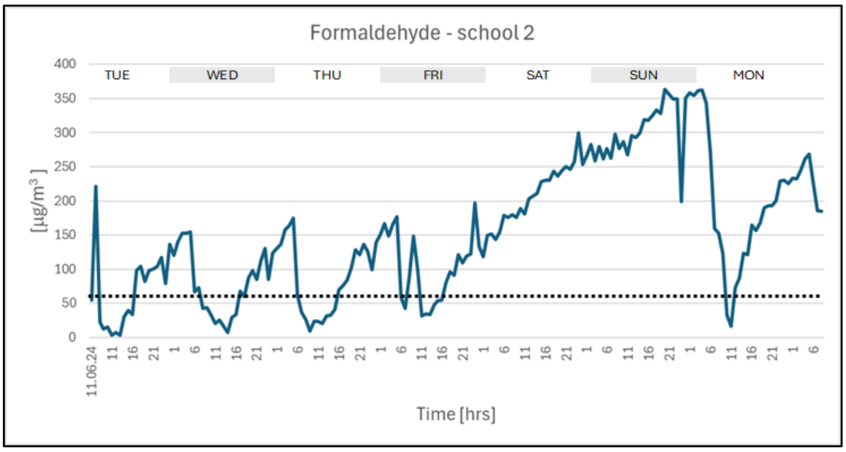

Figure 6. 1 hr conc. profile of Formaldehyde – school 2, dotted line represents the limit value

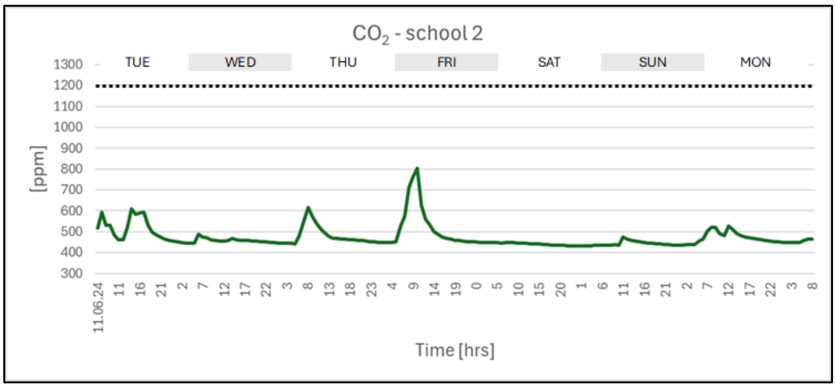

Figure 7. CO_2 concentration profile – school 2, dotted line represents the limit value

different ventilation pattern. Overall, the measured formaldehyde concentrations are higher than the limit.
The *CO_2 concentration* is shown in the Figure 7. The course of the concentration corresponds to a situation where the classroom is no longer used much towards the end of the school year, except partially on Thursday 13th June and Friday 14th June 2024, when students were present according to the normal regime. The maximum value of 1200 ppm was not exceeded.

3.3 School 3

Figure 8 shows the *TVOC concentration* in the third classroom. During the night, the TVOC concentration in the classroom increases, while during the day it decreases, which corresponds to the activation of the ventilation system.The highest TVOC concentrations during days when the building is fully in use are lower than when users are not present. In the classroom, the TVOC concentration was below the limit value of 3000 μg/m³ during almost all measurements. One extreme value can be recorded in the classroom on Thursday (31st October)in the morning. This level was almost 5000 μg/m³. It can be assumed that the source is some unique activity of the users. The concentration of formaldehyde is consistent with this. *Formaldehyde concentration* (shown in Figure 9) is relatively low on average throughout the period, suggesting that production

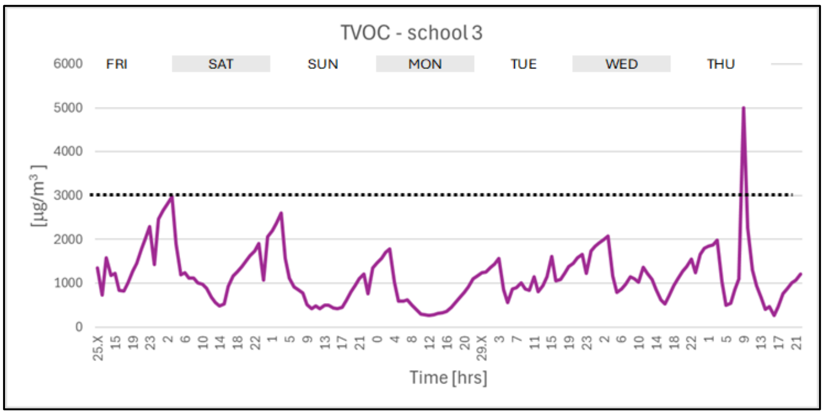

Figure 8. 1 hr concentration profile of TVOC– school 3, dotted line represents the limit value

is related to indoor furnishings. The concentration increases during the night and decreases during the day, presumably as the ventilation system is switched on/off. All values below the limit. Figure 10 shows that the trend in *carbon dioxide concentrations* corresponds to a situation where the monitored areas were not used during the weekend and then also on Monday, which was a public holiday. From Tuesday to Thursday the classroom was in normal use. Absolute values are fine, maximum value of 1200 ppm was not exceeded.

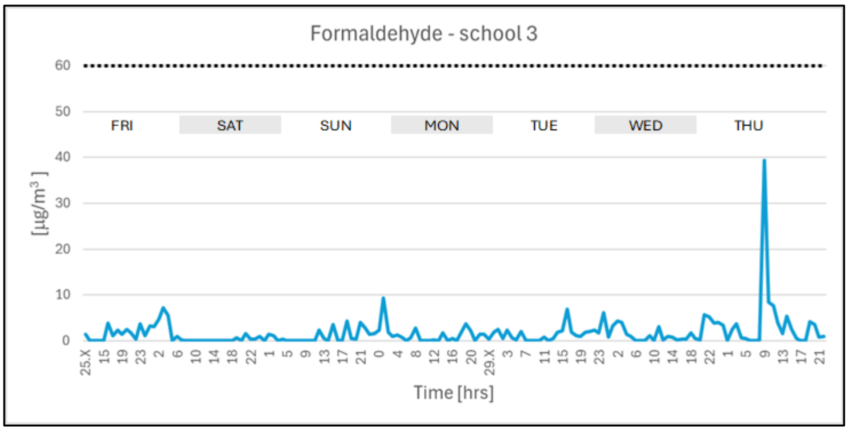

Figure 9. 1 hr concentr. profile of Formaldehyde– school 3, dotted line represents the limit value

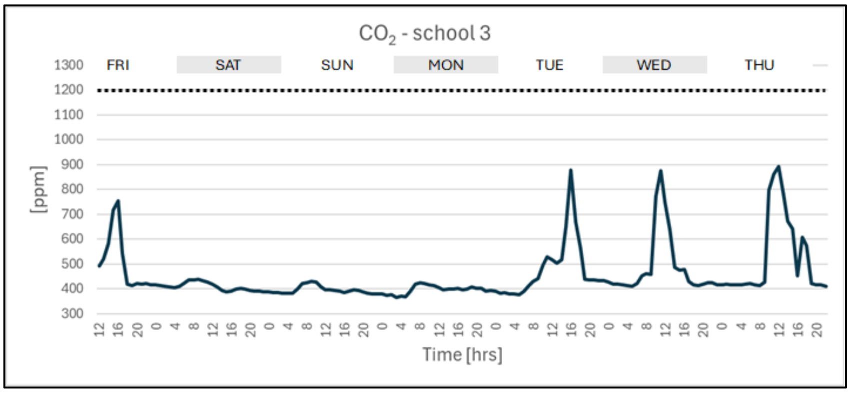

Figure 10. CO_2 concentration profile – school 3, dotted line represents the limit value

4. Conclusion

The results presented show that the air quality in school buildings freshly commissioned, whether after renovation or in new buildings, can vary considerably. Some of the buildings studied met the requirements of the applicable standards, either due to lower initial pollutant loads or appropriate ventilation system settings during operation. One school was found to have a very toxic environment even with the ventilation system in operation. Based on the measured concentration trends, it can be concluded that, in addition to the interior furnishings, user activity can also be a significant source of pollutants. For some buildings it would be appropriate to consider controlling the ventilation system not only based on carbon dioxide concentrations but also on VOCs concentrations.

Acknowledgements.
The generative AI tool Microsoft Copilot (2025) was used in the theoretical part of the introduction chapter for finding sources and phrasing.

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Circular economy, resilience and sustainability in building design

A Unified Approach to Reuse and Recycling LCA in Steel Construction

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Abstract. This paper offers guidance on modelling reuse and recycling in the life cycle assessment of constructional steel. Reusing constructional steel can significantly reduce greenhouse gas emissions, conserve natural resources, and minimise the environmental impact of construction works. A material that cannot be reused is typically recovered and recycled, resulting in only a minimal amount of untreated end-of-life waste. Steel can be repeatedly recycled but reuse can only be performed a limited number of times. This creates challenges in interpreting EN 15804 for simultaneous closed-loop recycling and open-loop reuse. The recently published methodology by World Steel Association addresses this issue but is not harmonised with the European standards. Our study shows how to convert World Steel Association's lifecycle models to EN 15804 and back. It demonstrates that if the open-loop reuse cycle is embedded in the closed-loop recycling, the whole system can be treated as closed-loop and simplified.

1. Introduction

The environmental impact of steelmaking in Europe has reduced significantly in the last decades due to more efficient production and recycling technologies. Today, the average CO_2 emissions intensity of 1 tonne of crude steel is 1.9 tonnes of CO_2 [1], which is almost half of its value from 1960s. This can be reduced to approx. 0.37 tCO_2e by recycling scrap and using renewable electricity in Electric Arc Furnaces (EAFs) [2-3]. Further reduction is possible with recirculation of reclaimed steel without melting. Reusing such steel can reduce the carbon intensity of the material to 0.05 tCO_2e [4-5] but requires products or structural systems suitable for separation and reuse. To acknowledge the recirculation potential of construction products, their Environmental Product Declarations (EPDs) contain declarations of the loads and benefits beyond the system boundary, so-called Module D. This module is compulsory for the EPDs according to EN 15804 [6].

Modern steel is almost 100% collected for recycling, which also means that the reusable products were originally made from a certain amount of scrap and will be collected for recycling after their last reuse cycle. Therefore, reuse is embedded in the recycling loop as described in

Figure 1 where M_{in} and M_{out} are amounts of secondary material entering or exiting the system and M_{in}^{*} and M_{out}^{*} are amounts of steel scrap used for the first production of the reusable product and recovered after the product is not reusable anymore. Downstream material losses in the recycling process are expressed in constructional steel by the efficiency factor Y.

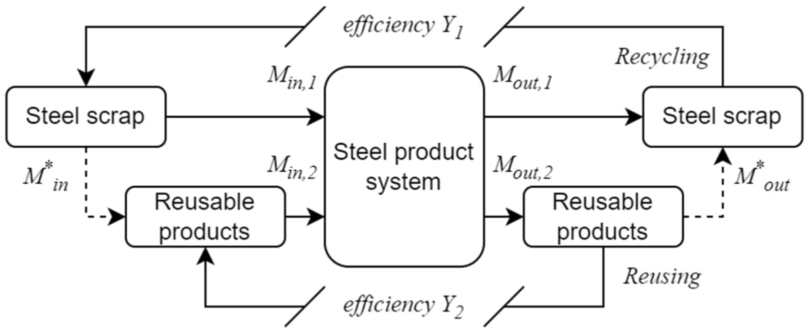

Figure 1. Material flows of constructional steel recycling and reuse

Reuse and recycling are fundamentally different processes. Reuse avoids melting, allowing a product to be used again with minimal processing, though it may only be feasible a limited number of times. Recycling, on the other hand, involves melting steel scrap to create entirely new products, enabling infinite cycles. While steel recycling rates are already high, reuse remains limited due to low supply and demand, design and legislation constraints, and uncertain properties of components. Increasing reuse requires design incentives and market adaptation. A stronger connection to circular economy principles could enhance the approach, while policies, or real-world applications can support the credibility and practicality of the approach. Ultimately, steel products that are unsuitable for reuse are recycled, ensuring continuous material circulation, while reused steel often contains some recycled content from its original production.

Steel recycling can be considered as closed-loop process, and therefore the emissions substituted by recycling correspond to the virgin material product as explained in ISO 14044 [7] and the Life Cycle Inventory (LCI) methodology of the World Steel Association [8-9]. Reuse of steel is, however, an open-loop process with a limited number of cycles. The following sections will explain different modelling approaches for reuse and recycling of constructional steel with the focus on the loads and benefits for Module D1 related to circulation of secondary materials.

2. CEN methodology

The loads and benefits of future recycling, recovery and reuse are part of mandatory Module D reporting requirements used for the Environmental Product Declarations in the EU. Their calculation shall follow the allocation procedure of reuse, recycling, and recovery of materials in Section 6.4.3.3 of EN 15804 [6] published by the European Committee for Standardisation, CEN.

In Module D1, the net impacts related to the export of secondary materials are calculated by adding all output flows of a secondary material $M_{MR,out}$ and subtracting all input flows of this secondary material $M_{MR,in}$ from sub-modules, modules and from the total product system, by adding the impacts connected to the recycling or recovery processes from beyond the system boundary up to the point of functional equivalence where the secondary material substitutes primary production $E_{MRafterEoW,out}$ and subtracting the impacts resulting from the substituted production of the product from primary sources $E_{VMSub,out}$ and by applying a justified value-correction factor to reflect the difference in functional equivalence where the output flow does not reach the functional equivalence of the substituting process $Q_{R,out}/Q_{Sub}$. Formula D.6 of EN 15804 shows the practical implementation of this methodology (see Eq. (1)).

$$e_{moduleD1} = \sum_i \left(M_{MR,out,i} - M_{MR,in,i}\right)\left(E_{MRafterEoW,out,i} - E_{VMSub,out,i}\frac{Q_{R,out,i}}{Q_{Sub.i}}\right) \quad (1)$$

It should be noted that interpretation of this formula is still not clear i.e. unless reuse and recycling are treated separately, the net flow of secondary material can be interpreted as zero [10]. If we consider reuse and recycling as two different processes, Eq. (1) will result in the sum of two independent impacts, recycling and reuse, that can be calculated separately without taking into account the initial production of the reused material M^*_{in} and final recycling of the reusable material M^*_{out} (see Figure 2). This interpretation is used for the constructional steel recycling and reuse in several guides [11-12] and in prEN 17662 [13].

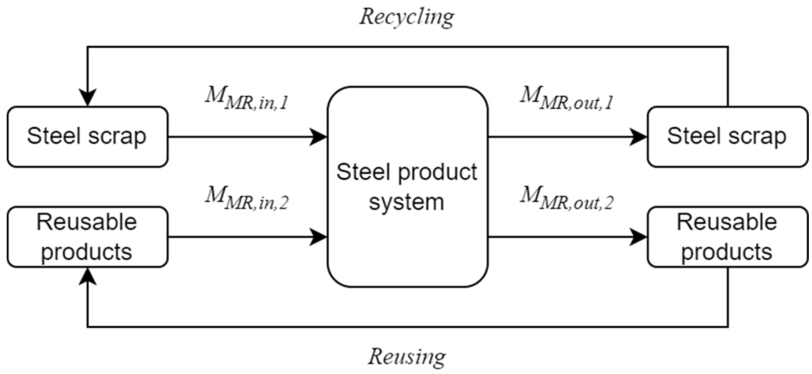

Figure 2. Material flows of constructional steel recycling and reuse according to CEN methodology

We will explain the following sections why it is possible to disregard the external flows M^*_{in} and M^*_{out} in the LCA of constructional steel and under which conditions the same approach can be used for the different materials.

3. World Steel Association methodology

The new Guidance of methodologies for modelling reuse and remanufacture in LCA studies by the World Steel Association [14] describes three methods to account for reuse and recycling: (1) end-of-life method, (2) market-based method and (3) multiple use method. In this paper, we will focus on the end-of-life method, which is directly related to the CEN methodology described in the previous section. The method considers reuse as an open-loop process with a limited number of cycles between the production and recycling of the reusable material, where the effect of external flows of steel scrap M^*_{in} and M^*_{out} is included in the calculation (see Figure 3).

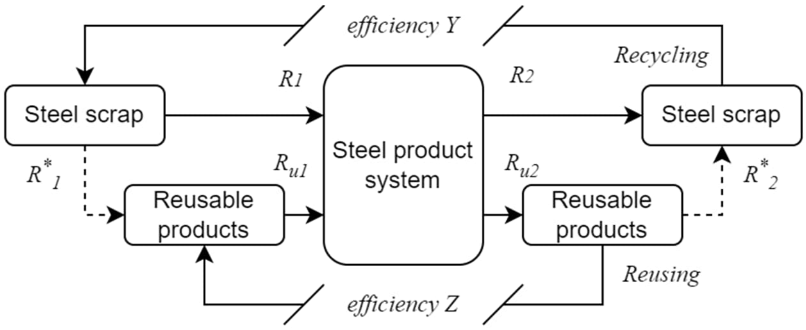

Figure 3. Material flows of constructional steel recycling and reuse according to World Steel Association

3.1 Net benefit of recycling

The net impact of the recovery and production of steel from scrap $LCI_{for\ scrap}$ (or X_{sc} in [14]) was already established in 2011 [8] and follows the Eq. (2) where X_{pr} is the LCI for theoretical 100% primary steel production, from the Blast Oxygen Furnace (BOF) route (assuming 0% scrap input), X_{re} is LCI for 100% secondary steel production from scrap in the EAF (assuming 100% scrap input) and Y is the process yield (or efficiency) of the EAF process (more than 1 kg scrap is required to produce 1 kg steel) [14].Then the net impact related to steel recycling can be calculated by multiplying the net material flows and the scrap LCI as described in Eq. (3),

$$LCI_{for\ scrap} = X_{sc} = \left(X_{pr} - X_{re}\right)Y \quad (2)$$

$$net\ benefit\ of\ recycling = \left(R_2 - R_1 + (R_{u2} - R_{u1})(R_2^* - R_1^*)\right)X_{sc} \quad (3)$$

where the difference between direct material input R_1 and output R_2 is added to the external flows R_1^* and R_2^* applied on the part of the product that is reused with input R_{u1} and output R_{u2} (see Figure 3). It should be noted that all the material flows in Eq. (3) are assumed to be fractions of total product mass and the resulting net impact will be the amount of emissions or resources consumed per unit of mass (e.g. tCO_2e/t).

3.2 Net benefit of reuse

The cradle to gate LCI, including the end-of-life impacts of recycling, for a product (or part of the product) that is suitable for reuse or remanufacture $X_{inc\ recycling}$ is calculated by correcting the LCI for the manufacture of the original product X_m by the burdens and benefits of recycling steel at the product first manufacturing and its final disposal (see Eq. (4)). Then, the calculation of the LCI of the reusable product in the Eq. (5) is presented by the difference between $X_{inc\ recycling}$ and LCI for 100% refurbishment for reuse or remanufacture of a steel product X_{refurb} multiplied by the process yield Z in a similar way as Eq. (2). The net impact of reuse is again obtained by multiplying LCI with the net difference between the reused and reusable fraction of the product R_{u1} and R_{u2} (see Eq. (6)).

$$X_{inc\ recycling} = X_m - (R_2^* - R_1^*)X_{sc} \quad (4)$$

$$LCI_{for\ a\ product\ that\ can\ be\ refurbished} = \left(X_{inc\ recycling} - X_{refurb}\right)Z \quad (5)$$

$$net\ benefit\ of\ reuse = (R_{u2} - R_{u1})LCI_{for\ a\ product\ that\ can\ be\ refurbished} \quad (6)$$

3.3 End-of-life formula

The end-of-life method of World Steel Association results in the calculation of *LCI including end of life for a reused or remanufacture product* which is the sum of the manufacturing impacts and the net benefits of recycling and reuse. Adding manufacturing impact to their net benefits is sometimes called the 0:100 approach and it can be demonstrated that the resulting LCI is unable to show the differences between various manufacturing processes. Therefore, the CEN methodology strictly separates the calculation of net benefits $e_{moduleD}$ from the other impacts.

In this paper, we will focus only on the part of the end-of-life formula, the combined net impact of recycling and reuse. This should correspond directly to EN 15804 methodology for loads and benefits of future recycling and reuse but is based on different material flows (compare Figures 2 and 3). Moreover, the EN 15804 methodology does not recognize the effect of downstream material losses in the recycling and the reuse process (Y and Z in Eq. (2) and Eq. (5)) and the World Steel Methodology does not account for the quality of the recovered materials and products (see $Q_{R,out}/Q_{Sub}$ in Eq. (1)). The value of $e_{moduleD1}$ based on the model described in Figure 3 should be negative of the sum of reuse and recycling net benefits according to the World Steel Association's methodology (see Eq. (7)).

$$e_{moduleD1} = -(net\ benefit\ of\ recycling + net\ benefit\ of\ reuse) \tag{7}$$

4. Compatibility of CEN and World Steel Association LCA models

Despite the fundamental differences in modelling of material flows, we proved that CEN methodology and World Steel Association's methodology lead to the same result [14]. The following sections will explain how to simplify the World Steel Association model to match Eq. (1) from EN 15804 and how to expand the CEN model to the format of Eq. (7).

4.1 Reducing open-loop World Steel Association model to closed-loop CEN model

The net benefit of recycling can be expressed by combining equations Eq. (2) and Eq. (3), and separating impacts related to the external flows R_1^* and R_2^* as in Eq. (8). Similarly, by combining Eq. (4) to (6) and separating the external flows we obtain net benefit of reuse in Eq. (9).

$$net\ ben.of\ recycling = (R_2 - R_1)(X_{pr} - X_{re})Y + (R_{u2} - R_{u1})(R_2^* - R_1^*)(X_{pr} - X_{re})Y \tag{8}$$

$$net\ ben.of\ reuse = (R_{u2} - R_{u1})(X_m - X_{refurb})Z - (R_{u2} - R_{u1})(R_2^* - R_1^*)(X_{pr} - X_{re})YZ \tag{9}$$

It is reasonable to assume that the yield (or efficiency) of the reuse process Z is equal to 1. Then, after adding the net benefit of reuse to the net benefit of recycling, the terms related to the external flows R_1^* and R_2^* will be cancelled out and Eq. (7) can be written as Eq. (10).

$$e_{moduleD1} = (R_2 - R_1)(X_{re} - X_{pr})Y + (R_{u2} - R_{u1})(X_{refurb} - X_m) \tag{10}$$

As can be seen, the Eq. (10) based on the World Steel Association's methodology takes the form of Eq. (1) from EN 15804, where the quality factors are equal to 1 and the steel scrap flows are corrected by the yield factor Y. This shows that the combined effect of closed-loop recycling and open-loop reuse of steel is equal to the sum of these effects calculated separately with open-loop allocation. In other words, when the open-loop reuse cycle is embedded in closed-loop recycling, the whole system remains closed-loop and the knowledge of R_1^* and R_2^* is not required.

If the variables listed in Table 1 remain the same, both equations (Eq. (1) and Eq. (10)) will produce the same value of $e_{moduleD1}$.

Table 1. Corresponding parameters of CEN methodology and World Steel Association's methodology

Column heading	CEN	World Steel Association
amounts of input and output recycled material to the product system	$M_{MR,in,1}$ $M_{MR,out,1}$	R_1 R_2
amounts of input and output reused material to the product system	$M_{MR,in,2}$ $M_{MR,out,2}$	R_{u1} R_{u2}
specific emissions from recycling of the current system and specific emissions of the primary material	$E_{MRafterEoW,out,1}$ $E_{VMSub,out,1}$	X_{re} X_{pr}
specific emissions from reuse of the current system and of the manufactured product	$E_{MRafterEoW,out,2}$ $E_{VMSub,out,2}$	X_{refurb} X_m
quality correction factor	$Q_{R,out}/Q_{Sub}$	1.0
yield (efficiency) of the recycling and reuse process	Y_1, Y_2	Y, Z

4.2 Expansion of closed-loop CEN model to open-loop World Steel Association model

Observant reader already noticed that while Eq. (7) and Eq. (10) produce the same result, their components related to reuse or recycling are not equal. Open-loop model in Eq. (7) increases the benefits of recycling by the effect of the external flows in comparison to the closed-loop model in Eq. (1) or Eq. (10). On the other hand, the benefits of reuse in the open-loop model are decreased by the same amount (see Eq. (4)) because the substituted emissions or resources cannot be based on the virgin material production anymore. The problem of closed-loop and open-loop allocation is explained in more detail in ISO 14044 [7].

If the LCA assessment requires reporting effects of reuse and recycling separately (e.g. $e_{moduleD1.1}$ and $e_{moduleD1.2}$), the more complicated open-loop model shall be used because it corresponds to the real product system described in Figure 1. In this section, it will be shown how to construct such a model within the scope of EN 15804.

First, we must establish the effect of external flows of the steel scrap in Eq. (11), where M_{in}^* and M_{out}^* are the amount of scrap used in the manufacturing process of the product before it (or its part) is reused for the first time and the amount of scrap recovered from the product after it (or its part) cannot be reused anymore, and M is the total amount of material in the product. The second step is to update the values of $M_{MR,in,1}$, $M_{MR,out,1}$ and $E_{VMSub,out,2}$ according to Eqs. (12) to (14). This procedure is explained in detail in the methodology report of the ADVANCE project [15] and is demonstrated in several examples.

$$\Delta M^* = (M_{out}^* - M_{in}^*)/M \quad (11)$$

$$M_{MR,in,1}^* = M_{MR,in,1} + M_{MR,in,2} \cdot \Delta M^* \quad (12)$$

$$M_{MR,out,1}^* = M_{MR,out,1} + M_{MR,out,2} \cdot \Delta M^* \quad (13)$$

$$E_{VMSub,out,2}^* = E_{VMSub,out,2} - \left(E_{VMSub,out,1} - E_{MRafterEoW,out,1}\right)(Y_1/Y_2)\Delta M^* \quad (14)$$

After substituting the values $M_{MR,in,1}$, $M_{MR,out,1}$ and $E_{VMSub,out,2}$ with their corrected counterparts in Eq. (1), the overall impact $e_{moduleD1}$ will remain unchanged. However, its recycling and reuse components will be aligned with the World Steel Association methodology.

4.3 Comparison of closed-loop and open-loop models

The comparison between both models was performed on five scenarios proposed by the World Steel Association [14], where the external flows of 1 tonne of steel product are M_{in}^{*} = 0.07 t and M_{out}^{*} = 0.95 t (R_1^* and R_2^* in [14]). The yield factors are Y_1 = 0.92 [8] and Y_2 = 1 (Y and Z in [14]). The LCI of steel scrap $(E_{MRafterEoW,out,1} - E_{VMSub,out,1})Y_1$ = 1.62 tCO_2e/t (X_{sc} in [14]). GWP of manufacturing of the new product and the refurbishment of the reused one are then $E_{VMSub,out,2}$ = 2.7 tCO_2e/t and $E_{MRafterEoW,out,2}$ = 0.1 tCO_2e/t (X_m and X_{refurb} in [14]). The net material loads of the calculated scenarios are presented in Table 2. It should be noted that the net loads in Table 2 are negative values of net benefits (see Eq. (3) and Eq. (6)) and their sum corresponds to the negative value of World Steel Association's end-of-life method without the manufacturing part.

Table 2. Net impacts based on the scenarios from the World Steel Association guidance [14]

Material flows [t]	(A) No reuse, 95% end of life recycling	(B) 100% reused input	(C) 100% reused output	(D) 100% reused input and output	(E) 50% reused output
$M_{MR,in,1}$ (R_1)	0.07	0	0.07	0	0.07
$M_{MR,out,1}$ (R_2)	0.95	0.95	0	0	0.5
$M_{MR,in,2}$ (R_{u1})	0	1	0	1	0
$M_{MR,out,2}$ (R_{u2})	0	0	1	1	0.5
Open-loop net loads [tCO_2e/t] according to Eq. (7) and World Steel Association's methodology					
recycling	-1.43	-0.11	-1.31	0.00	-1.41
reuse	0.00	1.17	-1.17	0.00	-0.59
total ($e_{moduleD1}$)	-1.43	1.06	-2.49	0.00	-2.00
Closed-loop net loads [tCO_2e/t] according to Eq. (1) and CEN methodology					
recycling	-1.43	-1.54	0.11	0.00	-0.70
reuse	0.00	2.60	-2.60	0.00	-1.30
total ($e_{moduleD1}$)	-1.43	1.06	-2.49	0.00	-2.00

As can be seen from Table 2, both models produce the same total net loads of reuse and recycling across all scenarios. When dealing with recycling only (scenario A), both models are identical. However, with the addition of reuse, the closed-loop model shows larger difference between recycling and reuse components of the model (scenarios B, C and E). The reason is that the open-loop model considers part of the impacts of the reused material to be attributed to recycling because of the original material production and the final scrap recycling after the last reuse cycle. The recycling flows are increased (see Eq. (12) and Eq. (13)) and the emissions substituted by reuse are proportionally decreased (see Eq. (14)).

5. Summary and conclusions

This study demonstrates that it is possible to align the World Steel Association's methodology [14] with EN 15804 [6], which is commonly used for the development of Environmental Product Declarations (EPDs) in the EU. If the efficiency of the reuse process is 1.0, both methodologies produce equivalent results in terms of the total impact of recycling and reuse. However, their components related to recycling and reuse are different with the open-loop (Figure 1) and closed-loop (Figure 2) model. Both methods can be used to determine the total impact of combined recycling and reuse (e.g. Module D1 in EPDs), and the World Steel Association method can be further simplified without the need of external flows R_1^* and R_2^*. This is particularly important for businesses dealing with reused material, where the original amount of scrap R_1^* is not always known [5]. On the other hand, it is not recommended to report contribution of recycling and reuse separately with closed-loop model without the additional parameters M_{in}^* and M_{out}^*.

The calculations described in this paper are generally not restricted to constructional steel. These models can be applied also to materials suitable for closed-loop recycling, such as plastics or glass, where reuse is feasible. However, further methodology development is required for materials unsuitable for closed-loop recycling. Examples of different materials are given in [15].

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Accelerating Municipal Building Decarbonization: Tools and Strategies for Sustainable Retrofits

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Abstract. To meet European climate targets and Austria's 2040 climate neutrality goal, a significant increase in the national retrofit rate is essential. The project IncorporatEE, funded under the EU's Horizon 2020 program, addresses this challenge by optimizing processes for sustainable renovations in the Austrian cities of Salzburg and Villach, facilitating the decarbonization of municipal real estate portfolios. By analysing current procedures, the project identified areas for improvement and developed targeted recommendations and tools. Three preparatory phases—real estate strategy, portfolio analysis, and budgeting—are integrated into standard project planning, ensuring sustainability is early considered in project selection and budgeting. Clear, verifiable sustainability goals are assigned to planners and contractors, with quality assurance methods in place to monitor compliance. To support the implementation of sustainable retrofits, alternative financing models, such as through green bonds or contracting agreements, are explored and compared. Key tools developed include a portfolio management cluster table, a sustainability criteria catalogue based on Austria's "klimaaktiv" standards, process charts and sample tender texts to streamline and standardize sustainable retrofits. Pilot projects tested these tools, generating insights and fostering internal expertise. Additionally, task overviews and linked training videos help municipal staff adopt these approaches more effectively. In summary, the publication presents valuable enhancements to planning processes, enabling municipalities to embed sustainability in the decarbonization of their building portfolio, increasing both quality and quantity of municipal retrofits.

1. Introduction

1.1 Policy Background and Decarbonization Requirements

European cities are facing increasing regulatory pressure to reduce the carbon footprint of their building stock. The European Union has legally committed to achieving climate neutrality by 2050, as outlined in the *European Climate Law* and operationalized through the *European Green Deal*. Austria has gone further by setting a national target of net-zero emissions by 2040.

The recast Energy Efficiency Directive (EED III), adopted in 2023, significantly strengthens requirements for the public sector: Member States must ensure an annual renovation rate of at least 3% of the total floor area of public buildings owned by public bodies. Additionally, the directive demands that all public buildings progressively meet minimum energy performance standards, with a focus on deep renovations and the phase-out of fossil heating systems. These requirements necessitate not only technical upgrades but also structural changes in how municipalities plan, budget, and implement renovation projects.

1.2 EU-Project IncorporatEE/SanierungsPLUS

The EU-funded project *IncorporatEE/SanierungsPLUS*, supports the cities of Salzburg and Villach in optimizing administrative processes to accelerate and enhance deep refurbishments and heating replacements in public buildings. This initiative aims to drive decarbonization within the cities' sphere of influence by strengthening municipal capacities and refining existing procedures through real-world case studies. The project operates on two levels:

Institutional Level – Developing and adapting methods for energy-efficient renovations to fit the cities' needs while establishing organizational units to ensure long-term expertise and resources.

Implementation Level – Testing and evaluating new processes through actual renovation projects. By applying enhanced planning methods, higher energy efficiency and increased use of renewable energy sources can be achieved and maintained through quality assurance.

1.3 Challenges in Sustainable Project Development

Project development, particularly for renovations, is inherently complex, requiring expertise across various disciplines. Project managers must balance user needs, safety, legal compliance, and budget constraints, all within tight timelines. Sustainability has long been a consideration, especially for public buildings, but growing concerns over climate change and resource scarcity demand a more integrated approach. This adds considerable complexity and often exceeds the capacity of existing municipal teams. Rapidly evolving regulations, coupled with technical uncertainties and budget pressures, increase the risk that planners default to conventional approaches, which may fall short of decarbonization goals.

Moreover, each city starts from a different baseline, e.g. in terms of data availability, institutional capacity, regulatory flexibility, and building stock characteristics. This is true not only across Europe but even within a single country such as Austria. As such, no single solution fits all, and not all challenges can be captured through the analysis of two cities alone. Nevertheless, the tools and approaches presented in this paper are designed to address common structural barriers faced by many municipalities: unclear early-phase decision-making, limited integration of sustainability in contracts, fragmented responsibilities, and lack of technical validation in planning. These aspects are broadly relevant and form the basis for transferable process innovations that can be adapted to local contexts with appropriate adjustments. By focusing on administrative process design, capacity building, and decision-support tools, rather than site-specific technical prescriptions, this work contributes practical methods that can help other cities navigate similar decarbonization challenges.

Similar challenges have been identified in EU-wide projects such as Act!onHeat, SmartEnCity, and GEO4CIVHIC, which primarily focus on technological innovations for decarbonizing urban buildings and districts. While these initiatives have demonstrated promising technical solutions, many of them reveal implementation gaps linked to insufficient process integration at the municipal level. This paper contributes to the field of applied municipal planning by demonstrating how sustainability goals can be operationalized through institutional processes. Unlike conventional manuals, the approach emphasizes procedural clarity and decision empowerment; elements critical for making renovation strategies effective and scalable across diverse municipal settings.

2. Analysis of the cities' internal processes

The project analysed existing project development and planning processes of municipalities to assess how well sustainability, particularly the decarbonization of building stock, has been integrated. Based on this assessment, recommendations were made to enhance these processes and ensure sustainability is systematically addressed. Additionally, existing responsibilities and decision-making structures were evaluated to determine their suitability for sustainable retrofits and identify areas for refinement. To address gaps, targeted training will be provided for existing staff, equipping them with well-prepared materials and tools on new methods. At the same time, additional personnel were introduced to focus on sustainability, taking on key roles as internal project experts.

2.1 Status Quo and Areas of Improvements

Municipalities followed the Austrian standard planning phases, as defined by service specifications ("Leistungsmodelle") of Graz University of Technology. These phases included:

- Phase 0: Strategy and initiation
- Phase 1: Planning (preliminary design, design, execution planning, and tendering)
- Phase 2: Execution
- Phase 3: Operation

These specifications form the basis for planner contracts and outline both mandatory and optional services for roles such as architects, building physics, and building services. However, contracting authorities may modify or expand these specifications, which also serve as a reference for fee negotiations.

The detailed comparison between the current state and recommended improvements, ensuring a more comprehensive and structured approach to decarbonization in building projects, is summarized in Tables 1–13 of the supplementary materials (*Comparison of Status Quo and Potential Additional Tasks*). These tables outline how sustainability considerations can be integrated into each phase of planning. Furthermore, the optional services within the standard service specifications have been expanded and refined to better address sustainability requirements. The full paper "Planning contracts: Fee Models and Service Specifications" is available online on the SanierungsPLUS project website (in German) [1,2].

3. Integration of sustainability aspects

3.1 Strategy Phase

In addition to the standard planning phases, the project identified the need for a preceding strategic phase. This phase focuses on overarching objectives, portfolio management, budgeting, and alternative financing models.

Many cities have climate neutrality goals, but these are often not directly linked to **a real estate strategy**. A well-defined real estate strategy should outline the desired quality of the building stock, using target criteria such as EU taxonomy compliance or specific emission reduction targets (e.g., 50% CO_2 reduction by 2030). This strategy helps determine whether buildings that fail to meet these criteria should be retained or phased out to avoid becoming stranded assets.

A key step is **analyzing the building portfolio** to create a roadmap for decarbonization. While municipalities often have structured data on their buildings, this is frequently insufficient for strategic decision-making. Critical data include building condition, energy consumption, technical systems, and potential future functional changes. Once comprehensive data is available, buildings can be ranked based on relevant indicators (e.g., energy consumption per m^2, use of fossil fuels, planned renovations). Buildings that show the need for improvement in one or more indicators can then be prioritized for accelerated renovation.

A **top-down budget** estimate, based on the portfolio analysis, provides a rough projection of the funding required to decarbonize the building stock. This estimate forms the basis for identifying additional financing options, such as green bonds, internal sustainability funds, public-private partnerships, contracting models, crowdfunding, or public subsidies.

In practice, renovations are often planned years in advance (e.g., within a five-year framework). To be included in the project plan, a renovation must first be requested by users or other stakeholders (e.g., a sustainability department). If approved, the project is added to the implementation list with an initial budget estimate (±40% accuracy) based on reference values. Future changes in demand, such as demographic shifts affecting schools and kindergartens, should also be factored into this planning. New sustainability criteria—often absent from existing benchmarks—must be integrated into budgeting. Although their impact on rough cost estimates is minimal, failing to account for them can lead to budget shortfalls that delay projects, ultimately hindering climate goals.

3.1 Proper Project Preparation

Effective preparation is key to embedding sustainability in the planning process from the start. This begins with refining user requirements by defining spatial and functional needs, user behaviour, and comfort expectations. These parameters should also anticipate future climate conditions to ensure long-term adaptability.

The early definition of **quality standards** and sustainability targets ensure that all planning decisions align with the municipal goals and contribute to decarbonization efforts. Sustainability aspects must be clearly outlined from the start, as retroactive implementation is often costly and impractical. In this stage, the feasibility of energy supply solutions may be assessed, first exploring ways to reduce energy demand (thermal retrofits), before identifying renewable energy solutions. A comprehensive feasibility assessment at this stage ensures that technically, financially, and environmentally sound solutions are selected, avoiding inefficient or short-sighted decisions later in the process.

The **selection of planners** plays a decisive role in meeting quality and sustainability targets. A well-structured selection process should be used, either through a comparative assessment of multiple proposals or via a competitive public tender. To ensure compliance with the defined quality criteria, these requirements must be explicitly included in the planning contract and verified during contract negotiations. This prevents ambiguities that could lead to lower-quality outcomes or sustainability compromises during implementation.

Furthermore, it is advisable to determine at an early stage which **additional planning services** will be required to provide essential insights for decision-making. Feasibility studies help assess the viability of renewable energy integration before the planning begins, while variant studies compare different systems, such as building envelope elements, heating and ventilation systems, and water distribution solutions. These assessments should not only consider technical and regulatory aspects but also organizational, environmental, and financial feasibility, particularly in terms of long-term operational costs. Advanced building simulations allow for more precise predictions of indoor climate conditions, energy demand, and overall performance, supporting informed choices that enhance both user comfort and efficiency. Facility simulation is a valuable tool for demand-oriented dimensioning of building technologies with the possibility of saving investment costs. Additionally, life cycle cost analyses offer critical perspectives on long-term financial implications, helping municipalities prioritize solutions that provide economic and environmental benefits over the entire building lifespan. A more detailed overview of additional engineering services with outlined approach is presented in Tables 14-17 (*Helpful Accompanying Studies and Services*) of the supplementary materials.

3.2 Quality Assurance

Quality assurance is crucial to ensure that all defined target criteria are met. Regular compliance checks throughout the planning process help to identify and correct deviations early.

Technical monitoring enables the verification of equipment performance and operational management by comparing actual performance with targets, either immediately after the trial run or within the first months of operation. This process helps detect hidden defects that could impact user comfort, increase energy consumption, or damage facilities. However, effective technical monitoring requires a detailed functional description based on performance indicators, which is often not included in standard planning and must be commissioned separately. As a guideline, the freely available technical monitoring framework developed by the German Working Group for Mechanical and Electrical Engineering of State and Municipal Administrations (AMEV) can be used [3].

Additional quality assurance measures include local construction supervision, product and chemical management, blower door tests for airtightness, and thermographic analyses for thermal bridges. Many of these are also necessary to earn points in building certifications or comply with EU taxonomy requirements—objectives that should be clearly defined at the project's outset or even independently of a specific project.

4. Implementation of sustainability aspects

Based on an analysis of existing processes, various tools have been developed to support the integration of sustainability aspects into project development and planning. These tools are designed to enhance decision-making, streamline planning, and facilitate the implementation of sustainable solutions. The key tools developed in the project are:

- **Cluster Table for Portfolio Management:** This table helps to identify the buildings most in need of retrofitting—particularly in terms of energy consumption and CO_2 emissions—to prioritize and accelerate their improvement.
- **Gap Text for User Requirements:** This document supports the identification of user needs, providing planners, particularly those responsible for building technology, with essential information for demand-driven planning.
- **Sustainability Criteria Catalogue:** Developed in collaboration with municipalities and based on the klimaaktiv criteria catalogue, this document establishes standardized sustainability criteria for public projects, incorporating additional municipality-specific priorities.
- **Process Charts**: Checklists are created for project development, planning, and execution of holistic renovations (deep refurbishments), as well as for subprocesses and partial renovations, ensuring a structured and efficient workflow.

- **Analysis of financing models**: To address financial barriers to sustainable renovations, various financing models have been evaluated for their suitability in generating additional budgetary resources for cities:
    - **Green Bonds**: Issuance of bonds dedicated to financing energy-efficient renovations.
    - **Internal Energy Efficiency Fund**: A fund that reinvests savings from demand-oriented planning into further sustainable measures.
    - **Active Funding Management**: Optimizing access to public and private funding opportunities.
    - **Energy Communities**: Leveraging collective investments and shared energy production.
    - **Savings Contracting Models**: Financing renovations through long-term energy cost savings.
    - **Public-Private Partnerships (PPP)**: Collaborations that share financial and operational responsibilities between municipalities and private entities.
    - **Crowdfunding**: Engaging communities in co-financing sustainable building projects.

Existing fee structures have been reviewed to explore ways to incentivize demand-driven planning - ensuring that building areas and technical complexity are kept to "as little as possible, as much as needed". Further elaboration on this topic is available online in the full paper *"Planning contracts: Fee Models and Service Specifications"* on the SanierungsPLUS project website (in German) [1,2].

4.1 Testing in Pilot Projects

The most effective way to refine these tools and methods is through **real-world application**. As part of the IncorporatEE/SanierungsPLUS project, pilot projects serve as test beds for implementing and evaluating various sustainability measures. Depending on the project's specifics, multiple tools have been tested, such as integrating sustainability criteria into architectural competitions, conducting feasibility and variant studies for water heating and renewable energy transitions, and performing thermal and ventilation simulations to optimize system design.

Additionally, tender texts for planning and engineering services have been successfully applied, while photovoltaic potential studies have provided valuable baseline data for future PV projects. These pilot projects have helped build expertise, ensuring that the knowledge gained will inform and streamline future sustainable renovations.

As part of the applied pilot projects, each measure was assessed in terms of its practical implementation, effectiveness, and potential for replication in future projects. For example, in the context of a school refurbishment, the planning process integrated text modules for building services planning, life cycle cost analysis, the calculation of EI10 (Disposal of Waste Indicator) and OI3 (Life Cycle Emissions) analysis to fulfil the "klimaaktiv"-criteria, as well as a variant study for hot water production and distribution. These elements led to a significant optimization of the technical concept.

Further, the energy and emission savings achieved by all real-world application projects are quantified. The IncorporatEE/SanierungsPLUS project's overall targets of reducing primary energy consumption by 55% and achieving annual greenhouse gas emission savings of 870 tonnes of CO_2 equivalent per year, compared to baseline operation, are expected to be met. These figures were derived from energy modelling and planning documentation and reflect the practical effectiveness of the applied methods.

4.2 Training Materials for Knowledge Transfer

While "learning by doing" remains the most effective way to familiarize stakeholders with new methods and tools, not all relevant personnel can directly engage with them through pilot projects. Typically, only project managers or internal sustainability experts involved in specific cases gain hands-on experience, leaving others in the department without direct exposure. Due to the demands of daily operations, knowledge transfer across teams is often insufficient.

To address this gap, the IncorporatEE/SanierungsPLUS project is developing targeted training programs for different groups. These trainings ensure that key sustainability principles, tools, and methodologies are accessible to a wider audience, enabling more project teams to implement best practices in their own work.

Figure 1 outlines the essential tasks that project managers should incorporate across planning phases to ensure sustainable renovations. The lower section of the figure presents the tools developed to support the implementation of these tasks. Given that one-on-one training is inefficient due to time and resource constraints, a structured training program is being developed, mirroring the framework of the figure (Tasks and Tools).

	Phase 0: Preparation	Phase 1: Planning	Phase 2: Execution / Phase 3: Operation
Tasks	✓ Definition of project goals - sustainability goals ✓ Detailed usage requirements ✓ Feasibility study ✓ Renovation concept ✓ Budget (life cycle costs vs. investment costs) and deadlines ✓ Decision on the type and manner of a competition ✓ Preparation of planning contracts and service specifications ✓ Decision on whether to work with BIM	✓ Evaluation of competition entries with regard to sustainability ✓ Obtaining sufficient information for relevant system decisions (LCCA) ✓ Quality assurance of sustainability in • Construction: building envelope, comfort and quality of stay, recyclability, sustainable materials, climate change adaptation • HVAC: demand-based dimensioning and control, low tech, proportion of renewable energy sources, resource monitoring, energy-efficient components	✓ Quality assurance of sustainability ✓ building declaration, if applicable: product and chemical management, blower door, indoor air quality measurements (VOC) ✓ On-site construction supervision, commissioning management, technical monitoring ✓ Setting up temporary and continuous resource and operational monitoring for project acceptance and regular operation
Tools	✓ Sustainability criteria catalog ✓ Checklists / gap text for user requirements ✓ Text modules for planning contracts ✓ Adapted service specifications ✓ Tender texts and explanatory documents for: • Feasibility studies on refurbishment measures and energy supply options • Life cycle cost analyses	✓ Sustainability criteria catalog for tracking of qualities (QA) ✓ Tender texts and explanatory documents for: • Variant studies • Life cycle cost analyses • Building and system simulation • Quality assurance building technology / technical control • Support for building declaration • Technical monitoring ✓ Specifications for EMSR and monitoring concept ✓ Format templates for technical description of building technology (AMEV)	✓ Sustainability criteria catalog for tracking of qualities (QA) ✓ Tender texts and explanatory documents for: • Technical monitoring

Figure 1: Training Structure (Tasks and Tools) for Planning Sustainable Retrofits of Municipal Buildings. Tasks highlighted in green indicate topics with accompanying training or explanatory videos.

The training consists of short explanatory videos, each lasting no more than five minutes, covering key topics. The videos introduce relevant terminology, explain the background and importance of each task within the broader process, and demonstrate how the supporting tools can be applied. The videos will be integrated into the training platforms of the participating cities of Salzburg and Villach with some made mandatory for specific city personnel through service directives. Additionally, these materials will be freely available to other municipalities and interested stakeholders via the website of IncorporatEE/SanierungsPLUS project-partner e7.

5. Conclusion and Outlook

The *IncorporatEE/SanierungsPLUS* project has demonstrated that embedding sustainability in municipal renovation processes requires both structural and procedural changes. By integrating sustainability into strategic planning, refining project development workflows, and implementing quality assurance measures, cities can accelerate the decarbonization of their real estate portfolios. The development of targeted tools - such as portfolio management tables, sustainability criteria catalogues, and standardized process charts - provides municipalities with practical instruments to enhance decision-making and streamline sustainable renovations.

Pilot projects play a key role in testing and refining these approaches, generating valuable insights, and building internal expertise. Additionally, the introduction of structured training programs ensures that sustainability principles are understood and applied across municipal departments, fostering long-term capacity building.

Moving forward, the continued success of these efforts will depend on sustained political commitment, adequate funding mechanisms, and ongoing adaptation to emerging sustainability standards. The lessons learned from the cities of Salzburg and Villach can serve as a model for other municipalities looking to integrate sustainability into their renovation processes. While local boundary conditions such as regulatory frameworks, data quality, and institutional capacity may vary, the methods and tools developed in this project have proven robust across different settings. They offer a transferable framework for embedding sustainability into municipal renovation processes through process standardization, capacity building, and strategic planning support. By institutionalizing these improvements, cities can not only meet climate targets but also create more resilient, efficient, and future-proof public buildings.

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New materials and elements for sustainable buildings

Demonstration Cases for Energy Efficient Renovations Using Bio-Based Products

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Abstract. The European project BIO4EEB, which stands for "Bio Insulation Materials for Enhancing the Energy Performance of Buildings," is co-funded by the Horizon Europe program. It aims to develop and test bio-based insulation products on five real demonstration buildings and three virtual buildings across Europe. By testing these products at both real and virtual buildings, the project seeks to validate the market potential of smart, sustainable components made entirely or partially from biological materials that are non-hazardous. The primary goal of BIO4EEB is to encourage the use of bio-based insulation materials in housing renovation projects, in compliance with European legislation and industry standards. The project also aims to address the shortage of insulation materials by promoting the use of bio-based alternatives with a low carbon footprint, strong mechanical properties, and insulation performance that equals or surpasses conventional materials. This approach offers alternative solutions to meet growing demand and supply chain disruptions. This article will explore various application scenarios selected for real cases in the Czech Republic, France, Germany, Lithuania, and Spain, as well as virtual cases in Belgium, Hungary, and Italy.

1. Introduction

The EU climate targets open broad opportunities for tremendous growth in the building thermal insulation materials market owing to the increasing number of new residential buildings and deep renovation needs. According to current market research conducted by the CMI Team (Custom Market Insights), the European building insulation market is expected to record a compound annual growth rate of 2.89% from 2024 to 2033 [1]. One of the important changes that will be necessary for the construction industry with regards to the emissions reductions and the current energy crisis will be the wider, urgent and more intensive application of bio-based insulation and circularity principles as it tackles future growth [2].

The partners in EU Horizon project BIO4EEB have an ambition to address the gap in the residential building construction and renovation market with non-hazardous bio-based products designed to accelerate the uptake of circular practises. Several bio-based products and solutions were developed during the first 24 months of the project BIO4EEB. These products will be tested in several application scenarios selected for real demonstration cases in the Czech Republic, France, Germany, Lithuania, and Spain. Moreover, three virtual cases were also selected for Belgium, Hungary, and Italy to complement the real demo sites.

2. Exploration of bio-based alternatives

The large survey of the bio-insulating materials available in EU countries was performed within the BIO4FEEB project. These materials were compared with the conventional thermal insulating materials. According to the analysis and processing of desk research results the properties of the bio-based materials are comparable with the non-bio insulating products, as can be seen in Fig. 1.

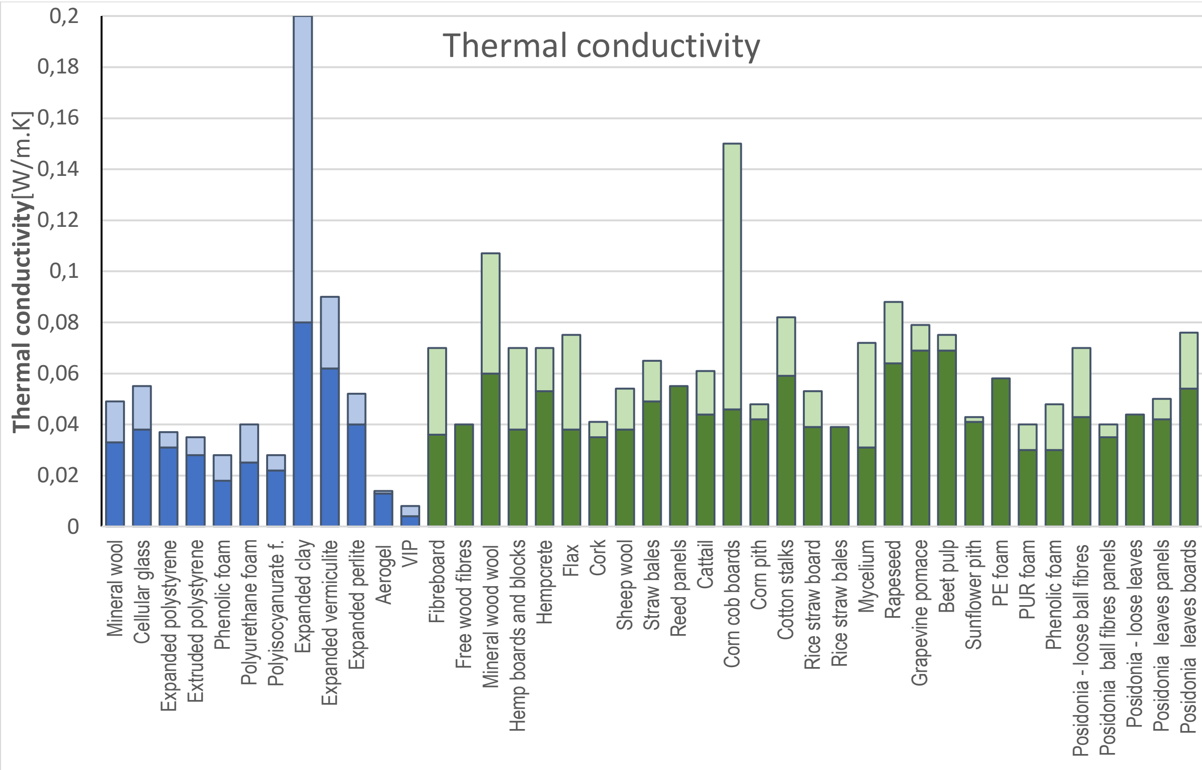

Figure 1. Thermal conductivity of thermal insulating products (blue – non-biomaterial, green -bio-based materials). [Deliverable D2.5, BIO4EEB project]

Basic environmental data were also obtained for both types of insulating materials. The environmental data of commercially available materials were obtained mostly from Environmental Products Declarations (EPD), provided by producers or from EPD databases (ibu-epd.com, inies.fr, epd-norge.no, daphabitat.pt, environdec.com). Gathering environmental data of non-conventional materials was difficult, since these materials are still under development and research and therefore their production is not established enough. Some data could be found in the scientific literature, nevertheless they are mostly incomparable to each other, because the approaches and boundaries differ substantially. The global warming potential (GWP) in kg CO2eq per functional unit (defined as the mass of material needed to obtain a thermal resistance of 1 m^2 K/W for a 1m^2 area) is given as an example in Fig. 2. The approach "Cradle to gate" was used, because the transport distances, assembling and handling of end-of-use materials can differ significantly in each country. The observed trend is that the global warming potential of bio-based materials is significantly lower than for other materials. For most bio-based materials it is even negative.

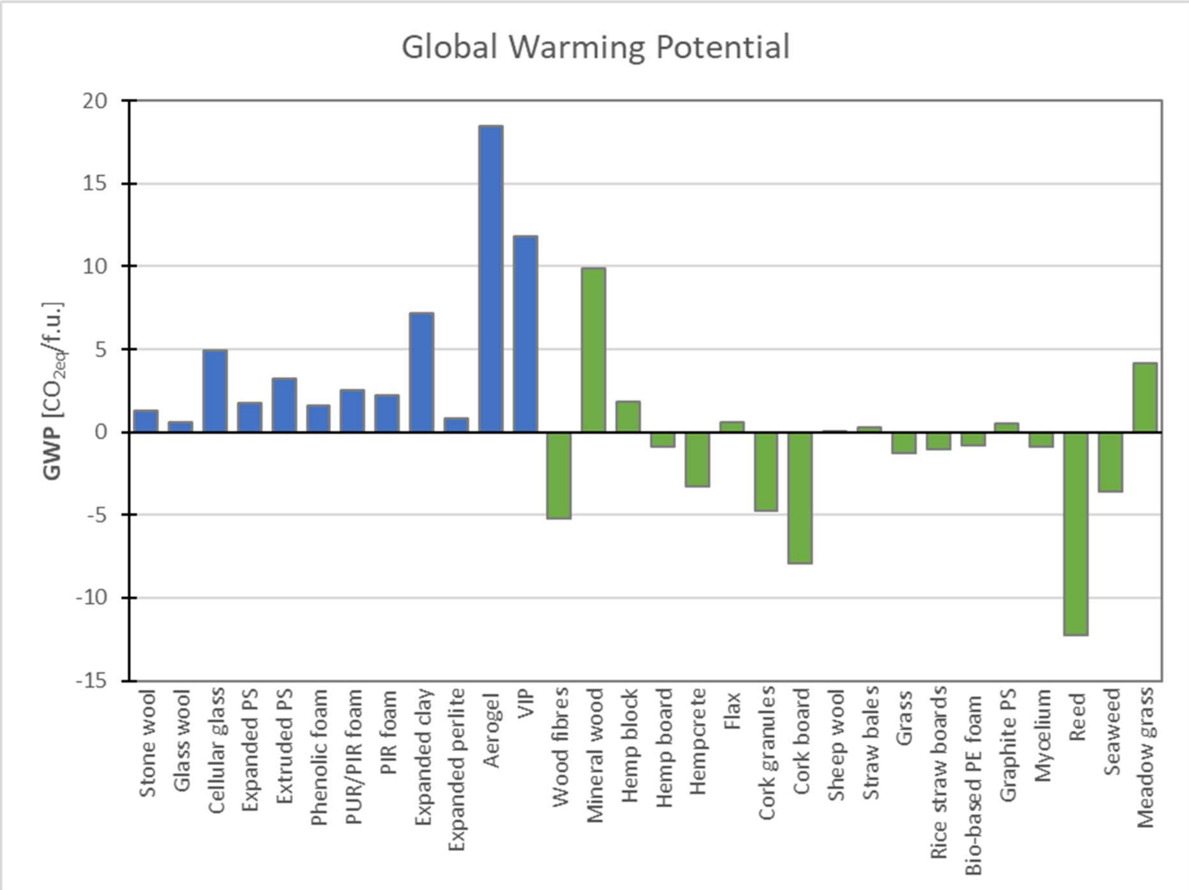

Figure 2. Thermal conductivity of thermal insulating products (blue – non-biomaterial, green -bio-based materials). [Deliverable D2.5, BIO4EEB project]

3. BIO4EEB innovative materials and products developed and tested on demo-sites

Following materials and products are applied in the demonstration cases:

3.1 Renewable Posidonia bio-based core panels and fibres [3] and [4]

Posidonia oceanica, commonly known as sea grass or "Neptune grass." is an endemic plant that grows in large quantities in the shallow waters of the Mediterranean Sea. The panels made from dead Posidonia leaves, bonded by plant-based epoxy resin achieved the thermal conductivity 0.05- 0.08 W/m·K with the bulk density between 159 and 289 kg/m^3.

3.2 Bio-based phosphorus nitrogen polyelectrolyte complexes (PEC) [5]

PEC complexes were prepared from chitosan and phytic acid, both of which are bio-based and renewable resources. PEC coatings were applied on a Posidonia panel sample.

3.3 Modified poly-lactide acid foams (PLA) [6]

Sustainable bio-based polyol derived from lactic acid designed to meet the requirements for application in the formulation of flexible polyurethane foams was developed.

3.4 Bio-based PUR sprayable foam [7] and PUR window frames [8]

Polyurethane foams from bio-based polyols and biomass-based isocyanate with bio content 75% were developed. The foam for window frames had thermal conductivity about 0.06 W/m.K with density 450 -500 kg/m^3. The fire resistance test confirmed that incorporating 3% ammonia polyphosphate into the bio-PUR formulation offers substantial fire resistance with self-extinguishing properties. The sprayable PUR foams achieved the thermal conductivity 0.022 W/m.K with density about 45 kg/m^3. Nevertheless, the bio-PUR foam had a moderate to high flammability, therefore it was determined that the inclusion of a fire retardant was necessary.

4. Real demonstration cases

4.1 Czech Republic

Semi-detached house in Prague originally built before the World War II. The building will be partly insulated with lightweight ventilated wood-based sandwich panels filled with mixture of posidonia and rice straw thermal insulation. The scope of the demonstration project is outlined in red in Fig. 3. The replacement of windows is not intended.

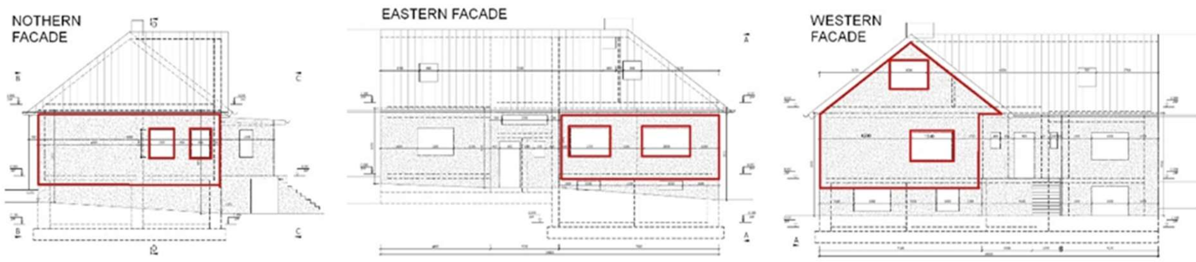

Figure 3. Scope of the Czech demonstration project

4.2 France

Industrial building "Halles des Ardoines" located in suburban area of Paris, see Fig.4. Curtain wall façade system using several bio-based products including the bio-based polyurethane frames with double glazing will be installed in the experimental zone.

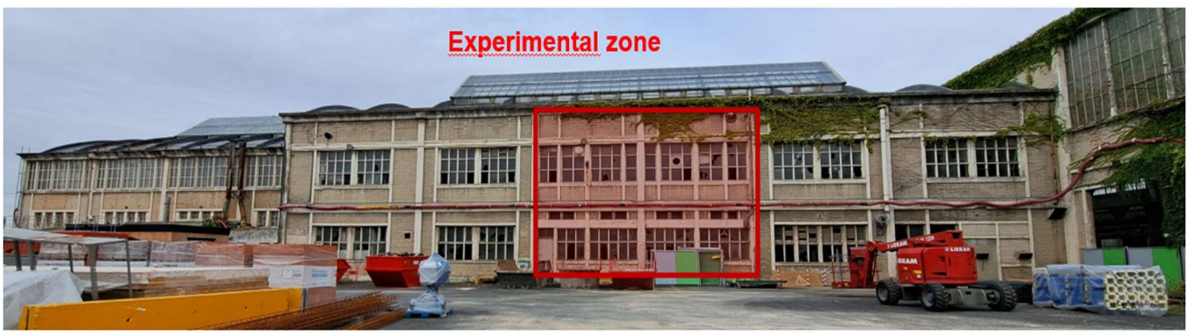

Figure 4. Presentation of the French demo case

4.3 Germany

Former office building built before the World War II placed in a large old industrial and storehouse site, see Fig.5. The building façade will be insulated with prefabricated bio-based light weight elements. The additional façade layers will integrate Posidonia external thermal insulation and a ventilated air gap. New double-glazed windows with bio-polyurethane frames will be installed.

Figure 5. German demo case. East and north elevation

4.4 Spain

Residential complex situated in northern part of Mallorca Island built in 1930s. The renovation will consist in internal insulation technology with Posidonia + PECs bio-based panels and replacement of original windows with double glazed bio-based polyurethane frames. The scope of the demonstration project is outlined red in Fig.6.

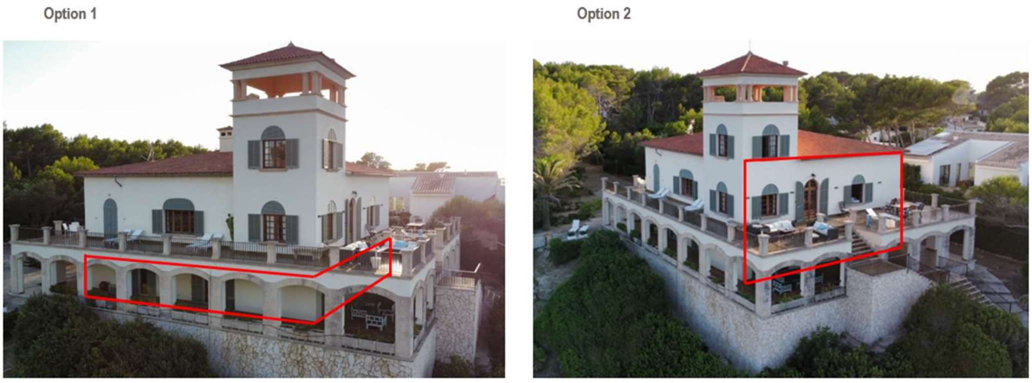

Figure 6. Scope of the Spanish demonstration project

4.5 Lithuania

Suburban two-family blocked house built in 2008 in Vilnius. Partial areas of the building envelope were selected for the demonstration project (see Fig.7). The highlighted parts of the building façade refer to combination of three different energy saving measures.

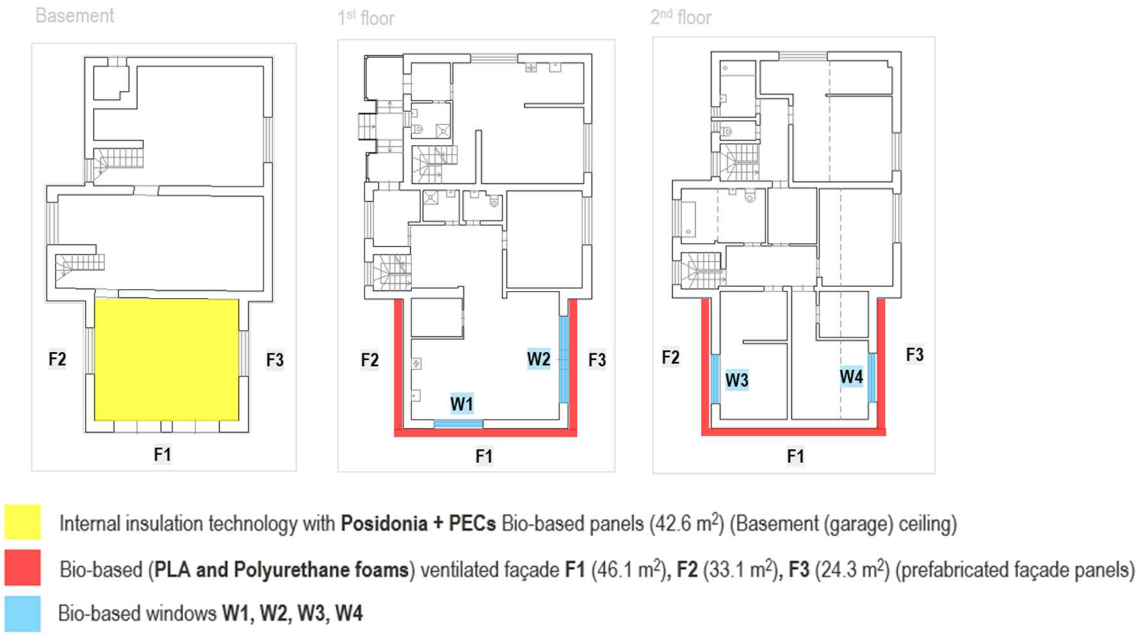

Figure 7. Technologies to be tested in the Lithuania demonstration project (façade concerned)

4.6 Evaluation and key performance indicators (KPI)

To set a benchmark for evaluation of the results, pre-intervention monitoring plans were created for each demo-site. Following IAQ parameters are monitored indoors: radioactive gas radon [Bq/m³], particulate matters PM 1 - PM10 [μg/m³], volatile compounds VOC [ppb], CO_2 concentration[ppm], relative humidity [%], indoor air temperature [°C]. Further, heat flux censors and surface temperature sensors were mounted on the wall indoors as well as outdoors. The monitoring will follow for one season after the retrofitting.

The collected data will be processed and used for the evaluation of relevant KPIs. The overview of most important KPIs for the project is presented in the Table 1.

Table 1. Generic matrix of KPI application on real demonstration sites

	Key Performance Indicators	LT	SP	GER	CZ	FR
Technical	Efficiency and low disruption of building envelope integration	X	X	X	X	X
	Compliance scores with building codes			X	X	X
	Customization		X		X	X
	U-value improvement	X	X	X	X	X
Environmental	Energy consumption reduction	X	X	X	X	X
	CO_2 emission reduction	X	X	X	X	X
	Circular potential	X	X	X	X	X
	Indoor environmental quality /IEQ)	X	X	X	X	X
Economic	Payback period (PP)	X	X	X	X	X
	Total cost reduction	X	X	X		

5. Virtual demonstration cases

The relevance of the virtual demo cases for the BIO4EEB project [9] is to serve as use cases preparing the real demonstration cases. The selection of virtual cases was made to identify possible bottlenecks and obstacles that might hinder the implementation of BIO4EEB solutions.

5.1 Relevant KPIs for virtual demo cases

For comprehensive assessment and alignment with the project needs an iterative approach shown in Fig.8 was adopted for KPIs selection. KPIs extracted from the building energy modelling include Predicted Mean Vote (PMV), Predicted Percentage of Dissatisfied (PPD) [10], total energy demand and separately energy demand for heating and cooling at each floor. Further, economic KPIs are evaluated such as payback period, net present value and operating cost reduction.

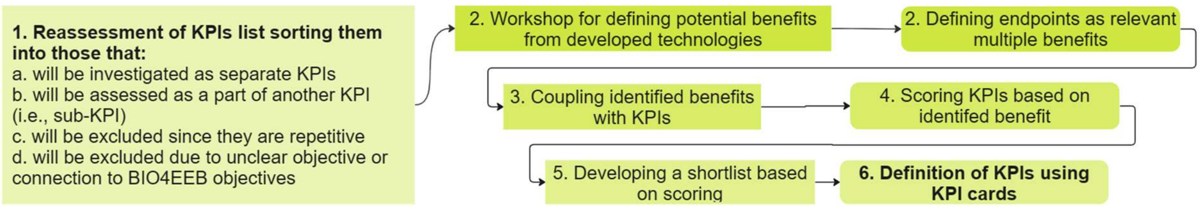

Figure 8. Methodology for KPIs definition

5.2 Application to real demo cases

To enable the assessment of the BIO4EEB solutions applied in the real demo cases, a set of surrogate models has been developed for each demo case, which were integrated into an Excel-based assessment tool for real demo cases. These models incorporate technical performance KPIs derived from building energy modelling, providing a simulation-based evaluation. Even though the surrogate models do not essentially replicate conditions of real demo cases, they offer a valuable preliminary analysis of the potential benefits of the BIO4EEB solutions.

6. Conclusions

The main objective of demo cases is to demonstrate that it is possible to provide affordable bio-based insulation solutions aligned with market needs and prove their applicability to different building typologies in various climate conditions and end-users' environments. This will be achieved through partial objectives which are as follows:

- Design of BIO4EEB solutions for their applicability in real and virtual demo sites according to the specificities of each demo site.
- Building performance pre-monitoring and post intervention monitoring.
- Validation and assessment of the BIO4EEB retrofitting strategies and their comparison with usual retrofitting scenarios.
- Property impact assessment through evaluation of key performance indicators.
- Translation of technical information and requirements to the publicly accessible BIO4EEB platform.

Acknowledgement

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Disclaimer

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Development of a Bio-Based Insulating Panel Based on Beached Posidonia

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Abstract. In recent years, reducing CO_2 emissions has become a priority, with a focus on optimizing building energy consumption. This study presents an innovative insulating panel made from beached posidonia and bio-based resin. While posidonia is already used for insulation in some Northern European countries, this research aims to develop a panel easily integrated into building facades. Utilizing beached posidonia helps address beach pollution and disposal costs. The panel seeks to replace synthetic insulation, promoting sustainable construction. The study describes the laboratory development phases, thermomechanical tests, and manufacturability. It also explores medium-large scale production and a prototype plant design, as well as the combination of posidonia with other natural materials.

1. Introduction

In recent years, efforts to reduce CO2 emissions have increased significantly due to the evident impact of human activity on climate. Zero-carbon buildings and optimized energy consumption play a key role in lowering the carbon footprint. The development of a bio-based insulating panel using beached Posidonia aims to mitigate beach tourism issues and disposal costs.
Although in Northern Europe a marine plant similar to Posidonia, Zostera marina, is used for the thermal insulation of buildings in loose form, the idea of using washed-up Posidonia oceanica, which is typically found in the Mediterranean, is an exclusive patent [1] of Sophia High Tech and Starcell S.p.A, two companies based in Campania, Italy. Thanks to the idea presented in this work, Posidonia can be used not only as a loose-fill material but also as a compact panel. This makes its integration into existing systems easier and allows for simpler handling during installation. Additionally, Posidonia repurposing provide an innovative, eco-friendly alternative to synthetic insulation.

This work details the laboratory development of the panel, including manufacturability and thermomechanical tests to identify the best formulation. Eco-friendly adhesives were tested, and design of experiments (DOEs) helped determine optimal product characteristics. A promising formulation was identified for industrial scale-up. The combination of Posidonia with other natural fibers were also explored to address recovery challenges.

2. Materials selection

At the beginning of the development phase, the materials intended for the production of the insulating panel were selected and analysed.

2.1 Beached Posidonia collection and characteristics

Posidonia is a Mediterranean aquatic plant growing in extensive underwater meadows and plays a vital ecological role by providing habitat for marine life and reducing wave motion to protect coastlines. When washed ashore, it forms large accumulations called "banquettes," which help prevent coastal erosion but also disrupt tourism, posing a challenge for coastal cities reliant on it [2]. For this study, beached Posidonia was collected from Montecorice, a coastal town in Campania, Italy, which faces recurring accumulation issues. While technically straightforward, the collection process was legally complex due to unclear regulations. After extensive negotiations with regional and national authorities, official authorization was secured to use Posidonia as raw material for research.

Figure 1. On the left, Posidonia meadows. On the right “banquettes” of Posidonia.

2.2 Natural Glues and Resins

To create a compact panel, it was necessary to use a substance capable of binding the fibers together. With the goal of developing a panel with a high bio-based content, various types of natural-origin or BIO-content glues and resins were investigated. Among the different products available on the market and those in the development phase made available by our suppliers, a two-component epoxy resin containing 46% carbon from natural sources [3], a water-based silane glue, and calcium caseinate were considered. Among the many options, including starch-based resins, lignin-based resins, polyurethane resins, and other natural-origin resins, these three products were selected because, according to their technical data sheets, they provide a good balance between the expected mechanical properties of the final product , the BIO content and human health safety. Completely natural-origin resins and glues would not have allowed for the production of a sufficiently strong and stable panel.

2.3 Rice Straw

During the project, a critical issue emerged regarding the use of Posidonia as a raw material for the production of insulating panels. Posidonia oceanica consists mainly of ribbon-like leaves up to 15 cm long. As a result, beached Posidonia appears in the form of thin fibers approximately 1–1.5 cm wide and on average 6–8 cm long. This characteristic allows the production of relatively lightweight and durable products, as these fibers have the ability to intertwine during the forming process. Additionally, the specific size of Posidonia leaves enables the creation of panels with a network of internal microcavities that trap air, enhancing the insulating properties of the panel.

However, during the collection process, it became evident that the size of beached Posidonia can vary significantly depending on several factors: accumulation location, exposure to weather conditions, mechanical action from machinery used for moving these deposits and abrasion caused by sand and wave motion. Due to these factors, the collected Posidonia can sometimes be highly fragmented, with fibers too short to interlace properly, compromising the structural integrity of the panel. In such cases, it is not possible to form a stable and resistant panel. For this reason, a solution was studied to utilize Posidonia with these characteristics by incorporating another natural fiber—rice straw.

Rice straw, a by-product of rice farming, consists of fibrous stalks left after harvesting. Traditionally discarded or burned, it is now recognized as a valuable material for sustainable construction. Repurposing rice straw into insulation panels helps reduce waste and provides an eco-friendly alternative to synthetic materials. The fibrous structure of rice straw allows it to be compressed into durable, lightweight insulation panels. It has excellent thermal and acoustic insulation properties, moisture resistance, and a high silica content, which enhances durability by preventing decay and mold growth. Additionally, it does not serve as food for insects due to its lack

Figure 2. On the left, chopped Posidonia collected from the beaches. On the right, 8g long leaves Posidonia (left) against 15g chopped Posidonia (right)

of nutrients [4]. Rice straw insulation is biodegradable and contributes to carbon sequestration. The filamentous structure of rice straw, which in some ways resembles that of Posidonia, allows for good mixing and homogenization with it. This helps provide adequate structural integrity to the panel, even when part of the Posidonia leaves has been broken down by weathering, thus ensuring their recovery and reuse.

3. Product Development

The development process of Posidonia panels is described below, focusing on the methodology used. The process involved multiple phases, first identifying a formulation for compact, stable, and durable panels, then optimizing parameters for maximum thermomechanical performance. Fire resistance and water absorption tests were also conducted.

For the development activities, various molds were designed and produced to create test samples of different sizes, necessary for optimizing the formulation and conducting tests: 150x150 mm aluminum mold (for panel thickness up to 20 mm), 300x300 mm aluminum mold (for thickness up to 150 mm), 450x450 mm aluminum mold (for thickness up to 150 mm) and 1350x1000 mm wooden mold (for thickness of 100 mm).

2.2 Manufacturability Test

An initial experimental campaign was conducted with the goal of selecting the optimal bio-based resin or adhesive to produce panels made of dried Posidonia leaves that are lightweight, stable, and easy to handle. Among the several products available, we focused our research on bio-based/eco-friendly product. Resins and glued investigated in the initial tests were selected from those available on the market, under development or customized based on specific criteria.

In line with the goal to create an eco-friendly product, the ecological content and the low impact on the environment and human health was a primary selection parameter. Furthermore, a required characteristic was the adhesive/resin's ability to give to the final product good compactness, stability, and a certain degree of manageability. Finally, good mechanical properties were also considered essential. While the panel is not intended for structural applications, sufficient mechanical strength is important to facilitate installation and ensure durability during use. For sure natural resins exist, but they are difficult to source and do not yet offer the same performance levels as traditional adhesives/resins derived from petroleum products. These resins often have low resistance to moisture, weather, and environmental agents, resulting in inferior mechanical properties in the final product. For this reason, it was decided to analyse products with a certain percentage of bio-based content. For each product a test was carried out by mixing small quantities of glue/resin and Posidonia in order to evaluate the miscibility, adhesion and solidification result. Mixing ratios (Posidonia to glue/resin weight) tested were 2:1 and 3:1 since the initial aim was not to find the best ratio but only to evaluate the best resin to form Posidonia panels. No evaluation on density has been made since the parameter was optimized subsequently. Using the 150x150 mold described previously, a series of 10 mm thick specimens were made. A bi-component epoxy resin with 46% renewable carbon content was chosen as it allows for good mixing with the Posidonia leaves and, once solidified, ensures compactness and stability.

After selecting the resin, efforts focused on optimizing the formulation for thermo-mechanical performance, manufacturability, compactness, and stability by testing two key parameters: density and mixing ratio. A DOE varied density from 50 to 650 kg/m^3 and mixing ratio from 1:1 to 6:1 (fibers to resin). Lower densities improved insulation by trapping air, while higher densities enhanced strength and compactness [5]. A higher mixing ratio increased natural content and insulation but could reduce strength and handling. Test specimens with thicknesses of 10, 15, and 20 mm were produced using a 150x150 mm mold, with a total of 111 tests conducted. In evaluating the results, consideration was given to the ability of the resin and fibers to homogenize properly, the compactness of the resulting specimen, its stability, its ease of handling, and the expected thermal and mechanical properties, as well as its ecological aspect. Preliminary considerations were also made regarding the expected costs: given that resin has a significantly higher cost than Posidonia—which can theoretically be sourced at zero cost (transportation costs will be addressed later)—solutions with a lower resin content were preferred. At the end of this test campaign, most promising formulations have been identified. In general, formulation with higher resin content have higher costs and poor thermal characteristic are expected. Also the environmental impact will also be greater and therefore these formulations have been excluded. On the other hand, formulations with too little resin or with densities that are too low show bad homogenization and do not have compactness, handling and stability characteristics required for use. Even in cases where the specimen was actually produced but was too dense or had an excessively high resin content, it was discarded. Most promising formulations (Ratio 4:1, Density from 50 to 200 kg/m3) show the best compromise between expected costs, weight, compactness and manageability.

Once the most promising formulations for manufacturability were identified, the focus shifted to studying panel thicknesses. Thin specimens were initially produced to optimize density and mixing ratio, while the second phase involved creating thicker specimens to approach the final product thickness. The goal was to determine the maximum thickness that could be produced without compromising stability and handling. Panels up to 100 mm thick were stable, compact, and easy to handle, with no issues expected during scale-up. However, for 150 mm thickness, stability decreased, and handling became difficult, leading to material loss and longer extraction times. However greater thicknesses are achievable with industrial systems.

Figure 3. Production of Posidonia panel sample with 300x300 mm mold, thickness 10 mm. On the left higher thickness sample.

2.3 Performance test and final characterization

Starting from the results of the first development phase, a series of tests was conducted to evaluate key characteristics of the Posidonia panels, such as thermal conductivity, fire resistance, and water absorption, in order to determine the formulation that could optimize these performances.

Thermal conductivity tests were carried out in accordance with the UNI EN 12667 standard in two distinct phases: in the first phase, different densities were tested, starting from the most promising formulations identified during the manufacturability test phase. Specifically, densities ranging from 50 to 200 kg/m^3 were tested with a mixing ratio of 4:1. Specimens of different thicknesses—20, 50, and 100 mm—were produced with the aim of verifying the variability of thermal conductivity with thickness. The results showed that the lowest thermal conductivity values (0,038 minimum) were achieved at a density of 100 kg/m^3, with optimal values observed up to 150 kg/m^3. As seen in the graph, the trend follows a "cradle" shape: for densities above 150 kg/m^3, the increased compaction required to compress the Posidonia leaves reduces the air cavities trapped within the panel. On the other hand, an excessive reduction in density leads to the formation of extended cavities that communicate with the panel's outer surface, limiting air entrapment. This trend is further confirmed by additional measurements performed with ISOMET instrumentation on higher densities. Although the obtained values are not as reliable as those obtained according to standard regulations, the trend remains consistent.

From the analysis of thermal conductivity values measured on different thicknesses, it was observed that, despite the Posidonia panel being essentially a non-homogeneous material, the thermal conductivity value remains substantially constant with thickness.

Furthermore, the most promising formulations were also subjected to water absorption tests (both partial and total immersion) according to ISO 16535, as well as fire testing according to UNI EN 11925-2. Given the nature of the analysed panels, which are composed of dried leaves forming multiple microcavities, water absorption was found to be relatively high, with increasing values as

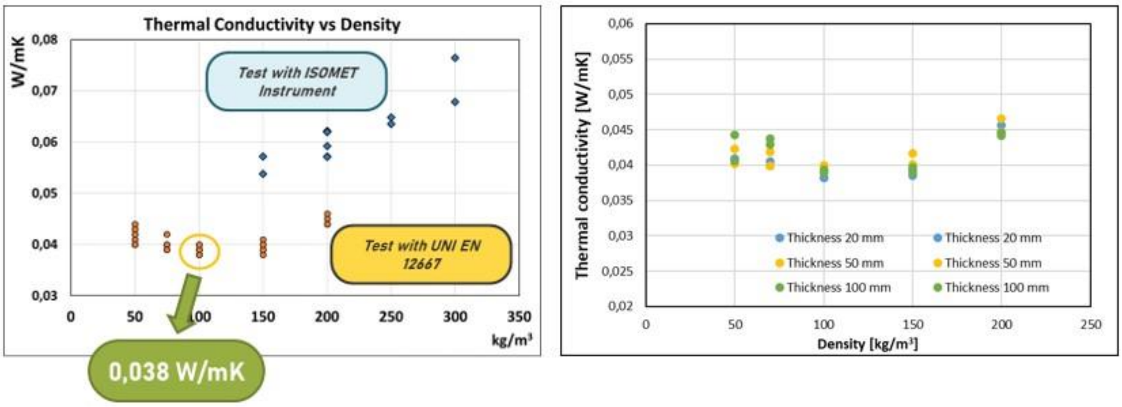


Figure 4. Thermal conductivity vs density (left). Effect of panel thickness on thermal conductivity (right)

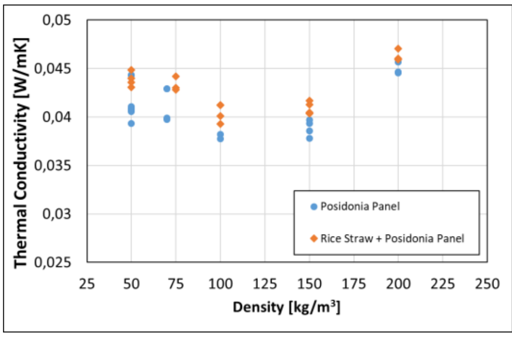
Figure 5. On the left, apparatus for fire resistance test. On the right, very low flame propagation on samples surface.

density increased. For the partial immersion test, values ranged from a minimum of 0.7 kg/m² for panels with a density of 50 kg/m³ to 1.7 kg/m² for panels with a density of 200 kg/m³. Slightly higher values were recorded for the total immersion test, ranging from 0.8 kg/m² to 1.8 kg/m². Regarding the fire test, samples of different densities were exposed to a direct 20 mm flame positioned at a 45° angle relative to the vertically placed panel. The panel was exposed to the flame for 30 seconds, with a total test duration of 60 seconds. During this type of test, the following aspects were observed: flame propagation on the panel surface, the formation of incandescent particles, and smoke generation. Additionally, the time required for the flame to completely penetrate specimens of 20 mm and 100 mm thickness was evaluated. This was achieved by installing a thermocouple on the back of the specimen to determine the exact moment the flame reached the opposite side. All the formulations tested demonstrated that the Posidonia panels are highly fire-resistant. In no case was there any flame propagation, with almost no presence of glowing particles. Smoke generation was also quite limited. According to the standards, the panels could be assigned a B class (the highest for products with high organic content) with d0 for the production of burning particles and s1/s2 for smoke generation. Regarding the penetration time, it was found that with higher panel densities, penetration times exceeding 15 minutes can be achieved with thickness of 100 mm. The experimental campaign concluded with a comprehensive characterization of the best formulations in terms of manufacturability, compactness, stability, and thermal properties, specifically densities of 100 and 150 kg/m³ with a 4:1 mixing ratio. The following table summarizes the tests conducted and the key results. Following the same approach, an optimal formulation was achieved with 60% rice straw, 40% dried Posidonia, and a fiber-to-matrix ratio of 3:1.

Density [kg/m³]	Thermal Conductivity [W/mK] UNI-EN 12667:2002	Water absorption [%] UNI-EN ISO 62:2008 method 1	COMPRESSION TEST UNI-EN 826:2013			Specific Heat [J/gK] ASTM C518
			Compressive strength [kPa]	Relative deformation [%]	Compression stress at 10% relative strain [kPa]	
100	0,37 @ 5°C 0,38 @ 15°C 0,40 @ 25°C	67	13400	56	25,9	1,60 @ 10°C 1,75 @ 30°C 2,03 @ 50°C
150	0,38 @ 5°C 0,39 @ 15°C 0,41@ 25°C	53	13700	60	12,9	1,66 @ 10°C 1,83 @ 30°C 2,09 @ 50°C

Figure 6. Summary of characterization of Posidonia panel.

The considered densities remained 100 and 150 kg/m^3. This formulation resulted in stable, compact, and durable panels with thermomechanical properties summarized below. Higher specific heat, compression resistance and lower water absorption were achieved but slightly



Density [kg/m³]	Water absorption [%] UNI-EN ISO 62:2008 method 1	COMPRESSION TEST UNI-EN 826:2013 Compression stress at 10% relative strain [kPa]	Specific Heat [J/gK] ASTM C518
100	37,8	13,8	1,85 kJ/kgK @ 10°C 2,02 kJ/kgK @ 30°C 2,23 kJ/kgK @ 50°C
150	34	63,9	1,75 kJ/kgK @ 10°C 1,89 kJ/kgK @ 30°C 2,46 kJ/kgK @ 50°C

Figure 7. Summary of performances of Posidonia + Rice Straw panel.

higher (+ 5% average) thermal conductivity.

4. Scale-up production process

In the final phase, the production process was scaled-up by developing a prototype process for medium-to-large-scale panel production. The process developed for producing the panels includes, after the collection phase, screening to separate the Posidonia from sand and various wastes, followed by washing to remove any sand still attached to the leaves. The moist Posidonia is then dried using a dryer powered by methane or electricity. The treated Posidonia is fed into a mechanical mixing stage in a tank with rotating parts that, in a short time compatible with the resin's pot time (components of the resin are mixed separately), homogenizes the fibers and resin, which is then deposited into aluminum molds made with honeycomb panels. The molds are subsequently placed in an oven for the curing process, which is essential to accelerate polymerization and improve the final properties. After about 1.5 hours at 70–80°C, the panels can be removed and stored. To properly calibrate the process, studies were conducted to determine the optimal curing time and the maximum producible size, initially using 1350 x 1000 wooden molds. Initially, a wooden mold was used, which highlighted the need to reduce the final panel size to 1200x600 to avoid issues with mold extraction, handling, and installation.

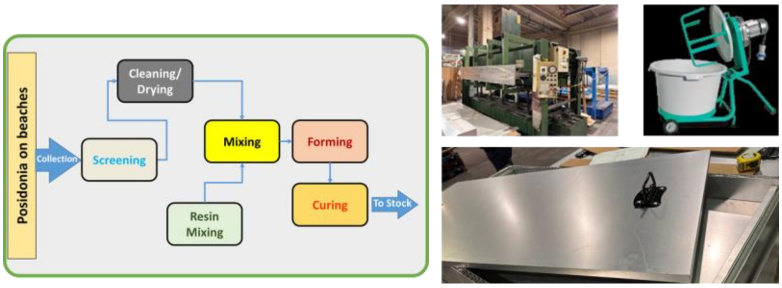


Figure 8. On the left, production process scheme. On the right, some production equipment: Curing oven, tank for mechanical mixing, mold made with aluminum honeycomb panels.

A small-scale, low-automation production facility has currently been set up to manufacture a series of panels intended for experimental use in democases across Europe. However, if an industrial-scale plant with a higher level of automation were to be implemented, the production capacity could become competitive with that of existing products made from other natural fibers.

5. Conclusions and future development

The paper aimed to develop an insulating panel with high natural content that competes with synthetic products while addressing local tourism issues caused by Posidonia accumulation. The process was detailed through all development phases, including test results, the design of an industrial process, and the creation of a prototype process for large-scale production. Two products were produced: one primarily from Posidonia and another combining Posidonia with rice straw, the latter of which will be used in the European Bio4EEB project in various buildings integrated into a ventilated facade system with performance monitoring [6]. Future work is exploring how to implement the described process to use a mix of Posidonia and resin to directly fill cavities, partition walls, and false ceilings. The resin enables the Posidonia to crystallize within the wall, eliminating the compaction that would otherwise occur over time due to moisture. A first phase of manufacturability testing was successfully conducted.

Figure 9. On the left, Posidonia + rice straw panel sample. In the middle, 1350x1000 mm Posidonia panel, 100 mm thickness. On the right, sample of a cavity filled with a mixture of

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Mycelium Composites for the Thermal Insulation of Building Envelopes: a Literature Review of Current Applications for Future Net-zero Carbon Buildings

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Abstract. Minimizing heat losses through highly insulating building envelopes is a widespread practice to reduce buildings' energy consumption. However, the embodied impact stemming from the production, installation and disposal of traditional fossil-based insulating components can still contribute significantly to the total carbon emission over a building's lifecycle. In this context, the use of bio-based materials is emerging as a promising alternative for climate mitigation due to their carbon storage capacity. Among these, Mycelium-Based Composites (MBCs), grown from fungal filaments on organic substrates, offer a small footprint, economically valuable, lightweight alternative to fossil-based thermal insulation, such as polystyrene and polyurethanes. While most of the past literature studies on mycelium-based structures have mostly focused on broad applications for their acoustic and mechanical performance, only a few separate studies have investigated their possible applications as buildings' thermal insulating materials. In this context, this paper provides a systematic literature review on mycelium thermal insulating composites in constructions, focusing on their fabrication methods and their diverse compositions, depending on the adopted fungus and substrate typologies, material densities and substrate combinations. By doing so, this study aims to highlight best practices and propose guidelines for their potential application in buildings, for future development of mycelium-based thermal insulation components in the construction industry.

1. Introduction

1.1 Background

The construction sector is one of the major contributors to the global amount of CO_2 emissions, accounting for around 40% of the total amount of energy consumption (1).

To mitigate it, it is crucial to promote the adoption of passive techniques to reduce the energy requirements of buildings. In this context, the implementation of thermal insulation materials has gained significant interest in the past few decades to reduce buildings' thermal loads in all climate zones (2,3), from Equatorial to Temperate. However, most established building insulation materials, such as stone wools, glass wools, and lightweight polymeric foams, like expanded polystyrene (EPS), and polyurethane (PU) foam, are produced through processes that are heavily reliant on fossil fuels and involve substantial energy inputs, resulting in a Global Warming Potential (GWP) ranging from 0.92 $kgCO_2$ /kg for stone wools to 5.84 kg Co_2/kg for EPS, compared to wood fibres accounting for 0.21 $kgCO_2$/kg (4). Moreover, their recycling, reuse, and landfill management are complex (5,6). In this regard, recent studies indicate that, with buildings becoming more and more energy-performative throughout their operative lifecycle, the impact of the embodied carbon of building materials used to achieve this can contribute significantly, ranging from 10% to as much as 80% of the total emissions over a building's lifecycle (7).

1.2 Mycelium-Based Composites: an alternative thermal insulation material

In this context, bio-materials emerge as a valuable alternative for the production of insulating materials, due to their ability to absorb carbon along with their growth and then store it once used for building applications - which makes them potentially low-carbon - and their biodegradability.

Among them, more specifically, the use of Mycelium-Based Composites (MBCs) has emerged due to their low density and porosity, which makes them a potential alternative to replace fossil-based, synthetic materials such as EPS and PU (8). Despite their environmental challenges, these materials remain prevalent in construction due to their market maturity and economies of scale, which pose an obstacle to the use of alternative solutions.

Mycelium is the vegetative structure of filamentous fungi (9) and can bind organic matter through a network of hyphal micro-filaments (10), forming a composite material. Once deactivated before the fruiting body emerges, to avoid it from spreading spores, representing the main risk for human health, MBCs can be used for various applications, from biomedical to packaging and construction materials. Mycelium functions as a natural adhesive, enabling the creation of entirely bio-based composites (11), which have shown to be low-density, high-porosity (12,13), clean and safe (14) and competitive with traditional insulating materials, while still being low-carbon and completely biodegradable (15,16). Additionally, they might offer several advantages over polymeric foams, including low cost of production, fast renewability, and carbon capture and storage (16–18), while enhancing circular processes and lifespan by adding value to agricultural and industrial waste, used as substrates, transforming them into high-end products (19,20).

1.3 Research aims and questions

Although research in mycelium for the built environment has been carried out since the early 2000s (15), research specifically focused on its use for thermal insulation remains limited and has only emerged in the last decade.

This paper aims to identify, collect, and organise these studies through a systematic literature review, to define common trends and variables that characterize this otherwise fragmented body of research, investigating their overall thermal performance, types and densities of substrates used, the species of fungi adopted and different incubation periods.

2. Materials and methods

Between April and September 2024, a systematic bibliographic search was conducted to identify current research on myco-materials as thermal insulating materials for construction applications.

The review, considering publications in peer-reviewed literature, combined a first four-step literature review as proposed by (21) and a second step of snowballing (22).

2.1 Scopes and screening criteria

Data were collected from Scopus and Web of Science by using a search string consisting of 3 main elements, including for each variant of commonly used terms:

1. Mycelium
2. Thermal insulation
3. Building application

The research was confined to English-language papers within the field of Engineering, with no chronological or geographical restrictions applied. Moreover, papers were further selected based on the presence of quantitative data on the thermal characterization of MBCs, to reply to the following questions:

1. What is the reported thermal performance of mycelium composites?
2. Which types of substrates have been used for the development of thermal applications of mycelium, and which ones have shown better results?
3. What fungal species have been used in developing thermal-based mycelium applications?
4. Is the incubation period of samples affecting the thermal performance of the resulting MBCs?

By doing so, 70 papers were selected, (53 from Scopus and 17 from WoS). After screening the articles' titles, their abstracts and conclusions for relevance, and excluding the ones repeating on the two platforms, 19 articles remained, on top of which the author added 3 papers through a process of snowballing.

5. Results

The conducted literature review displayed a growing interest in the topic over the last ten years.

Literature reports thorough investigations concerning substrates' combinations and conditions (size and pressure), densities, incubation periods of samples and level of hygroscopicity, and fungal strain applied, intending to define eventual patterns of fabrication for their potential further application in real-world case studies. In this regard, a small portion of the papers (23–25) among the selected ones reports simulations on case studies to define energy and environmental performances of MBCs under certain climatic conditions.

3.1 Organic substrate typologies

Substrate typologies are key to understanding the overall properties of MBCs (26), and thus also their thermal performance, as they represent the main mass of the developed materials, with mycelium working mostly as a binder (27).

White rot fungi grow on a wide range of organic substrates, which provide nourishment and promote the development of mycelium networks (28). Most of the selected studies used either agricultural or forestry residual byproducts, enabling the re-entry of bio-wastes into the circular economy and transforming organic residues into high-value products. Indeed, the literature includes studies on ligno-cellulosic bio-residues coming from different sources, as shown in Table 1. In this regard, (8) and (29) investigated the effects of different types of agricultural by-product fibres on the MBC properties, to demonstrate the direct relation between the properties of the resulting material and the ones of the substrates. The thermal performances of MBCs made of *Trametes Versicolor (T. Versicolor)* and, distinctively, flax, flax dust, flax long treated fibres, flax long untreated fibres, flax hurds, wheat straw dust and wheat straw were compared in (8).

Table 1. Mycelium composites identified in the literature review.

Substrate	Fungal strain	Density (g/cm^3)	Incubation time (d)	Λ (W/ mK)	Measuring method	Source
Wheat straw	P. Ostreatus	0.05-0.12	10-20	0.12-0.54	GHP	(35)
Pulp paper	P. Ostreatus	-	28	0.06	-	(29)
Beech sawdust	P. Ostreatus	-	28	0.07	-	(29)
Rice husks	P. Ostreatus	0.17-0.21	30-35	0.07-0.08	QTM	(37)
Mahogany sawdust	P. Ostreatus	0.21	30-40	0.07-0.08	QTM	(37)
Rice husk-mahogany sawdust	P. Ostreatus	0.15-0.24	30-40	0.07-0.08	QTM	(37)
White ash chips	P. Ostreatus	-	14	0.03-0.04	TPS	(31)
Poplar sawdust	T. Versicolor	0.1-0.11	14	0.04-0.05	TPS	(32)
Birch sawdust	T. Versicolor	0.21-0.29	14	0.05	TPS	(32)
Rye berries	P. Ostreatus	0.06	15	0.07	DBM	(38)
Beech shives	G. Lucidum	0.21	21	0.05-0.07	-	(25)
Beech shives	T. Versicolor	0.2	12	0.07	-	(25)
Mischantus fibres	G. Resinaceum	0.12	17	0.09-0.10	GHP	(30)
Wheat straw	*O. Latermarginatus*	0.05	56	0.08	TLH	(33)
Wheat straw	M. Minor	0.06	56	0.08	TLH	(33)
Wheat straw	G. Resinaceum	0.06	56	0.08	TLH	(33)
Bamboo	P. Ostreatus	0.23	18	0.08	TPS	(23)
Birch sawdust	P. arcularius	-	28	0.06	-	(20)
Birch sawdust	T. suaveolens	-	28	0.05-0.06	-	(20)
Birch sawdust	T. pubescens	-	28	0.05	-	(20)
Flax	T. versicolor	0.13	16	0.06	TPS	(8)
Hemp	T. versicolor	0.1	16	0.04	TPS	(8)
Wheat straw	T. versicolor	0.9	16	0.04	TPS	(8)
Hemp	G. Lucidum	0.08	14	0.05	HFM	(34)

Hemp	P. Ostreatus	0.10	14	0.07	HFM	(34)
Processed cellulose+hemp	G. Lucidum	0.11	14	0.06	HFM	(34)
Processed cellulose+hemp	P. Ostreatus	0.11	14	0.07	HFM	(34)

* DBM: Divided Bar Method; GHP: Guarded Hot Plate; HFM: Heat Flow Meter; QTM: Quick Thermal conductivity Meter; TPS: Transient Plane Source; TLH: Transient Line Heat

The obtained thermal conductivity ranged from 0.04 W/(mK) for both hemp and straw to 0.06 W/(mK), for flax hurds, showing that the thermal conductivity of these MBCs depends on their density/porosity and the substrate chemical composition rather than the morphology, as demonstrated by the negligible effect on the thermal conductivity of the different flax fibre types.

In this regard, the impact of porosity and density on the thermal performance of MBCs was investigated in (30–32) by using different particle sizes of the same substrates, confirming that materials with low density and high porosity are highly effective as thermal insulators. For instance, *Pleurotus Ostreatus (P. Ostreatus)* grown on rye grains and white ash chips with different particle sizes and high porosity (>75 %) showed low thermal conductivity values (31), as shown in Table 1.

Moreover, MBCs made of poplar and birch sawdust with good thermal and mechanical properties were produced in (32) by modifying the substrate type, size, and mycelium abundance to generate a multiscale hierarchical porous structure. MBC obtained from *T. Versicolor* cultured on large-sized poplar substrate and large porosity (93%) showed the best performances, with thermal properties comparable to EPS. (Table 1).

3.2 Fungus typologies and incubation periods

Most of the reported studies utilize 3 main species of fungi: *T. Versicolor, P. Ostreatus or G.,* both *Resinaceum and Lucidum.*

The impact of different fungi, given a fixed substrate, on the final thermal performance of the resulting materials was analysed in (33) and (34).

In (33) three species of basidiomycete fungi, - *Oxyporus Latermarginatus (O. Latermarginatus)*, *Megasporoporia Minor (M. Minor), G. Resinaceum* – were adopted to manufacture mycelium bricks in combination with wheat straw, finding that performance differences were not significant, (Table 1).

G. Resinaceum and *P. Ostreatus* were compared in (34) by combining them with hemp and entirely, detecting better thermal performance for samples using the first one.

The literature also documents the effect of incubation periods on the thermal performances of the resulting MBCs.

The same type of samples was compared in (35) underlining that samples incubated for longer periods have lower thermal conductivity than those incubated for shorter amount of time (Table 1). In this context, in (36) the water content of samples and their impact on thermal performances was analysed by testing both dried and wet samples, due to the replacement of moisture in the substrates with air during the drying process.

In line with the other studies, (37) explored the time variable in combination with substrate typologies and conclude that the thermal conductivity is more dependent on the substrate type and water content than on the incubation time, thus corroborating the findings of (8) and (29).

3.3 From the material fabrication to the architectural application: energy simulations on real case studies

A few studies (23,24,38), after characterising the thermal performance of the fabricated MBCs, assessed their energy and environmental performance over time by combining Energy Simulations and Life Cycle Assessment (LCA). By doing so, the attention shifted from the scale of the material to the architectural one, and explores the potential benefits given by their actual applications in the long run.

An analysis on Energy Plus evaluated the performance of MBCs made of rye berries and *P. Ostreatus* (0.07 W/mK) in comparison with conventional natural insulation materials, - i.e., Lightweight Expanded Clay Aggregate (LECA) and Expanded Vermiculite (EV)-, across different US Climate Zones (38). Building insulation made of MBCs was found to provide the reduction of indoor temperature fluctuations, the total annual heating and cooling energies, and the total annual CO_2 emissions for buildings located in most of the US Climate Zones, with the only exception of Zone 1, the very hot climate zone.

Similarly, the architectural application of mycelium was examined in (24) on a multilayer wall in Marrakech, Morocco. Using both a Life Cycle Cost Analysis (LCCA) and 2D Computational Fluid Dynamics (CDF) simulations, this study demonstrated that the thickness of mycelium insulation had a significant impact on energy savings, increasing them from 56% to 93%, while the time shift and decrement factor revealed high thermal inertia. Moreover, in accordance with (38), mycelium was proven to be more efficient than EV and LECA when coming to energy performance.

(23) investigated the carbon savings potential of a MBC made of bamboo and *P. Ostreatus* (0.08 W/mK), by applying it as Exterior Thermal Insulation Composite System (ETICS) in the renovation of an existing reference façade with selected end-of-life. The results showed low carbon emissions compared to alternative bio-based insulation solutions due to the high content of biological wastes and the lack of artificial binders.

6. Final considerations and conclusions

This work displayed current research on MBC materials for the thermal insulation of building walls.

Reported articles displayed a thermal performance values ranging from 0.03 W/mK to 0.54 W/mK, due to differences related to substrates typology, incubation periods and composites' densities. More specifically, the analysed studies underlined that fungi species and incubation periods do not particularly impact the resulting thermal conductivity, while substrate properties and moisture of the sample have a major impact.

Among the agro-industrial residues used as substrates, wheat straw and hemp showed promising performances (8), while, among residues coming from the forestry sector, composites made with white ash chips displayed a noticeable thermal performance (31).

As above mentioned, incubation period doesn't have a strong impact on the final thermal performance of the sample, although it's still possible to detect a slightly better performance in samples incubated for longer (35).

To conclude, MBCs thermal performance, along with their thermal stability and fire resistance, strength and acoustic performance might enable them to compete with other comparable products on the market, such as EPS (0.03–0.04 W/mK), PU foam (0.02–0.03 W/mK) and phenolic formaldehyde resin (0.03–0.04 W/mK) foams. However, to achieve more extensive application and market penetration, the durability of such composites over time shall be further tested. Indeed, the hygroscopic nature of bio-based materials might lead to a gradual reduction of their thermal performances. While the surface patina of these composites may mitigate their hydrophilic behavior to some extent (8), comprehensive long-term studies conducted under real use conditions are essential to determine to which extent hygroscopicity may impact their thermal properties over time.

Moreover, the selected articles do not mention any certified product yet. While a few companies, such as MOGU (https://mogu.bio/) and Ecovative (https://ecovative.com/), are already active in the market with mycelium-based products, they do not currently provide statements confirming compliance with relevant certifications.

In this context, future research should focus on the development of standards regarding material production, testing and assessment, to enable industrial scalability and cost-effectiveness (15).

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Ventilation Systems To Reduce Moisture Levels In Buildings

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Abstract. Many existing buildings are affected by rising moisture within their walls and other structures. This paper describes methods to reduce moisture level in building structures using underground ventilation systems. The study compares traditional and modern approaches to this method, which can be applied in both floor (crawl spaces) and walls as ventilated cavities. This system is particularly suitable for historical buildings, where the use of modern rehabilitation techniques is greatly limited because of preservation of cultural heritage. Traditional methods rely on the principle of natural air flow, achieved by using the height difference between intake and exhaust holes. Their effectiveness depends on the proper design of dimensions, hole locations and suitable external boundary conditions, such as temperature and air humidity. Due to the variability and uncertainty of the boundary conditions and even by incorrect design, the effectiveness of these methods is often significantly reduced. Modern methods are based on forced and controlled ventilation within the cavities, which is ensured by a fan placed at the exhaust hole. When the fan operates, air is drawn in through the intake holes and flows through the cavity. In case of forced ventilation, many risk factors can be reduced by controlling system and ventilation settings.

1. Ventilated cavities

Ventilated cavities are gaining importance for existing buildings, particularly for historic buildings and cultural heritage, where the use of modern methods is typically prohibited. These systems have been used for approximately 4,500 years. The principle of this method is to separate the treated structure from the source of moisture using an air cavity through which air flows, thereby drying out the structure. The low air velocity is ideal for less heat loss in winter. At the same time, even this relatively low velocity is sufficient for the method to be functional and for moisture to be drawn away from the cavity space [1].

The fundamental requirements for the air entering the cavity are low relative humidity and a higher temperature, ensuring that during its flow through the cavity the air can absorb water vapor molecules diffusing from the structure. Otherwise, condensation could occur, which would not dry out the structure but instead lead to further moisture accumulation [2].

Ventilated systems are typically designed in combination with other direct, indirect, or supplementary remedial measures, including mechanical and chemical methods, drainage systems, the application of dimpled membranes, and terrain adjustments surrounding the building. Ventilated systems can be categorized based on several criteria:
By the location of the air cavity within the structure:

- Wall air cavities (vertical)
- Floor air cavities (horizontal)

By their placement relative to exterior wall:
- On the exterior side
- On the interior side

By the ventilation method:
- Non-ventilated
- Ventilated

Ventilated systems are further subdivided based on the position of intake and exhaust openings:
- Intake and exhaust holes to the exterior
- Intake and exhaust holes to the interior
- Intake holes to the interior and exhaust holes to the exterior

By the time of the construction:
- Original ventilated cavities built with the structure
- New ventilated cavities built retrospectively

By the air flow method:
- Natural
- Controlled

2. Natural ventilation in wall cavities

Air cavities with natural airflow are a traditional solution that has been used for thousands of years. The principle of natural ventilation, in addition to proper system design, depends on boundary conditions such as temperature, relative humidity, and air velocity. Airflow in the cavity can occur between the intake and exhaust holes depending on the height difference and the temperature gradient between these holes (stack effect) and due to the air velocity around the intake holes [3]. The position of the intake and exhaust holes determines which of these factors will affect the airflow in the cavity. The greater the height difference between the inlet and outlet, the greater the pressure gradient and the more efficient the flow. To prevent access by animals, clogging by leaves or waste, it is necessary to equip the holes with a protective grille.

2.1 Wall cavities on the whole height of the floor from the interior side as a partition wall

In the case of air cavities formed by a partition wall on the interior side, several solutions are possible depending on the position of the intake and exhaust holes (Figure 1).

If the intake and exhaust holes are designed to face the exterior, the temperature difference between the intake and exhaust points is small and has negligible effect on the airflow within the cavity. In these cases, reliance must be placed on the air velocity. As the outside cold air enters the cavity, the partition wall must be insulated with thermal insulation.

The situation is markedly different when the intake holes are located in the interior and the exhaust holes in the exterior. Due to the temperature difference between the interior and exterior environments and the height difference between the intake and exhaust holes, moist interior air is ventilated to the exterior. This is typical during winter, where the interior temperature should be significantly higher than the exterior, resulting in heat loss as warm interior air escapes to the outside. In summer, when the exterior air temperature exceeds the interior temperature, the airflow direction reverses, leading to heat gains, which is inappropriate and should be prevented, for example, by installation of a fan at exhaust hole. The issues of heat loss and gain can be also partly solved by the installation of closure dampers. However, prolonged closure would disrupt the ventilation system, so the use of a fan is recommended to ensure that no external air enters the cavity.

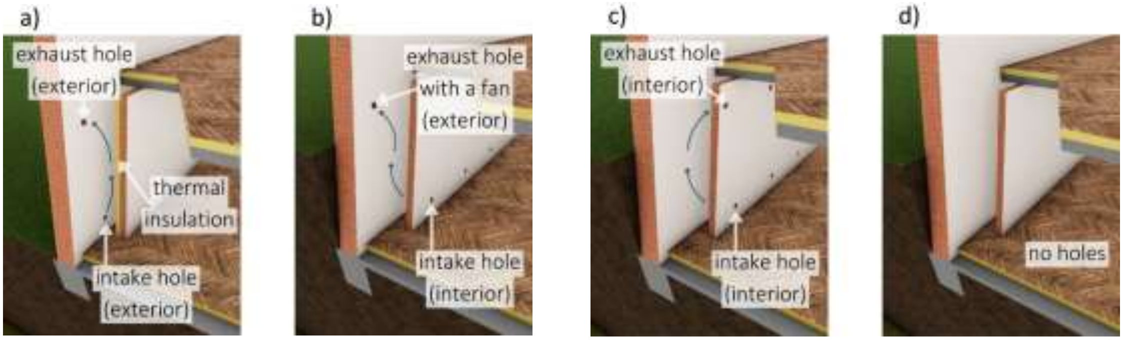

Figure 1. Wall cavities on the whole height of the floor from the interior side as a partition wall. a) both intake and exhaust holes in exterior, b) intake holes in interior, exhaust holes in exterior, c) both intake and exhaust holes in interior, d) no holes (closed cavities).

If both holes are in interior, under the conditions of normal use, there is no airflow and, in addition, humid air saturated from the cavity is returned to the interior air, thus worsening the indoor microclimate. At the same time, the low ventilation intensity and increased humidity in the cavity create an ideal environment for the formation of mould, allowing its spores to enter the interior through this system.

Designing unventilated (closed) air cavities for treated structures exposed to rising damp is highly unsuitable, as no air circulates in the cavity, preventing moisture evaporation from the structure. Over time, this moisture accumulates within the cavity, associated with the formation of mould.

2.2 Wall cavities on the exterior side below ground level

For cavities below ground level, the separation of the exterior wall from the moisture source (rising damp and ground water in the soil) is significant for this system. This cavity has specific dimensions (height, width), with the height of the cavity potentially spanning the full height of the wall (from the top of the foundation structure to ground level) or only part of its height.

In the case of cavities constructed to the full height of the wall, it is important to maintain a sufficient frost line of the foundation structure to avoid freezing of the foundation footing. The cavity wall structure can be built using masonry (precast concrete blocks, bricks, stones), concrete, or reinforced concrete. It can be designed to be self-supporting (resisting lateral soil pressure through its own weight) or supported (with local supports along its length). The choice of material and structural system depends on specific conditions, such as cavity height, where the value of lateral pressure increases with greater height, the position of windows and load-bearing walls of the building for the possibility of placing supports, etc.

Cavities spanning the full wall height can be designed as open systems, where air enters and exits along the entire cavity length, or as covered systems, where the cavity is sealed at ground level (e.g., with a reinforced concrete slab), and air enters and exits only at specific points. In both cases (open or covered systems), proper drainage must be ensured. Open systems are susceptible to rainwater infiltration, while closed systems may face condensation risks under certain conditions.

For open cavities, due to the height difference between the ground level and the cavity bottom, it is necessary to prevent falls by installing a metal grating or railings. Cavities should be insulated against ground moisture, with this insulation protected (e.g., by a dimpled membrane) in the backfill to prevent damage. To facilitate a smoother evaporation of moisture from the masonry, it is advisable to remove the existing plaster. However, since the treated area is visible in an open cavity, this option must be considered carefully for aesthetic reasons (Figure 2).

Figure 2. Open wall cavity below ground level for the full height of the exterior wall.

In covered systems, the risk of falling is eliminated by covering the cavity. Similar to interior wall cavities, the intake and exhaust holes of a covered cavity can be positioned in many ways. Air can be both supplied and exhausted from the exterior, or air from the interior can be supplied and then exhausted through the cavity to the exterior. The key requirement is that these holes must not be located in the roofed part of the cavity due to the ingress of rainwater into the cavity (or measures must be provided to prevent such ingress).

A covered system can be constructed up to ground level or only partway up the wall, with the remaining height above the cavity up to ground level backfilled with soil. The covered portion of the cavity should be sloped so that rainwater seeping through the soil backfill drains away from the exterior wall. The sloped ceiling and the backfilled section of the exterior wall must be waterproofed to prevent moisture from wicking back into the wall above the air cavity, which would compromise its effectiveness. This waterproofing layer should be protected with a dimpled membrane or geotextile to prevent damage during backfilling. The existing plaster in the treated area should be removed, and the joints in the ventilated cavity should be raked out to a depth of approximately 20 mm to maximize the evaporative surface area. Special concrete elements can also be used to construct such air cavities [4, 5].

Additional remediation measures are carried out (sloping the terrain away from the building, pavement, etc.). For historical buildings or cultural heritage, these measures must consider preserving the original character and appearance of the building (Figure 3).

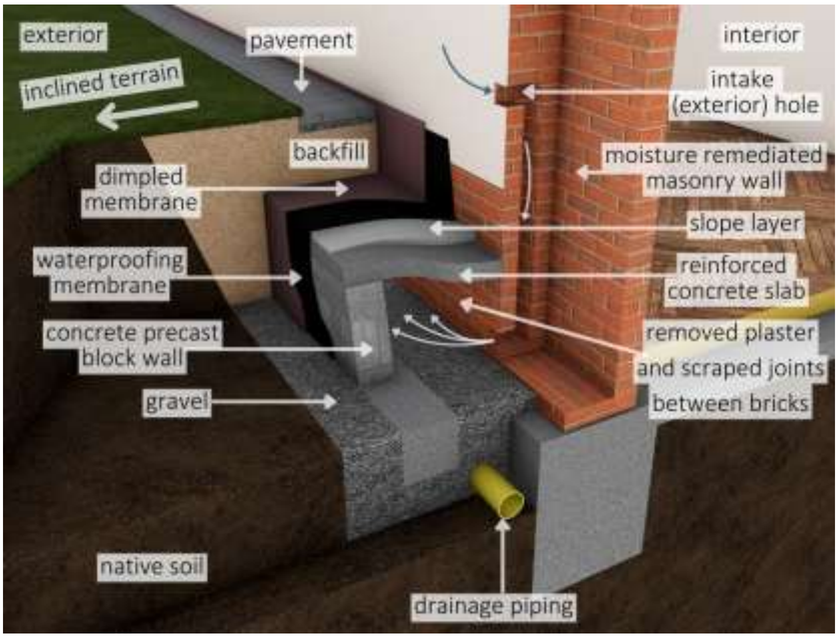

Figure 3. Covered wall cavity below ground level for part of the external wall height.

2.3 Wall cavities on the exterior side above ground level

Wall cavities above ground level work on a similar principle, where the airflow dries the wall in the area of its plinth. The cavity structure projects in front of the face of the exterior wall and thus has a fundamentally different character to the appearance of the building, unlike cavities located below ground level where the cavity is visually concealed.

The construction of the cavity can be either masonry (self-supporting) or anchored (suspended) to the exterior wall, typically in the form of cladding. The main requirements for the plinth wall material are high hydrophobicity and mechanical resistance. At certain distances, it is advisable to provide drainage in the foot of the wall, as water can still occur in the cavity area despite perfect design. The upper edge of the cavity must be covered, typically with sloped metal flashing with a drip edge to direct rainwater away from the treated wall. Airflow is ensured by appropriately placed intake and exhaust holes, slots or joints between suspended tiles. The minimum width of the plinth cavity should then be at least 50 mm, otherwise the airflow would be significantly restricted. As with cavities under ground level, it is advisable to remove existing plaster from the wall in the cavity area and scrape out mortar from the joints to maximize the evaporation surface area (Figure 4).

In general, wall cavities are mostly combined with other remediation measures. Similarly, it is also possible to combine different variants of air cavities. The situation is always dependent on the specific case of the treated wall and the given boundary conditions [6].

It is important to design sufficient cavity dimensions (height and width) so that the pressure gradient of the air is greater than its pressure loss due to the incised resistances in the cavity space. Studies show that the current application of the natural airflow method is not very effective for the remediation of masonry in historical buildings. The efficiency of the method is influenced by the material composition (homogeneous or heterogeneous) and the thickness of the treated wall, where the evaporation effect diminishes as the wall thickness increases, leading to a lower percentage reduction in moisture content. A greater reduction in rising moisture levels can be achieved by applying air cavities on both sides of the wall [7, 8, 9].

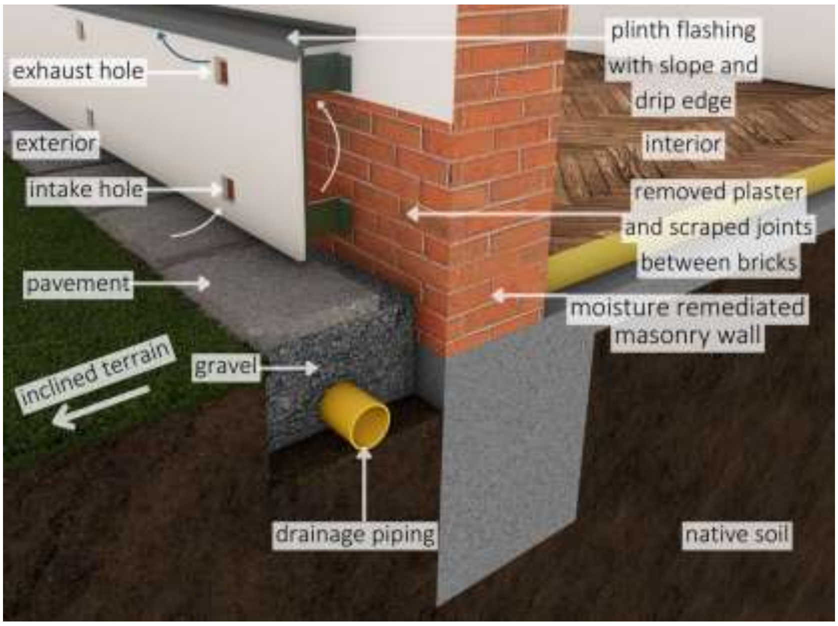

Figure 4. Plinth cavity above ground level on the exterior.

3. Natural ventilation in floor cavities

The primary purpose of implementing ventilated floor cavities is, similar to exterior wall cavities, to separate the floor structure from the moisture source by creating an air barrier. This separation prevents capillary rise from the subsoil into the floor structure. The moisture is carried away as water vapor by the flowing air, thus preventing the potential risk of water vapor condensation on surfaces. Without this ventilation, the moisture act on the structures would be much greater. In addition to protection against moisture, the cavity also serves as a protection against radon that penetrates from the subsoil.

Airflow is again provided by the appropriate number, location, size and maintenance of intake and exhaust holes, with intake holes on the windward side of the building and exhaust holes on the leeward side for better air circulation. CFD calculations in Ansys-Fluent determined that designing intake and exhaust holes directly opposite each other is not appropriate, as the supplied air is not distributed throughout the entire cavity and instead flows directly from the intake hole to the exhaust hole [1].

3.1 Floor cavities created by ceiling structure

For this type of floor cavity, the cavity space is created by the use of a load-bearing horizontal structure with a subsequent floor composition. This load-bearing structure can be made of reinforced concrete (monolithic slab or prefabricated panels), steel or steel-concrete (steel beams with profiled sheets and a concrete overlay), timber or other materials.

This type of structure is particularly suitable for historic and cultural heritage buildings as it offers a solution using traditional materials and technologies, which may be required for this type of building. If the cavity is of sufficient height, its space can be used for maintenance and regular monitoring. The easily controlled and well-ventilated cavity has a height of 600 mm and should be cross-ventilated from at least two sides (Figure 5).

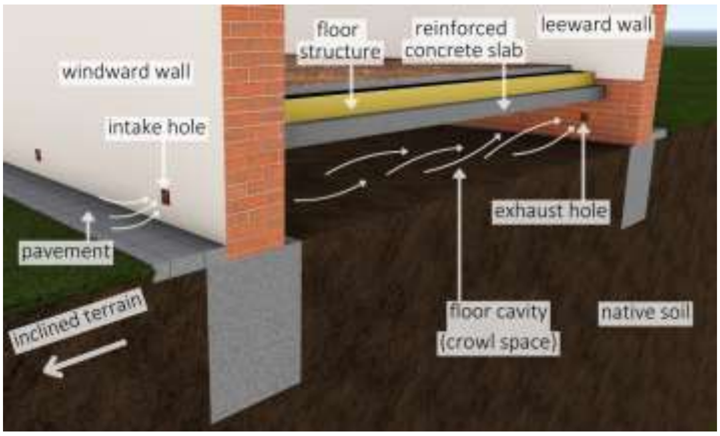

Figure 5. Floor cavity created by ceiling structure.

3.2 Floor cavities created by special plastic modules
The floor cavity space is formed using prefabricated, typically plastic modules. Arranging these modules creates not only an interconnected ventilation space but also serves as permanent formwork for concrete infill and subsequent floor layers. The cavity height can be designed freely, depending on the height of the modules offered by the manufacturer (up to 700 mm) [1, 10].

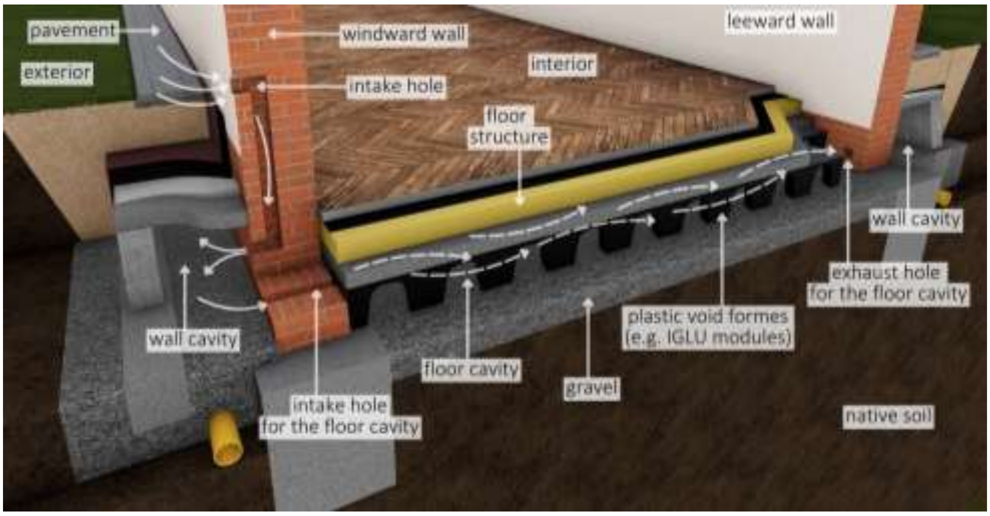

Figure 6. Floor cavity created by special plastic modules (IGLU modules).

4. Controlled ventilation

The functionality and efficiency of natural airflow in cavities are often limited. Common causes include poorly designed ventilation systems, inadequate maintenance, and the significant influence of external boundary conditions. These problems can be solved by a controlled ventilation system where airflow is ensured by a fan [11].

A fan is installed at the exhaust holes, creating a negative pressure in the cavity during its operation. This negative pressure causes the air in the cavity to move towards the exhaust holes and the air to flow through the intake holes, strategically positioned to ensure airflow across the maximum surface area of the cavity. Unlike natural ventilation methods, airflow in this system is not dependent on external factors such as temperature differences, air velocity and other factors that are essential to the natural method. Additionally, air entering the cavity can be preheated, increasing its moisture absorption capacity and reducing heat losses. However, operating such systems requires a power supply, and regular maintenance is crucial to ensure proper functioning.

The primary goal of ventilation methods is to evaporate moisture from the building structure and expel it from the cavity into the surrounding environment. However, under specific boundary conditions, the opposite effect can occur, where unsuitable external air can cause the cavity to become damp. This may happen, for example, when the external surfaces of the structure are cold, and warm, humid air is drawn into the cavity. Upon contact with the cold structure, the air cools significantly, loses its moisture absorption capacity, and condensation occurs on the structure's surface.

To prevent this issue, the system can be configured to operate only under suitable conditions, with specific operational schedules and intervals. Designing such a system requires detailed analysis using computational software, followed by on-site evaluation and validation. A significant advantage of the controlled method is its potential application in existing ventilation systems that previously relied on natural airflow. Since these buildings already have ventilation spaces in place, adapting them to a controlled ventilation system can be done relatively easily and without major destructive interventions. Comparison with natural ventilation in terms of its efficiency (e.g., level of moisture reduction, financial costs connected with its operation) will be part of future research. This method presents a significant yet underexplored potential and is one of the few methods available when choosing to remediate historic and heritage protected buildings.

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Durable VO_2-based Coatings: Effects of Concrete Curing on Surface Moisture, Adhesion, and Thermochromic Properties

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Abstract. Heating, ventilation, and air conditioning (HVAC) systems, essential for thermal comfort, rely heavily on fossil fuels, contributing to climate change and extreme weather events. Currently, HVAC systems have accounted for over 60% of total building energy use in EU countries. Improving the thermal performance of building envelopes is critical for curbing HVAC consumption. Thermochromic VO_2-based coatings offer significant potential due to their ability to dynamically switch between heat-absorbing and heat-reflecting states in response to temperature. However, the application of VO_2-based coatings on opaque building surfaces, such as concrete, remains largely unexplored. In this study, we developed a VO_2-based thermochromic coating formula integrated superhydrophobicity and strong adhesion, simultaneously achieving a contact angle of 151° and adhesion strength of 4.85 MPa. The performance of VO_2-based coatings was further evaluated by applying the coating on the surfaces of concrete samples with different curing times. Results showed that applying the coating on the surface of concrete cured for 6 and 12 h caused severe peeling and cracking. In addition, achieving simultaneous superhydrophobicity and strong adhesion required a curing time of at least 24 hours (concrete paste with low water required a shorter curing time) at room temperature or 12 h at 60°C. The coating reflection results indicated that a shorter curing time (6, 12 h) might lead to a slightly higher reflection due to the exposure of the underlying concrete. This work provides guidance on the application of coatings on opaque building substrates, contributing to sustainable building material design and energy-efficient building strategies.

1. Introduction

Building energy cost accounts for 30-40% of global energy consumption and approximately 30% of energy-related carbon emissions[1-3], and this trend keeps increasing. Notably, Heating, Ventilation and Air Conditioning (HVAC) systems, essential for maintaining indoor thermal comfort, contribute to over 60% of total building energy consumption in EU countries and Russia[4], and 40% in the US and China. The European Commission has highlighted that 85% of EU buildings were constructed prior to 2000, with 75% of these structures demonstrating poor energy performance. Enhancing the energy efficiency of buildings is therefore critical for reducing energy costs for citizens and small enterprises, as well as for achieving a zero-emission and fully decarbonized building stock by 2050. These energy and climate challenges underscore the urgent need for innovative and energy-efficient solutions in building infrastructure[2, 5, 6].

Optimizing the building envelope structure is key to achieving high thermal energy efficiency. While thermal insulation materials with low thermal conductivity such as expanded polystyrene board and polyurethane foam can effectively reduce heat exchange between the interior building and the external environment[7], several challenges remain including time, space considerations, the invasiveness of interventions, costs, and the workload associated with refurbishment. Adaptive facades technologies (AFTs), such as thermochromic coatings (TCs)[8], smart ventilated windows[9], and building-integrated photovoltaics[10], offer co-optimization strategies of energy efficiency, reducing total energy demand by up to 40% and minimizing the need for thick insulation layers[11]. Among AFTs, TCs provide a passive, dynamic, and energy-efficient solution by automatically switching between highly absorptive and highly reflective states in response to temperature without requiring external power or mechanical components[12-14]. Monoclinic vanadium dioxide (VO_2 (M), hereafter referred to as VO_2), recognized for its fascinating metal-insulator transition property (MIT) and substantial thermochromic modulation capability, exhibiting transparency to near-infrared (NIR) light at temperatures below the critical temperature (T_c, ~68 ^oC) but more reflective to NIR light above it, has been considered as one of the most competitive TCs[13]. However, VO_2 still faces challenges such as poor durability[15, 16], and VO_2 on opaque surfaces has not been much explored yet.

The accumulation of dust and organic contaminants on the surface can reduce light exposure and impair the optical properties of VO_2, leading to the need of self-cleaning properties for enhanced durability[17]. This can be achieved through two primary approaches: 1) Hydrophilic, photocatalytic materials such as TiO_2 are employed to accelerate the degradation of organic matter[18]. 2) Superhydrophobic polymers such as polydimethylsiloxane (PDMS), polystyrene, and polycarbonate can be used to decrease the surface energy to achieve self-cleaning performance[19]. Additionally, poor adhesion of the coating to substrates, such as concrete, can lead to peeling, bubbling, and cracking under mechanical stress, compromising long-term stability. Factors such as coating formula design[20] and appropriate application conditions[16], including the surface moisture of concrete, play a significant role in achieving robust adhesion. However, integrating superhydrophobicity with good adhesion is inherently challenging, as superhydrophobicity typically require low surface energy, whereas strong adhesion necessitates high surface energy for a robust connection between the coating and substrate. Balancing these opposing properties is a key challenge in coating design, and studying the influence of the concrete's surface moisture can provide practical guidance for the application of coatings on concrete surfaces. Nevertheless, studies on durable VO_2-based coating formulations for concrete surfaces remain scarce.

In this study, we developed a durable VO_2-based thermochromic coating formulation by dispersing VO_2 particles and hydrophobic SiO_2 particles into PDMS and epoxy in butyl acetate. VO_2 particles were synthesized via a hydrothermal method, with tungsten acid added during synthesis to modify the T_c of the VO_2 particles. To optimize durability, we adjusted the ratio of PDMS to epoxy and evaluated the surface moisture of the coating and adhesion with concrete by measuring the contact angle (CA) and pull-off strength. The coatings were applied to concrete with different curing times, and their CA, adhesion, and thermochromic reflection (at 5 °C and 45 °C) were characterized to assess curing effects. This work provides a solution to the durability limitations of VO_2-based TCs and advanced practical use of VO_2-based TCs on large-scale opaque building surfaces, contributing to sustainable solutions for highly energy efficient buildings.

2. Experimental Section

2.1 Materials

Oxalic acid dihydrate ($H_2C_2O_4$·$2H_2O$, for synthesis) was purchased from Supelco® Analytical Products (Merck KGaA, Germany). Vanadium pentoxide (V_2O_5, 99.6%) and tungstic acid (H_2WO_4, 99+%) were obtained from Thermo Fisher (Kandel, Germany). Hydrophobic fumed silicon dioxide particles (SiO_2, 10 nm) were obtained from Carl Roth (Karlsruhe, Germany). Butyl acetate ($C_6H_{12}O_2$, <= 100 %) were supplied by Sigma-Aldrich, Merck Life Science BV (Hoeilaart, Belgium). SYLGARD™ 184 silicone elastomer (PDMS, part A) with curing agent (part B) was the product of Dow Chemical Company (Michigan, American) and Epoxy resin (SUPER SAP® 100/1000, including CLR (part A) and CLF (part B)) was provided by Entropy Resins (Wesel, Germany). The concrete bricks with flat surface were supplied by Prefaxis. All chemical reagents in our experiments were used without further purification. Ultrapure water (MQ, 18.2 MΩ·cm, 25 °C) used as the reaction solvent was obtained by purification of deionized water with a Merck system.

2.2 Preparation of durable VO_2-based thermochromic coating

The VO_2 particles were synthesized via a hydrothermal method[21]. In a typical procedure, 4.15 g $H_2C_2O_4$·$2H_2O$ was dissolved in 50 ml ultrapure water. 3 g V_2O_5 (V_2O_5:$H_2C_2O_4$·$2H_2O$=1:2), 0.206 g H_2WO_4 (the added atomic percent of W is 2.5 at%), and dissolved oxalic acid aqueous solution was added into the Teflon liner and the liner was put into a stainless-steel vessel. The whole vessel was then put on a hotplate stirrer, the temperature was set to 240 ^{o}C and a reaction duration of 24h was taken. After 24 hours, the temperature was set to 40 ^{o}C and the solution was left to cool down. The obtained solution was centrifuged and washed twice using ultrapure water and once with ethanol, and dried overnight at 60 ^{o}C to obtain the VO_2 particles.

The above obtained VO_2 particles and as-received hydrophobic SiO_2 were dispersed in 10 ml butyl acetate solvent for ultrasound 30min. Then PDMS part A and Epoxy part A were added into this solution to stir for 20 min until they were completely dispersed. PDMS part B and Epoxy part B were subsequently added to the solution to keep the ratio of PDMS part A: part B as 10:1 and Epoxy part A: part B as 100:45. Varying coating formula with different content of PDMS and epoxy were prepared by adjust the weight ratio of PDMS(A+B) to Epoxy(A+B) at 1:3, 1:2, 1:1 and 2:1 (Total weight of PDMS(A+B) and Epoxy(A+B) is consistent). These solutions were stirred at 1000 rpm for 2h to obtain the varying coating formula, recorded as VO_2 (1:3), VO_2 (1:2), VO_2 (1:1)and VO_2 (2:1). These coatings were applied to concrete specimens (supplied by Prefaxis) via a glass rod to determine the CA and pull-off strength.

2.3 Preparation concrete cubes and application of coatings

The concrete mixtures were prepared by weighing cement, water and aggregates (including 40% sand, 25% limestone 4/6.3 and 35% limestone 6.3/20) in a proportion of 1:0.6:6.1 (Formula A). To establish comparative surface moisture conditions, another mixture with lower water content (Formula B) was specifically formulated with a composition of 1:0.4:4.7 with aggregate distribution of 44% sand, 11% limestone 2/6.3 and 45% limestone 6.3/14. For both formulations, the preparation followed the same protocol: aggregates and cement were initially mixed in a concrete pan mixer for 1 min, followed by water addition and additional mixing for at least 1 min. The resulting mixtures were poured into 10×10×10 cm^3 molds and compacted on a vibration table to prevent honeycombing. After curing (6, 12, 24, 48 h at room temperature and 12, 24 h at 60 °C), the cubes were demoulded and immediately coated with the optimal durable formulation. For each condition, two concrete cubes were prepared with coating applied to three surfaces. The coated samples were designated as V6, V12, V24, V48, V12-HT and V24-HT, respectively. After applying coatings, concrete samples based on Formula A was cured for 28 days and concrete samples based on Formula B was cured for 48 h in 80 °C water bath for the subsequent tests.

2.4 Characterizations and tests

The CA data were measured using the PGX+ pocket goniometer (TQC Sheen, Netherlands), with at least three measurements performed on each of the three coated surfaces per sample. The relative moisture of concrete and adhesion of coatings to concrete were tested by a concrete moisture meter and pull-off adhesion testers, respectively (PosiTest CMM, PosiTest AT-M, DeFelsko@, US) for 5 times on three surfaces per sample. Dollys with a diameter of 20 mm were fixed on the coating surface using the appropriate glue. After curing the glue for 48 h, the pull-off test was conducted and the highest adhesion strength before pulling apart was recorded. For each sample, five dollies were distributed across the three coated surfaces to ensure representative sampling. The reflection spectra (900-2500 nm) were recorded using a near-infrared spectrometer (900-2500 nm, NIR Quest+2.5, Ocean Insight, UK) equipped with a light source (wavelength range: 360-2400nm).

3. Results and Discussion

3.1 Preparation of durable VO_2-based thermochromic coating

Hydrophobic PDMS is one of the most commonly used materials in achieving self-cleaning performance by decreasing the surface energy, whereas epoxy provides excellent adhesion and serves as the binder in coating formulations. However, simultaneously achieving superhydrophobicity and strong adhesion presents inherent challenges due to their conflicting surface energy requirements. In our preliminary studies, a baseline 1:1 PDMS-to-epoxy ratio was first evaluated based on its balanced composition. Subsequently, the CA and adhesion test results from this intermediate ratio guided the selection of additional weight ratios (1:3, 1:2, and 2:1) to systematically investigate the property compromise. This extended ratio range covers adhesion-favorable (1:3) to hydrophobicity-favorable (2:1) formulations, allowing for a comprehensive evaluation of their competing effects on the coating performance. The optimal balance between these contradictory properties can thus be determined through comparative analysis.

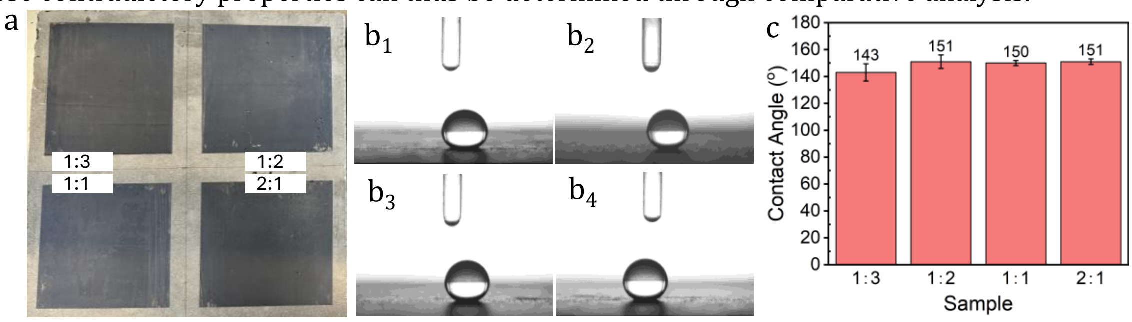

Figure 1. (a) Photographs of VO_2 (1:3), VO_2 (1:2), VO_2 (1:1) and VO_2 (2:1). (b) Images and (c) Histograms of contact angle for the four coatings (with error bars).

The coatings with varying PDMS : epoxy ratios of 1:3, 1:2, 1:1, and 2:1 were applied on the as-received concrete surfaces (Figure 1a) and the CA data were tested and recorded (Figure 1b$_1$-1b$_4$ and 1c). The CA of the $VO_{2\text{-}1:3}$ sample was measured to be 143°. With an increase in the relative PDMS content, the CA of VO_2 (1:2), VO_2 (1:1) and VO_2 (2:1) were 151°, 150°, and 151°, respectively, all exceeding 150°, indicating superhydrophobic properties. Therefore, to achieve superhydrophobicity, the ratio of PDMS to Epoxy should not be lower than 1:3.

The adhesion property of the coating on concrete was further evaluated by pull-off tests (Figure 2a and 2b). For VO_2 (1:3), the substrate fracture was observed, with some concrete fragments remaining adhered to the coating without detachment. This indicates that the coating exhibited excellent adhesion to the concrete, and even under conditions of concrete fracture (the average tensile strength of concrete was 2.9 MPa), the coating and concrete surface remained partially bonded. A similar substrate fracture was observed for the VO_2 (1:2) coating, albeit with a smaller area of concrete fragments attached to the coating. This suggested that the adhesion between the coating and concrete gradually diminishes as the relative content of the epoxy component decreased. This trend was further demonstrated by the results for the VO_2 (1:1) and VO_2 (2:1) coatings, where adhesive fracture was observed between the coating and concrete without concrete fracture. The data presented in Figure 2b provide a more quantitative illustration of adhesion strength of these coating with concretes. As the relative content of the epoxy component decreased, the avarage pull-off strength declined from 5.32 MPa (VO_2 (1:3)) to 4.85 MPa (VO_2 (1:2)), then to 3.20 MPa (VO_2 (1:1)), and finally to 1.38 MPa (VO_2 (2:1)). According to literature[22], a pull-off strength of at least 3 MPa is required to ensure adequate adhesion between the coating and concrete. Therefore, a PDMS:epoxy ratio of either 1:3 or 1:2 is recommended to achieve optimal adhesion performance.

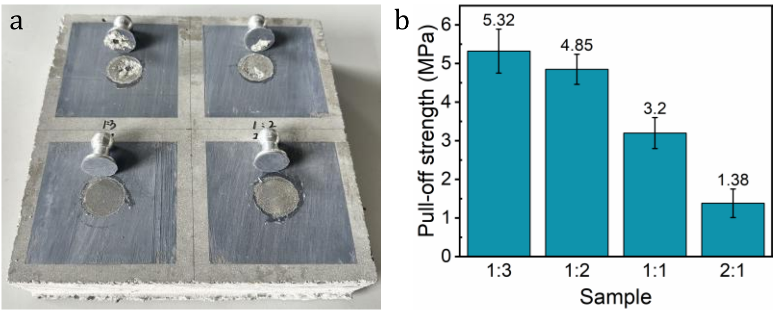

Figure 2. (a) Interface photographs of VO_2 (1:3), VO_2 (1:2), VO_2 (1:1) and VO_2 (2:1) after pull-off test. (b) Histograms of pull-off strength values of four coatings (with error bars).

Based on the above results, we preliminarily identified a durable coating formulation that achieves both superhydrophobicity and strong adhesion with a PDMS-to-epoxy ratio of 1:2.

3.2 Investigation of effects of concrete curing on CA, adhesion, and thermochromic properties of VO_2 coatings

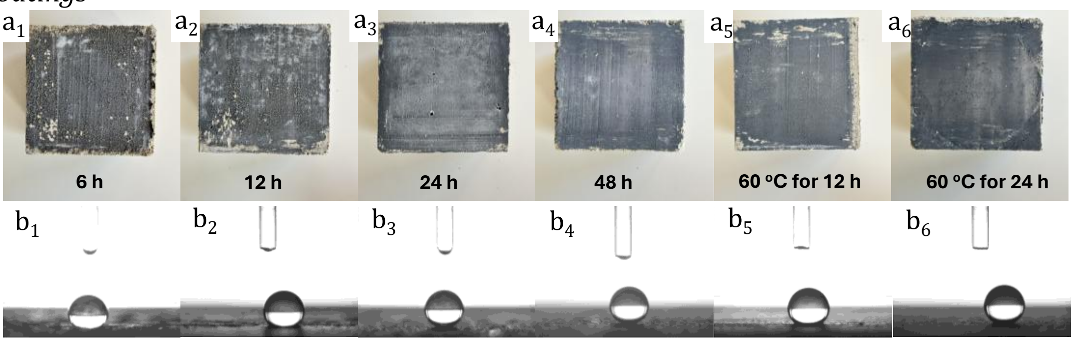

Figure 3. (a_1-a_6) Photos and (b_1-b_6) CA of the coatings V6, V12, V24, V48, V12-HT and V24-HT.

The surface moisture of concrete, influenced by curing time, temperature, humidity, etc., may lead a significant difference in the adhesion of coatings with the concrete. Investigating the effect of concrete surface moisture on coating performance can also provide guidance on the optimal timing for coating application in practical scenarios. Therefore, the prepared durable coating formulation was applied to concrete surfaces with different curing times, including 6, 12, 24, 48 h at room temperature and at 60 °C for 12 and 24 h, respectively. After applying coatings for 48h, photographs of these coatings (V6, V12, V24, V48, V12-HT and V24-HT) were recorded and presented in Figure 3a$_1$-a$_6$. For V6, severe peeling and cracking were observed, and the coating could be easily scraped off, indicating poor adhesion between V6 and the concrete. The reason might linked to the incompatibility between high surface moisture of concrete at a curing time of only 6 h and the organic components in the coating formulation (PDMS and butyl acetate), due to which the coating could not penetrate the micro voids of the concrete surface to form good adhesion through mechanical interlocking. When applying the coating after the curing time of concrete increased to 12 hours (V12), significant peeling and cracking were still observed. When the curing time was further increased to 24 hours (V24), no significant peeling or cracking was observed, and the coating adhered well to the substrate. A similar result was observed for V48, with no noticeable peeling or cracking. This suggested that V24 and V48 showed lower surface moisture content when applying coatings, facilitating better adhesion. In industrial applications, some companies accelerate the curing process by heating concrete during curing to reduce production cycle times. Therefore, we also cured concrete samples at 60°C for 12 h and 24 h, followed by coating application, obtaining samples V12-HT and V24-HT. For V12-HT, minor surface cracking was still observed, whereas V24-HT showed no visible cracking of the coating. This suggested that a 12-hour curing at 60°C may not be sufficient to reduce surface moisture to a level for coating application, whereas a 24-hour curing duration was long enough.

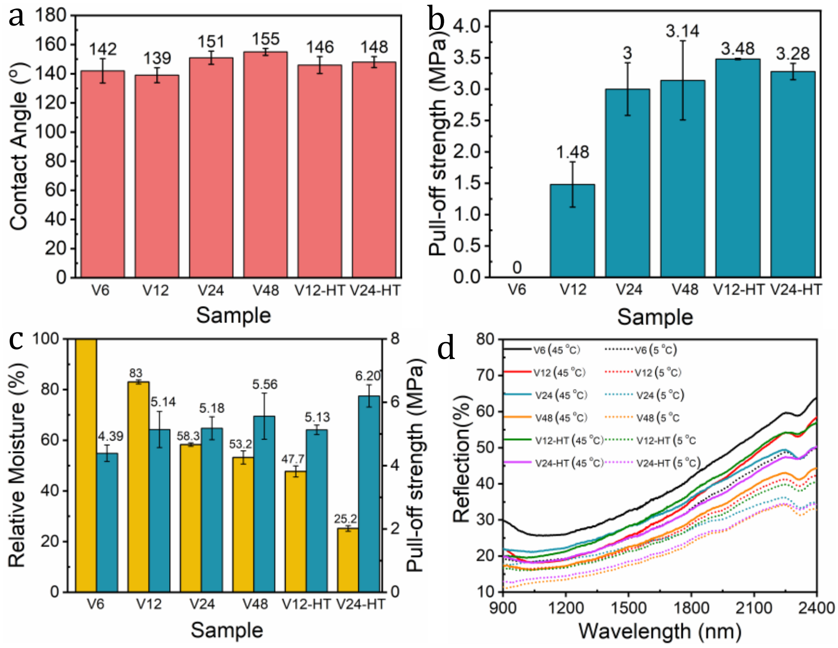

Figure 4. (a) Histograms of CA, and (b) pull-off force for V6, V12, V24, V48, V12-HT and V24-HT (Formula A). (c) Histograms of relative moisture of concrete surface before being coated and pull-off force (Formula B), and (d) reflection for V6, V12, V24, V48, V12-HT and V24-HT (Formula A).

The CA of all coatings were measured (Figure 3b$_1$-b$_6$ and Figure 4a). Samples V6 and V12 showed relatively low CAs (142° and 139°, respectively), likely due to microvoids or incomplete coating formation caused by high surface moisture or poor adhesion. In contrast, samples V24, V48, V12-HT, and V24-HT exhibited significantly higher CA of 151°, 155°, 146°, and 148°, respectively, indicating improved surface uniformity and hydrophobicity. The slightly lower CA of V12-HT (146°) compared to V24 and V48 may be attributed to surface microcracks. However, the higher CA of V24-HT (148°) suggests that heat treatment enhances surface compactness by accelerating moisture reduction and curing. Pull-off force tests (Figure 4b) revealed a progressive increase in adhesion with curing time. V6 showed no measurable adhesion due to excessive surface moisture. V12 achieved 1.48 MPa, and adhesion improved to 3.00 MPa and 3.14 MPa for V24 and V48, respectively. Heat-treated samples (V12-HT and V24-HT) exhibited slightly higher adhesion (3.48 MPa and 3.28 MPa), confirming that elevated curing temperatures improve bonding by reducing moisture content more effectively.

Due to the high water content in Formula A, the surface moisture values could not be measured as they exceeded the range of the concrete moisture meter. To establish a wider range of surface moisture conditions and enable moisture-adhesion correlation analysis, Formula B with reduced water content was specifically developed. The relative moisture and adhesion results were recorded in Figure 4c. For early demolding (V6), surface moisture exceeded measurable limits, and adhesion was 4.39 MPa. As curing time increased, moisture decreased and adhesion improved, supporting the negative impact of high moisture on coating adherence. Concrete cured at 60 °C for 12 h showed surface moisture of 47.7% and adhesion of 5.13 MPa, similar to that of V24 and V48. This suggests that brief heat treatment mainly reduces surface moisture, while internal moisture may still hinder curing. In contrast, 24 h heat curing resulted in the lowest moisture (25.2%) and highest adhesion (6.20 MPa), further confirming the importance of moisture control for effective coating–substrate interaction.

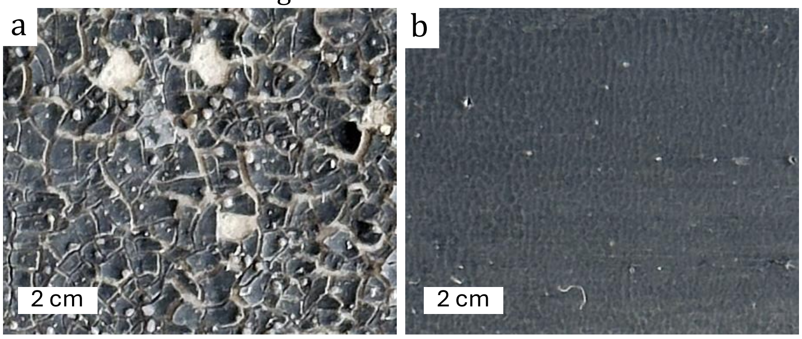

Figure 5. Surface morphology of (a) V6 and (b) V24-HT.

All coatings exhibited a distinct thermochromic transition, with higher reflection at 45°C than at 5°C (Figure 4d). V6 with shorter curing durations demonstrated higher overall reflection, likely due to increased surface roughness enhancing diffuse reflection. As shown in Figure 5a, the V6 coating exhibited edge curling that exposed the lighter-colored concrete substrate beneath it, which had higher reflection and thus contributed to the increased reflection of V6. This may be detrimental to energy efficiency during winter, as the season typically requires coatings with low-reflection and high-absorption property. In contrast, V24-HT showed no observable coating cracks or exposed concrete substrate (Figure 5b), resulting in lower reflection. Notably, the temperature-induced reflection variation remained consistent across all samples, indicating that curing conditions had minimal influence on the intrinsic thermochromic behavior of the VO_2.

Prolonged curing enhances both hydrophobicity and adhesion of VO_2/PDMS-epoxy coatings on concrete substrates. Considering the practical implementation, Optimal performance was achieved with a PDMS-to-epoxy ratio of 1:2, applied to concrete cured for at least 12-24 h at room temperature (depending on the initial water content of concrete) or 12 h at 60 °C. These findings provide practical guidance for optimizing coating durability and energy efficiency for buildings.

4. Conclusion and Outlook

This study developed a durable VO_2-based thermochromic coating with integrated superhydrophobicity and strong adhesion for application on opaque concrete surfaces. The optimized 1:2 ratio of PDMS to epoxy achieved a CA of 150.6° and adhesion strength of 4.85 MPa, demonstrating its excellent durable properties. The effect of concrete curing time on coating performance was systematically analyzed. Coatings applied to insufficiently cured concrete (6–12 h) suffered severe peeling and cracking due to excessive surface moisture. In contrast, curing for at least 24 h at room temperature (concrete with low water content may require a shorter curing time) or 12 h at 60°C significantly improved adhesion and hydrophobicity. Reflection results showed that shorter curing times might lead to slightly higher reflection due to the exposure of underlying concrete. This work provides practical guidelines for optimizing VO_2-based coatings on concrete, ensuring long-term performance and energy efficiency in building applications.

Future studies should focus on long-term durability in terms of anti-oxidation and breathability properties. A durability assessment, for example in a high-temperature and high-humidity environment, is necessary to evaluate practical durable performance. Additionally, integrating VO_2-based coatings with photocatalytic or phase-change materials could further improve self-cleaning and passive thermal regulation. Experimental and numerical verification should be conducted to evaluate the practical energy-saving performance of the VO_2-based thermochromic coatings. These efforts will advance smart, energy-efficient coatings for sustainable architecture and global carbon reduction.

Acknowledgements

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Decision-support tools, assessment, and modelling for building design

Cost Efficiency in sustainable neighborhood planning – analysis of experience reports

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Abstract. The need for new housing construction in Germany is calculated to over 372,000 units per year (DIW, 07.06.24). The building sector, however, significantly contributes to greenhouse gas emissions, and new residential construction is associated with large future investments. This study investigates the hypothesis that sustainable housing does not necessarily lead to higher overall construction costs as compared to conventional housing construction. The aim is to identify key components for cost savings in ecological housing to provide decision-making support for stakeholders in the construction industry. First, best practice examples in sustainable housing were collected and published on the project website. For comparison, specific measures of 'sustainable' or 'conventional' housing construction were defined and evaluated in mainly three thematic areas: energy & climate protection, mobility and building materials & healthy living. For each of these measures, specific levels of 'sustainability' were defined (high, medium, low), along with references provided for the conventional form of the measure in order to model and compare construction costs. In cooperation with the BKI Construction Cost Information Centre (BKI GmbH, Stuttgart) and other partners, data both on actual costs of housing projects as well as on planning strategies to reduce costs were collected and allocated to the measures. In result, this study presents new findings on planning and construction strategies that allows for both cost-effective and sustainable housing construction. To this end, findings from over 20 in-depth interviews with experts in the subject areas will be presented.

1. Introduction

The German federal government has set a target of constructing up to 400,000 new homes annually to address the growing demand for rental apartments in the major cities in Germany. However, the construction and operation of buildings are major contributors to greenhouse gas emissions. According to the Climate Protection Act, Germany aims for net greenhouse gas neutrality by 2045. Buildings in Germany, however, account for approx. 30% of such emissions in 2023 (BMVU 2023), which underlines the urgent need for a shift towards more sustainable housing construction. Although the environmental advantages of ecologically oriented neighborhoods are recognized, there has been limited research on their economic implications, highlighting a critical area for in-depth study.

The aim of the study is to record, analyze and systematically document construction costs and cost reduction potentials of ecologically sustainable compared to conventional neighborhoods and settlements. Hence, this study focuses on new housing construction at the neighborhood level. A neighborhood is defined as: “a spatially coherent area that is often characterized by a common development over time, for example by similar building typologies, and/or by comparable types of use. The size of a neighborhood allows for a detailed consideration in which energy, building culture and social aspects can be taken into account.” This includes both purely residential and mixed-use districts with minimal non-residential functions. Recently, neighborhoods have gained prominence in research as a key unit for studying the implementation of eco-friendly and energy-efficient designs. (BBSR and BBR 2021). The present study complements such studies in order to gain new insights into the economic aspects of ecological neighborhoods and settlements.

Previous research (DGNB 2020, F+B 2016, Blauel, C. et al. 2018, BBSR and BMI 2019) has analyzed the construction costs of housing based on specific parameters. However, these studies have not explored the feasibility of developing ecological and cost-effective residential districts simultaneously. The proposed study aims to fill this gap by comparing the economics of ecological housing construction with conventional new housing construction. It seeks to test the central hypothesis that sustainable housing construction need not be more expensive than conventional methods.

2. Method

2.1 Modeling

In the first step, examples of sustainable construction projects were researched and published on the project website “O2W project website” - at https://o2w.sdg21.eu/ (ikre, greenUp 2025).

In the second step, a system for data collection was developed that summarizes the main methodological steps. The analysis and comparison of construction costs are highly complex. In order to reduce this complexity, different main focus areas were developed with a focus on 1)

Table 1. Ecological standards in the field of energy

Ecological standards	Indicator	Reference	Low	Medium	High
Building energy standard	Cost*/m² living area	KfW 55, 65% EE	KfW 40	PH	Effizienzhaus Plus
Primary energy demand	Cost*/m² living area	0,55	0,4	0	>0%

*average building costs; positions 300&400 (DIN276)

Table 2. Ecological standards in the field of mobility

Ecological standards	Indicator	Reference	Low	Medium	High
Required number of parking lots	Nr. of parking lots/resident unit	City-specific number.	<1 - 0,61	0,25 - 0,60	<0,25
E-charging infrastructure	%/number of parking lots	% legal preparation	<30%	30%-60%	>60%
Mobility concept		None		Existing	

Table 3. Ecological standards in the field of building materials

Ecological standards	Indicator	Reference	Low	Medium	High
Share of wood-/renewable raw materials in the construction	Cost/m² living are	<10%	<30%	<60%	>60%
Share of recycling material	Cost/m² living are	<10%	<30%	<60%	>60%

energy, 2) mobility and 3) building materials. Sustainable building measures were then defined in each main focus area. As a result, a model was developed that defines the term "sustainable new housing construction" by defining measures of sustainable housing construction for this study and thereby narrowing down the subject of the study. Reference values were developed that represent sustainable construction in three levels - low, medium and high (see table 1-3) along with references provided for the conventional form of the measure in order to model and compare construction costs. In result, key cost parameters were allocated to each level of the measures.

2.2 Interviews with stakeholders in new residential construction

To explore the key research objectives, in-depths interviews with key stakeholders were conducted. Qualitative interviews, a fundamental method in qualitative social research, are highly effective for gaining in-depth insights into the subjective experiences and perspectives of participants (Ulrich 2016). The goal of these interviews was to analyze strategies for sustainable and cost-effective construction and to gather cost data from projects. A set of key questions was developed to guide the interviews, listed in Table 4. An exploratory approach was used, employing qualitative in-depth interviews to capture and critically examine information during the interview process. Interviews involved open-ended questions, allowing respondents to answer in their own words. Questions were adaptable, enabling the interviewer to delve deeper into topics or omit resolved questions, thus allowing the interview to be less structured by the questionnaire and more shaped by the interviewee's contributions. This flexibility enhances the depth and detail of the exploration (cf. Döring 2023: 360ff.).

Table4 . Interview question guide

Category	**Content of the main questions**
Energy	Description of energy concept, building energy standard, cost group with highest savings potential, quality, specific costs
Mobility	Sustainable mobility concepts, influence of mobility solutions on planning, parking space key, specific costs
Building materials	Decision on sustainable building materials, costs of sustainable construction, cost group with highest savings potential, quality, specific costs

Architectural practices, investors and developers were identified as the main relevant stakeholders for this study, as these stakeholders have data on completed new residential construction projects. For the data collection, 20 interviews were conducted in the period from April 2024 to February 2025.

The interviews were conducted partly in person, but mainly digitally via Microsoft Teams and recorded as audio files. The audio files were transcripted to text files which served as the basis for the content analysis and coding with MaxQDA software. Following inductive category development, main codes and subordinate sub-codes based on the main focus areas were extracted from the interviews (see table 5). The frequency of the codes cannot yet reliably indicate which categories carry more weight than others, but will be taken into account in the analysis.

2.3 Comparison of cost parameters in the various fields of activity

2.3.1 With regard to "building materials", data on real-world examples in new residential construction are analyzed in cooperation with the Building Cost Information Center of the German Chambers of Architects (Baukosteninformationszentrum Deutscher Architektenkammern, BKI GmbH, Stuttgart).The cost data and life cycle data stored in the BKI "Construction Atlas KA2" (BKI 2024 a) are used as a data source to calculate comparative values for ecological and conventional construction measures. All Materials used in the „Eco" or „Conventional" variants are calculated from average cost data for all materials drawn from the BKI database and calculated against the quantity take off of the standard building. The calculation refers to a standard building that is stored in KA2 with a complete quantity structure. Those measures are selected as "eco" measures that were marked as "ecological" in the interviews, while the conventional measures mentioned in KA2 are retained (see Table 5). The model then presents the respective results of the life cycle analysis before Global Warming Potential (GWP) and cost data for the building, once as an "eco" variant and once as a "conventional" variant. The results are available not before 05/2025 and will be reported elsewhere.

2.3.2 Cost data for the "Mobility" main focus area comes from various sources. The core results from the interviews relate to measures for sustainable mobility in the neighborhood and win-win situations in the area of sustainability with simultaneous cost savings (e.g. reducing parking lots, dispensing with underground parking and dispensing with wide access roads is sustainable and cost-effective). However, not only win-win situations were identified, but also measures of sustainable construction that leads to higher construction costs (e.g. ramps for bicycles, new mobility services such as sharing; 'mobility hubs' on site or pilot projects for sustainably logistics on site). Information on cost data were generated from the interviews or provided by interview partners, but also from cost databases such as that of the BKI (e.g. for underground parking lots).

Table 5. Overview of the code structure

Main Code	Sub Code
Mobility (38)	Bicycle/pedestrian traffic, parking lots, mobile stations
Building Material (34)	Serial/modular construction, building energy standard, construction
Energy (14)	Operation, energy system, energy technology, renewable energies
Planning process (39)	Communication, relationship of trust, key players, tendering, awarding, urban planning/design, financing/funding
Infrastructure (21)	Waste disposal, trees, drainage, development

3. Results

The results presented are taken from the most informative interviews or stakeholders conducted with Gernot Vallentin (ArchitekturWerkstatt Vallentin), Jan Schreiber (ZRS Architekten), Max Mannschreck (Werner Sobek), Matthias Rottmann (De Zwarte Hond), Christoph Theiling (p+t Planung) and Steffen Reinecke (Zukunftsnetz NRW) (see bibliography).

During the evaluation process, main codes were defined, which are based on the main focus areas but also include other aspects: Mobility, building materials, planning process, energy and infrastructure. The subordinate sub-codes can be assigned to the main main focus areas and also to the planning process (see Table 5).

A total of 146 codes were assigned to text segments from the processed interviews relating to the main focus areas. By doing so, we for example identified overlapping or contradictory statements on strategies for cost-effective and sustainable new residential construction or determined cost data. Also, some oft he interview data pertain to specific case studies, e.g. „Ellener Hof“ in Bremen (Theiling, Rottmann, Schreiber), „Kokoni One“ in Berlin (Schreiber), „P18“ in Stuttgart (Mannschreck) and „Prinz-Eugen-Park“ in Munich (Vallentin).

The aspect of cost savings are being highlighted throughout all the interviews, however, high heterogeneity in data can be found with regard to innovative sustainable elements and the associated costs. Hence, we analyzed this heterogeneity in more detail, e.g. different priorities can be identified for the implementation of the strategies, with different levels of ambition for sustainability goals. The projects have different prerequisites; the funding is different and the investors have different motives. Depending on the main focus area, strategies can already be worked out. The results in the main main focus areas are summarized below.

Planning process

According to Rottmann, a successful sustainable neighborhood development relies on key players demonstrating a commitment to sustainability, as seen in the Ellener Hof project, where for example architects were selected in competition processes explicitly taking into account their pre-experience in timber construction to meet sustainability objectives. (Rottmann 2025: 16). Likewise, planning competitions need to be based on an evaluation of concepts and / or based on fixed price guarantees to ensure both quality and cost efficiency (Rottmann 2025: 40, 170). "in-efficient competition processes" can lead to a cost increase of 20 - 50%. Often, the wrong methods are used and the wrong time for the competition process is chosen (Vallentin 2024).

In the case of the Ellener Hof a design manual for the whole development area (“neighbourhood”) was worked out that helped minimizing costs by avoiding excessive design requirements for each building design, such as unnecessary loggia insulation (Rottmann 2025: 166).

Trust between property owners and the city is crucial, as exemplified by addressing residents' concerns about parking lots and preserving old trees to avoid political issues and extra costs. Problems could be “communicated” (Rottmann 2025: 66) which saved time and such construction costs: “the time aspect should not be forgotten. It also costs money.” (Rottmann 2025: 184).

The project's financing strategy involved the right to construct a building on land owned by another person (“building lease”) to prevent speculation and ensure affordable housing (Rottmann 2025: 40). This aligns with the social goal of securing long-term capital for the foundation that owns the land rather than maximizing short-term returns (Rottmann 2025: 154).

Sustainable transport / mobility

Minimizing the amount of parking lots enhances cost-efficiency and sustainability: For the example of underground parking, Schreiber is quoted to say that underground parking heavily adds to building costs and reduces sustainability” (Schreiber 2024: 14). In the case of the “P18 neighborhood”, despite having underground parking, residents prefer using area's intermodal connections instead and the parking lots in place are almost not used until today (Mannschreck 2024: 23).

At Ellener Hof, mobility hasn't been a major cost factor as partly assembling parking decks are built on ground level instead of an underground garage, which would also could have damaged the existing trees by lowering the groundwater level (Theiling 2025: 16). Planning fewer parking lots also reduces transport areas and streets, which leads to reduced costs and minimizes car traffic within the neighbourhood (Rottmann 2025: 16). Rottmann also explains the project teams' strategy to maintain a low parking ratio: "We initially based our parking lot calculations to a certain building density, which initially was designed for three level buildings throughout the development site, including visitor spaces and access road dimensions. Later on in the project, the city allowed for exemptions of the 3-levels rule and allowed to four-story buildings universally, but we did not have to provide for more parking lots" (Rottmann 2025: 16).

Discussions on reducing parking lots should also consider integrating (electric-) car and bike sharing concepts (Vallentin 2024: 17). Although not heavily emphasized in interviews, one example is the Ellener Hof bicycle station, which includes sharing and a DIY-workshop (Theiling 2025: 76). However, strategies for 'mobility hubs' in neighborhoods were not detailed, and no specific funding provided (28). Reinecke notes that recommendations for 'mobility-hubs' should be highly individualized, as costs vary depending on the size and distribution of the system (Reinecke 2024: 24, 74).

By reducing the number of parking lots, significant savings can be achieved, as the cost per underground parking space can sum up to €45.000 (Vallentin 2024). These reductions can be facilitated by integrating mobility services, such as stations offering car-sharing. For instance, Connected Mobility in Düsseldorf established mobility-hubs for a total of €205.000 (net), including 8 parking spaces, 4 of which are for (electric-)Car-Sharing, 5 bicycle racks, 2 cargo bike racks, 1 scooter module, 1 closed bicycle parking facility, 1 roof 3m x 4m, 1 bicycle repair box and including other elements such as a bench, network connections, signs, markings and civil engineering work.

Assuming that a mobility-hub can save parking spaces and that each car used in car-sharing can reduce the number of parking spaces by between 5 and 16 (StMB 2022 and Nehrke 2023), the mobility-hubs described above could save up to 40 parking spaces (assuming Car-Sharing replaces 10 private cars), which corresponds to total cost savings in this example of up to €1.80 million.

Building materials and construction

Vallentin highlights that construction costs often include unnecessary expenses due to oversizing in components and services. Although timber construction is favored for its cost benefits over solid construction, it somewhat falls short in fire and noise protection. One strategy to address this issue is to not compare timber directly to solid / mineralic construction, at least in terms of sound insulation, and only comply with the minimum requirements (Vallentin 2024). Schreiber notes that despite timber being slightly more expensive in production, timber construction have great benefits in terms of increased living space which adds to cost-efficiency. (Schreiber 2024: 106 and 110). Also, some projects such as Prinz-Eugen-Park, demonstrates good cost-efficiency in timber construction, where total construction costs (BK 300 and 400) sum up to just approx. 2500€/m^2 (ArchitekturWerkstatt Vallentin 2020).

Another important topic mentioned is modular and serial construction. In the P18 project, modular and serial timber frame construction has proven effective, as "82.5% of materials are reused, reaching nearly 100% when recycling is included" (Mannschreck 2024: 118). Modular building processes reduce material mass and hence help to reduce costs on building structure

(Schreiber 2024: 120). Also, modular building processes and high completion levels of up to 95% in the case of Stuttgart's P18 help cutting on-site work and costs, which helps to limit construction costs in the case of P18 to approx. 2000€/m^2 (BK 300 and 400 in 2021) (Mannschreck 2024: 90).

Main focus area: Energy

According to Vallentin, [energy-efficient] buildings can be anything form extremely cost-efficient to extremely expensive. In short, compactness and controlled ventilation are decisive for a reduction in energy parameters. With regard to costs and energy technology, most interviewees emphasized to compromise between cost-efficiency and energy targets. For instance, Schreiber is quoted to say that to construct buildings without mechanical ventilation systems can lead to relatively high energy standards up to EH 40 while being very cost-efficient (Schreiber 2024: 64, Mannschreck 2024: 51). Reducing energy standards from EH 40 to 55 gives more room to other planning principles such as generating more living space by thinner wall constructions (of at least four centimeters) (Schreiber 2024: 72, 92). Likewise, Rottmann is quoted to say that constructing to high levels of energy efficiency such as to the EH 40 standard is uneconomical and excessive. Moving away from this would reduce costs (Rottmann 2024: 102). Vallentin considers current ventilation systems to be oversized and therefore very expensive.

With regard to energy systems, the project “Ellener Hof” for example is connected to the municipal district heating network and partly equipped with photovoltaic panels (Rottmann 2025: 84). “Kokoni One” aims to function as a climate-neutral district and has drawn up a concept for the entire district with the help of an energy contracting provider, which also handles the financing and operation of the local heating network (Schreiber 2024: 62). This district networking is a great advantage for distributing surplus energy (Schreiber 2024: 62). P18 is not connected to the municipal system, as it does not need to import energy due to surplus PVT collectors (Mannschreck 2024: 47). Also, all the maintenance costs are covered (58).

4. Conclusion

A particularly important finding was the identification of win-win situations that combine sustainable and cost-effective construction.

Reducing the number of parking lots and streets to a minimum can significantly reduce construction costs and also help to reduce motorized individual transport and GWP. Avoiding underground garages has additional positive effects on the ecosystem (Schreiber, Rottmann, Vallentin).

There are more win-win situations in the field of building materials and construction. Eliminating the basement in residential construction, especially in combination with timber construction, is cost-effective and sustainable (Schreiber, Vallentin). Timber walls can also lead to thinner wall construction, which results in a surplus of living space and therefore economic benefits (Schreiber). If material is reduced and saved in building construction in order to build as light as possible, concrete can be saved for underground and basement construction (Mannschreck).

With regard to infrastructure, the project “Ellener Hof” demonstrates cost savings by having all rainwater infiltrate onsite (Theiling 2025: 34). “The areas that have to be provided with these basins are areas that somehow add to street space, but they have a quality because they are green and climate-improving” (Theiling 2025: 38).

However, there are sustainable planning measures that lead to higher building costs. For example, a ramp for bicycles is expensive (Mannschreck), the provision of sharing services can also result in higher costs, but can be financed with subsidies, e.g. the Ellener Hof bicycle DIY-workshop (Theiling). This also includes mobility-hubs, which must be planned on a site-specific basis. Central logistics delivery, such as the goods distribution station in the Ellener Hof, can be established with specific contractors. Modular construction with wood is worthwhile from 10 to 20 modules (Mannschreck 2024: 102). The interview data and cost data need to be further analyzed to complete the picture and identify planning strategies in more detail.

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Design management: Improving the environmental performance of industrial buildings with the implementation of Building Information Modeling

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Abstract. Several studies highlight the potential of implementing Building Information Modeling (BIM) to transform data and information sharing into a more dynamic and effective process. In the context of sustainable design, BIM tools can support integrated and collaborative work, offering significant potential to identify and implement sustainable practices. In recent years, the design team of a major Brazilian public company has adopted BIM in its design processes for industrial buildings. Therefore, the purpose of this article is to present the experience of implementing BIM in the development of architecture design for industrial buildings, carried out by the design team. One of the main objectives was to use BIM tools to improve the environmental performance results of the designed buildings. The implementation process, led by the company design team, is in its final stages and includes diagnostic, planning, and execution phases. This paper concludes by outlining the main impacts and transformations in the design process observed so far, along with current results and expectations for future phases. Anticipated outcomes include improved collaboration across disciplines, automated processes for enhanced environmental performance, and reduced design development time. **Keywords:** BIM, Design management, Industrial buildings, Complex projects, environmental performance.

1. Introduction

Design process management has proven to be effective in mitigating problems commonly associated with building production. One of its main objectives is to improve the overall quality of the design process [1,2,3]. A hierarchical structure implies that parts of the process are more easily controlled than the whole, while the sequential approach fails to consider the design process holistically and tends to treat all activities equally. As a result, optimal options for subsequent stages and their interactions may be overlooked [4].

Shifting towards a collaborative and integrated approach significantly changes the design process, affecting both methodology and outcomes. Within this context, BIM (Building Information Modeling) emerges as a disruptive technological innovation that enables collaborative and integrated information management. This transition transforms the traditional linear process into a collaborative, integrated and simultaneous one.

However, there are few studies exploring the specific challenges encountered by offices specializing in industrial building design, particularly within public institutions and companies, during BIM implementation. In Brazil, the adoption of BIM remains relatively slow and is still undergoing a process of acceptance among design offices.

In 2017, the Strategic BIM Implementation Committee was stablished to formulate policies that encourage BIM adoption across public and private sectors. The committee's mandate includes setting parameters for public procurement, developing technical standards, and offering training programs to achieve widespread BIM adoption by 2028 [5]. The initiative is supported by the National Strategy for the Dissemination of BIM, which defines implementation strategies and outlines the responsibilities of the management committee [6].

This article presents a case study of BIM implementation within the design management processes of a Brazilian public oil, natural gas, and energy company known for managing highly complex projects. The main goal of this initiative is to create a more dynamic and effective design process, with particular emphasis on improving the environmental performance of the buildings designed.

2. Design management, BIM and Sustainability

2.1 Design management

Design management refers to the structured process of organizing all phases of development, coordination and execution, with the goal of constructing a building. The effectiveness of this process relies heavily on management procedures that facilitate the planning and execution of design activities. As such, a multidisciplinary approach, active interaction, transparency, and comprehensive control of the entire process are essential components [7].

Among the possibilities offered by the information technology aiming to facilitate this process, BIM is highlighted. However, it is important to note that traditional design development procedures are not well-aligned with the collaborative nature of BIM workflows. Model validation, BIM execution plan, types of deliverables, new procedures, disciplinary integration, and information management all require structural and organizational shifts [4, 8].

2.2 Building Information Modeling

Building Information Modeling is the digital representation of the physical and functional characteristics of a building. It facilitates the sharing of data and serves as a reliable foundation for decision-making throughout the building's life cycle.

BIM enhances the efficiency and dynamism of data and information exchange, improves communication among design team members, and ensures the integration of environmental performance requirements [9]. By centralizing design data, BIM helps identify incompatibilities and evaluate the impact of design decisions more effectively [7].

Eastman [9] points out that BIM enables the creation of accurate virtual models to support decision-making across all design phases, allowing comprehensive analysis and management of environmental performance throughout the life cycle of a building.

BIM's implementation fosters integration among different design disciplines and enhances the visualization of data and design information, leading to more efficient and higher-quality construction outcomes. As a result, there is better teamwork collaboration, improved workflow transparency, and interoperability.

In this scenario, BIM is not only appropriate but recommended for use in complex design projects. For the company in this study, it offers improved interdisciplinary integration, better communication and information management, and enhanced environmental performance.

2.3 Sustainability and buildings

Environmental concerns related to human activity are central to the sustainability debate, especially as urban development continues to impact future generations.

In the construction sector, sustainability entails incorporating environmental, social, and economic principles throughout a building's life cycle. Architecture with high environmental performance aims to minimize environmental impact, reduce natural resource consumption and pollution, promote occupant health, and encourage energy efficiency [4, 10].

Bloomberg *et al.* [11] emphasize how BIM's collaborative and integrated nature supports a sustainable design approach. BIM enables effective communication, centralized data management, and inclusion of sustainability criteria in the design process.

Efficient information and communication management are crucial for including environmental performance parameters [4]. Therefore, BIM's collaborative and integrated workflows significantly contribute to achieving higher environmental performance in building design.

2.4 BIM and Environmental Performance of Buildings

Using BIM in design development fosters an integrated view of the process, contributing to key objectives outlined in Agenda 21 for the Brazilian construction sector. These goals include reducing material waste, improving energy efficiency, conserving water, enhancing indoor air quality, and optimizing construction methods [12].

In Brazil, standards such as NBR 15220 (Thermal Performance of Buildings) [13] and NBR 15575 (Performance Standard for Residential Buildings) [14], along with international environmental certifications like Leadership in Energy and Environmental Design (LEED) and *Haute Qualité Environnementale* (HQE), which deal with the environmental performance of buildings and have specific items to measure energy performance.

BIM facilitates environmental performance improvements through interdisciplinary collaboration and communication, streamlined data visualization, document coordination, material information manufacturer to quantify costs, environmental analyses, and simulations. These features support more integrated design solutions aligned with sustainability requirements [4].

Eastman [9] asserts that BIM offers reliable data for simulations and environmental performance analyses. Vite [15] adds that elements such as orientation, shape, lighting, energy profiles, and materials can be assessed. Succar [16] highlights the advantages of multidisciplinary collaboration enabled by BIM for optimizing sustainable design solutions.

BIM's combination of geometric and physical modeling allows energy optimization and supports the development of energy-efficient, sustainable buildings. Throughout a building's life cycle, BIM can accelerate evaluations of retrofit opportunities prompted by technological advances.

Thermal-energy simulations further enable analysis of heating, ventilation, air conditioning, solar heat gain, occupancy, and passive strategies such as shading, aiding in the design and sizing of Heat, Ventilation and Air Conditioning (HVAC) systems. These simulations combine variables to estimate energy demand and enhance thermal performance.

3. Digital Transformation with Bim's Implementation in the Company's Design Sector

The subject of this case study is a Brazilian public corporation operating in the oil, natural gas, and energy sectors. The company is known for managing highly complex projects involving multiple disciplines.

In general, the company develops Conceptual and Basic designs internally and outsources the Executive design, construction and installation services. Its in-house design team is responsible for preparing Basic designs and overseeing Executive designs for industrial buildings such as: control rooms, laboratories, substations, loading/unloading stations and operational support buildings such as administrative offices, canteens, health units, entrance facilities, guardhouses, and locker rooms.

3.1. BIM Implementation

In recent years, the company has pursued digital transformation, including the automation of design development activities. This transformation has paved the way for the adoption of digital solutions such as BIM.

The architecture team initiated the BIM implementation in 2019, based on literature review and relevant training. So, a phased implementation plan was developed, including guidelines for BIM-based design development, early involvement of disciplines, revised contracting strategies, staff qualification, and the inclusion of new organizational roles.

The objectives defined for BIM included: automatic quantity take-off for cost estimation across all disciplines and, specifically for Architecture and HVAC, the inclusion of environmental performance criteria for design analysis.

In 2024, a consultancy was hired to continue the process. The work included reviewing the information and data defined and adjusting the strategic roadmap prepared by the Architecture team. As a result, the consultancy established a work plan consisting of the following BIM implementation stages: (1) Strategic diagnosis, (2) BIM Implementation Plan, (3) Training, (4) Pilot Project, and (5) Assisted Operation Support.

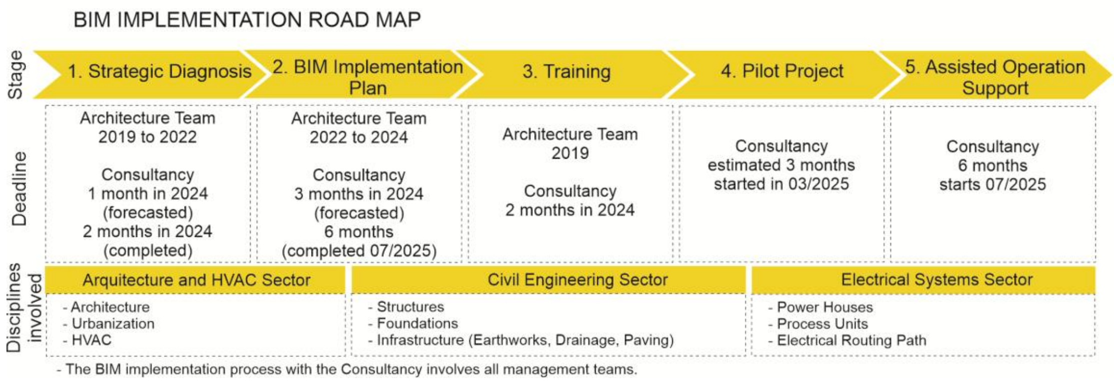

Figure 1. BIM Implementation Phases – Source: Authors

The diagnosis (Phase 1) for the implementation of BIM began in 2019 by mapping the organizational structure, analyzing current practices and technical infrastructure, and identifying relevant BIM applications for industrial building design. The planning phase followed, producing a BIM strategic plan with defined timelines and short-, medium-, and long-term goal.

Subsequently, a BIM implementation plan (Phase 2) was developed. This included training schedules, information organization, new procedures, data sharing protocols, a responsibility matrix, information flow definitions, and a BIM Execution Plan (BEP).

The BEP is a document that defines the general rules and guidelines for design development in BIM [9]. It outlines a sequence of actions: key documents, revised and new procedures, training types, information flows to foster collaboration, responsibilities, hardware adaptation and development of template standards and library.

Concurrently, Phase 2 included the Training (Phase 3) of the design team. Now, BIM implementation plan is in its final stages with the start of the Pilot Project (Phase 4). The Pilot Project phase involves defining the project to be monitored by the consultancy. It includes preparing the design team, monitoring proposed and executed workflows for developing the pilot project, and identifying gaps and proposing workflow adjustments. The importance of this stage lies in applying what has been learned and verifying necessary adjustments. During this stage, the Architecture, HVAC, Civil, and Electrical disciplines are working in an integrated and collaborative manner.

The Assisted Operation Support (Phase 5) involves monitoring and executing the implemented processes, measuring BIM process performance indicators, and presenting reports. Enabling an evaluation e validation of the process, identifying lessons learnt and opportunities for process improvement, followed by a review of procedures and consolidation of the BIM process.

3.2. Building Energy Modeling and Energy Simulations

Energy simulations integrated into the design process help analyze a building's environmental performance at various stages of its life cycle. Building Energy Modeling (BEM) can be used as a design tool—to test alternatives and meet energy targets—or as a validation tool to support environmental certifications [10].

In this case study, the adopted strategy for evaluating the environmental performance of industrial buildings included developing technical specifications. These outlined minimum requirements for calculating thermal loads for air conditioning, mechanical ventilation, and pressurization systems, enabling thermal-energy simulations based on the BIM process.

The main goal of these simulations is to assess the impact of energy modeling on overall building performance and to optimize energy system efficiency during the design phase.

The ASHRAE 209 standard [17], which defines minimum requirements for energy modeling, was used as a reference. This standard outline seven design modeling cycles, each with specific objectives, contributing to an integrative approach between architects and engineers.

3.3. Workflow for Analyzing Environmental Performance

The method includes simulations, calculations, predictions, optimizations aimed at improving thermal performance and assisting in the sizing of HVAC systems.

The design's modeling workflow consists of the following cycles: 1) Optimizing thermal performance; 2) Creating the energy model, 3) Configuring energy parameters, 4) Generating the analytical model, 5) Reviewing the model, 6) Producing results and 7) Performing additional workflow adjustments.

Model creation involves integrating architectural data and analyzing shape, orientation, and surroundings—factors that affect environmental performance. The energy configuration stage includes defining location, analysis mode, reference level, design phase, spatial resolution, and zone divisions.

The analytical model is then prepared for verification and validation prior to simulation. This stage evaluates variables such as solar radiation on glazing, heat transfer through the building envelope, internal loads (lighting, equipment, people), air renewal, and psychrometric processes (e.g., cooling, heating, and outdoor air loads).

Additional workflow refinements may be necessary to improve the accuracy of the energy analysis model.

4. Results Obtained and Expected

The analysis presented here reflects the experience of a design team working on complex industrial buildings. The lessons learned may offer guidance for other organizations implementing BIM.

The company's projects are complex and involve multiple disciplines, including those operating in industrial areas. To enable the workflow, it was necessary to understand the interactions among disciplines, redesign the workflow, the responsibility matrix, and the design schedule.

It is important to highlight that BIM implementation was not a linear process; several stages overlapped, such as the execution of the BIM Implementation Plan, Training, and the Pilot Project.

Several phases of the BIM implementation process have been completed, allowing for an assessment of both current outcomes and anticipated results. Key achievements include:

a) BIM Execution Plan (BEP): Enhanced communication and standardized design processes across disciplines (documentation, organizational chart, contracting and responsibilities). A BEP template was created and must be completed before each project starts.
b) BIM Workflow: The specificities of the BIM process and the complexity of the company's projects resulted in a new responsibility matrix and design schedule adjustments.
c) Integration of the design team with the consultancy: This was important for understanding the specifics of industrial building design and implementing a workflow suitable for such projects.
d) Design Team: The need for new roles was identified—BIM Leader, BIM Analyst, and BIM Integrator—and existing specialties responsibilities were revised.
e) Targeted Training: Improved the team's understanding of BIM. A learning curve was expected and accounted for.
f) Deliverables: Automated quantity take-offs reduced lead times and improved process transparency.
g) Common Data Environment (CDE): Improved information management through centralized documentation and transparent, integrated, simultaneous and collaborative workflows.
h) Pilot Project: It is under development and has taken more time than expected due to workflow adjustments and additional training requirements.
i) Creation of the BIM Core Group: A sector responsible for overseeing and executing the implemented processes, measuring performance indicators, managing information and the model, organizing the BIM workflow, and integrating with design coordinators.
j) Environmental performance: With BIM use, a better understanding of thermal comfort was achieved through analysis of building envelope characteristics, aiming to improve energy performance. It was possible to conduct an analytical evaluation using parameters such as location, building envelope, thermal properties of materials, lighting and

equipment rates, and the type of HVAC system to be used. From all these parameters, the building's energy model could be generated.

k) Digital Twin: The digital model created during the design phase could evolve into a Digital Twin using real-time data to support life cycle assessments.

Overall, BIM implementation has led to clearer interdisciplinary interfaces, fewer inconsistencies, reduction in time taken to prepare and review documents, improved energy performance analysis, and greater collaboration and integration.

During this period, the team encountered a series of difficulties such as: the best way to carry out the optimization cycles, defining the procedures and criteria for organizing information during the effective use of BIM, among others. It's interesting to point out the difficulty in integrating modeling software, even nowadays there are still gaps in the integration between the main market software, such as georeferencing.

With continued consolidation, BIM is expected to enhance the efficiency and transparency of the industrial building design process.

5. Recommendations

BIM implementation introduces both technological and organizational change in the design process. Therefore, it is essential to go beyond viewing BIM as merely a tool and to fully embrace it as a new process paradigm. And prevent that the design teams stand limited to implement only a technology and not a process.

Key recommendations based on the case study include:

a) Design Team Engagement and Pilot Project: Training the design team to understand BIM as a process was essential. The pilot project provided an opportunity to consolidate new knowledge.

b) Internal Expertise and Consultancy: Involving a BIM specialist within the team and hiring external consultancy proved valuable in navigating challenges.

c) Strategic Consultancy: Consultancy support helped address bottlenecks and optimize processes.

d) Targeted Training: Customized training focused on the particularities of industrial buildings prepared the team more effectively.

e) Institutional Support: Initially, implementation relied on internal efforts (Architecture design team), resulting in a long process. Dedicated consultancy accelerated the process by customizing tools and identifying additional training needs.

f) Information Management: Creating a structured common data environment greatly improved information flow and communication.

The most significant challenge was organizational and cultural disruptive changes. Shift from a sequential and linear to a collaborative and integrated design approach, which required cultural transformation.

6. Conclusions

The experience of implementing BIM in a public-sector company has shown that clearly defining the intended outcomes is essential. Until the institution had identified how it would use BIM, it was not possible to set concrete goals or understand the process changes required.

BIM implementation led to strategic and operational improvements in design quality, environmental performance, and design process transparency. The process required not only technical adaptation but also significant shifts in team mindset, structure, and workflows.

However, a segmented view of the design process is still observed, focusing mainly on the development phase with limited integration across other stages of the building life cycle. Integration with other company departments—especially those responsible for construction execution and facility management—remains the main challenge to continuing the BIM process with a life cycle approach and improved environmental performance.

Ultimately, the success of BIM implementation depended on institutional commitment, interdisciplinary collaboration, and the creation of an integrated system for managing design information and processes.

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Era of Digitalization and Sustainability - Multi-trade integrated Mechanical, Electrical & Plumbing Projects with Building Information Modelling - Asset Management and openBIM towards New Quality Productive Forces

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Abstract. The integration of Multi-trade Integrated Mechanical, Electrical, and Plumbing (MiMEP) with Building Information Modelling - Asset Management (BIM-AM) and openBIM standards offers transformative benefits for the operation and maintenance (O&M) industry. By adopting BIM, the MiMEP process is enhanced through precise planning, efficient design, and accurate visualization of complex systems, leading to significant reductions in project timelines and costs. The integration also facilitates seamless collaboration among various stakeholders, ensuring high-quality output, minimizing construction wastage and enhancing site safety. openBIM, with its emphasis on interoperability and standardization, further enhances this integration by enabling the exchange of consistent and reliable information in a vendor-neutral environment throughout the entire asset lifecycle. This open standards approach promotes transparency, flexibility, and scalability in MiMEP Repair, Maintenance, Alteration, and Addition (RMAA) projects, allowing for better decision-making and improved project outcomes. This paper highlights how MiMEP, openBIM, and BIM-AM can drive sustainable O&M through three RMAA projects in different systems. These projects demonstrate the practical application of these methodologies to address challenges in maintenance, repair, and retrofitting works, while improving coordination, reducing waste, and optimizing long-term performance.

1. Introduction

The construction and building services industries are continuously evolving to address the growing demand for sustainable, efficient, and high-quality solutions throughout the lifecycle of built assets. In particular, the replacement of mechanical, electrical, and plumbing (MEP) systems in existing facilities presents unique challenges due to the complexity of retrofitting, space constraints, and the need to maintain uninterrupted operations. The integration of MiMEP, BIM-AM practices, and openBIM standards has emerged as a transformative strategy. This approach represents a paradigm shift in how Electrical and Mechanical (E&M) replacement projects are planned, executed, and managed.

MiMEP technology introduces modular prefabrication and off-site integration, significantly reducing on-site labour requirements, safety risks, and project durations. When combined with BIM-AM, a framework that extends the utility of BIM into operations and maintenance, and openBIM standards that ensure interoperability and data longevity, this integrated methodology enables seamless collaboration and lifecycle management. Together, these tools empower stakeholders to enhance the productivity of O&M activities. By leveraging digital technologies and modular construction, this integrated approach contributes to the development of sustainable, high-performance building environments.

2. Problem Statement

The construction industry faces challenges in ensuring the sustainable O&M of MEP systems, particularly in RMAA projects.

2.1 Labour Shortages and Aging Workforce
Around 48,500 – 55,000 positions (i.e. skilled/semi-skilled workers, technicians, professionals) in the construction industry will fall short in year 2027, which contribute up to 25 % of the forecast demand. [1] Meanwhile, the proportion of the local population at the age of 65 and over would increase from 23% in 2023 to 28%, and median age would rise from 48.3 in 2023 to 50.2 in 2028, making it one of the highest among developed economies globally. [2] The ageing workforce would constrain labour supply and exacerbate the manpower shortage in the O&M industry, particularly in RMAA projects requiring skilled labour for complex retrofits and repairs.

2.2 Safety Concerns at Construction Sites
The number of fatal industrial accidents and the accident rate of the construction industry are the highest among all local industries. In year 2023, the construction industry had 20 fatal industrial accidents, which occupied 83.3% amoung all cases and industries. [3]RMAA projects, involving aging infrastructure with limited spaces, may elevate concern on safety and the impact on worker well-being and project timelines.

2.3 Slow Technology Adoption
Despite advances in BIM and related tools, the construction industry has been relatively slow to embrace digital transformation, especically in the small and medium enterprises and private sectors. [4] Limited adoption of openBIM and BIM-AM restricts collaboration, data sharing, and the ability to optimize project planning, particularly in the intricate environments of RMAA projects.

This paper examines how MiMEP systems, combined with BIM-AM and openBIM, can overcome these issues and enable sustainable O&M for MEP systems through practical insights from three RMAA projects.

3. Project Application

The integration of multiple technology in RMAA works were tested in different building services systems, including fire service, mechanical ventilation and air conditioning (MVAC) and renewable energy.

3.1 Replacement of Fire Service Pumps at Fire Services Department Rescue Training Centre

The replacement of fire service pumps presented unique challenges due to the high usage rate of the venue and the need to maintain uninterrupted operations. During the replacement works, the temporary suspension of the fire service system created a heightened fire risk, necessitating careful planning and swift execution. To address these challenges, MiMEP was adopted to modularize the pump set with its accessories and prefabricated off site. After quality checking, the pump modules were transported and installed on site. This MiMEP work flow significantly shortened 66% of the on-site installation time, completed in 2 days and minimized the disruption to the facility. In design stage, three-dimensional (3D) point cloud technology was used to scan the plant room and create BIM model. The model was utilized to evaluate various design options and delivery routes, enabling the selection of the optimal solution.

The construction of the BIM model, as well as the subsequent input of asset data, adhered to the latest BIM-AM 3.0 guideline issued by the Electrical and Mechanical Services Department (EMSD). This allowed asset data to be digitally stored in the BIM model with standard and relatable ontology between equipment. Furthermore, with the use of openBIM, the BIM model will be seamlessly migrated to the Asset Information Management Platform (AIMP) and Common Data Environment (CDE) at EMSD, ensuring efficient long-term management of the fire service system and enhancing the facility's operational resilience.

3.2 Replacement of Air Handling Unit (AHU) at EMSD Headquarters Building

Serving the busy headquarters main entrance lobby, it was essential that the operation of the headquarters remained uninterrupted during working hour. The adoption of MiMEP significantly reduced the on-site construction time for over 60%, inclduing the time for tesing and commissioning work. The MiMEP AHU was designed preassembled with all necessary accessories, including the chilled water modulating valve, control panel, air-side sensors, and CCMS interfacing port, to streamline on-site installation and minimize disruption on operation. A BIM model of the plant room was prior developed using Point Cloud scanning, which was leveraged during the design and construction stages to evaluate design options and optimize the delivery route.

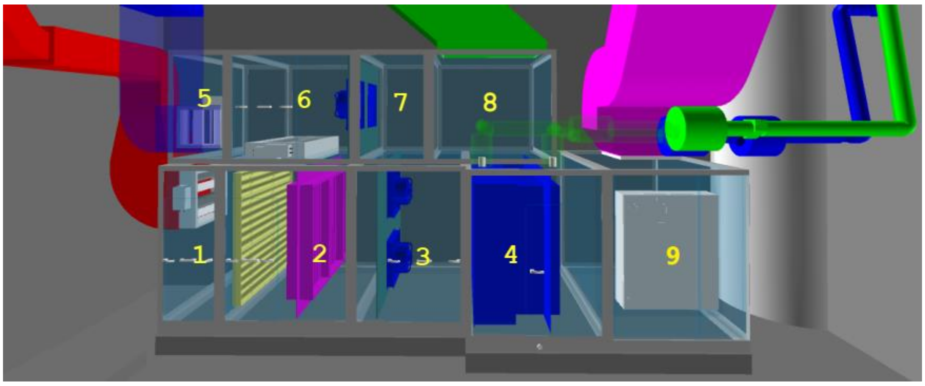

Figure 1. AHU modelized into 9 section for manufacturing and delivery into plant room.

The BIM model and subsequent asset data input were in compliance with the BIM-AM 3.0 guideline issued by EMSD. Following completion, the BIM model will be migrated to the AIMP and CED at EMSD using openBIM standards. This model will be utilized for daily operation and maintenance, enhancing the long-term efficiency and reliability of the air distribution system. By integrating advanced digital tools and methodologies, the project successfully overcame operational constraints while ensuring sustainable asset management.

3.3 Flexible PV cum MiMEP Installation at Lion Rock Park Management Office

The installation of flexible PV systems with MiMEP required only 3 days (up to 90% time saving) for on-site construction compared to the 4 weeks typical of other flexible PV installations without advanced methodologies, or the conventional 2-3 months for standard PV systems. [5] This expedited timeline is achieved through a streamlined workflow in which most construction activities, including the pre-assembly of flexible PV panels and comprehensive electrical components (e.g. inverters, meters, and protective devices) off-site. The on-site installation itself is simplified to basic tasks like securing bolts and connecting wires, which minimizes material waste and resource usage.

This efficiency is further enhanced by the integration of BIM and MiMEP, which collectively transform the construction process. BIM creates a detailed digital twin of the project, enabling the identification and resolution of potential design and construction conflicts before physical work begins. Meanwhile, MiMEP guide the prefabrication of components in a controlled factory environment, ensuring that elements are manufactured to precise specifications and delivered ready for installation.

The MiMEP speeds up the PV installation, allowing rapid deploying PV systems across various existing government venues, including those in remote areas with limited accessibility. This created the needs of Remote PV Management System implementation. The system architecture integrates a local renewable energy monitoring system at each site, connected via the Government Wireless IoT Network (GWIN). This setup collects real-time data, enabling comprehensive analysis of energy generation. The inclusion of Artificial Intelligence models enhances monitoring by providing predictive forecasting, system health assessments, and proactive fault detection and diagnosis. This approach improves maintenance efficiency, optimizes resource allocation, and ensures the reliability of renewable energy systems while advancing sustainable energy management.

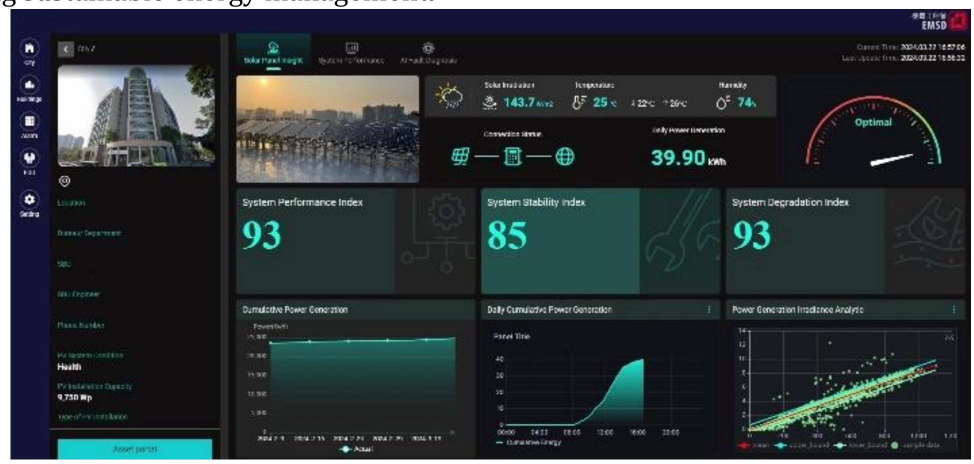

Figure 2. AI-enabled Remote PV Monitoring System [5]

4. Result Discussion

The above three pilot projects achieved great success, by significantly reduced the manpower requirement and on-site construction time.

4.1 Labour Shortages

The new approach in RMAA streamlined construction and operational workflows. Conventional RMAA projects often require multiple trades to work simultaneously on-site. MiMEP reduces the reliance on on-site labour through the off-site prefabrication and integrated multiple trades into one module. These modules are manufactured in controlled factory environments, minimizing on-site assembly tasks to simple installation processes. For example, the use of MiMEP not only has reduced demand of on-site labour manpower in above pilot projects, but also shortens project timelines and reduces interruption to normal operation. Additionally, MiMEP's modularity enhances productivity by improving build quality and reducing rework, further mitigating the effects of labour shortages.

Supporting MiMEP, BIM-AM and openBIM enhance labour efficiency by improving planning, coordination, and data management. BIM supports MiMEP by providing detailed design data that guides the prefabrication of modules. This ensures accuracy and reduces errors during on-site installation, further improving labour efficiency. BIM-AM provides a standardised digital representation of assets and their operational data, enabling maintenance teams to access equipment information quickly without requiring extensive on-site investigation or venue attendant. Meanwhile, openBIM ensures interoperability between software platforms, allowing project stakeholders to collaborate effectively without the need for additional manpower to manage data compatibility issues. Together, these technologies optimize workflows, reduce labour-intensive processes, and enable better resource management, making RMAA projects more sustainable and resilient in the face of workforce constraints.

4.2 Enhancing Planning, Coordination, and Safety

Construction sites in RMAA projects may pose safety risks to worker due to limited plant room spaces and work-at-height activity. MiMEP reduces time spent on-site by delivering preassembled systems, minimizing workers' exposure to relatively uncertain conditions. For instance, during the replacement of AHU at the EMSD Headquarters, the use of MiMEP significantly reduced the time and number of workers required in the small plant room. Also, traditional on-site assembly often involves multiple trades working simultaneously in same areas, increasing the risk of careless accidents. MiMEP eliminates this issue by delivering fully integrated modules to the site, reducing congestion and improving safety on site, allowing for better allocation of skilled labour across multiple-disciplines involved projects. MiMEP also reduces the need for manual handling of heavy equipment and tools on-site, as integrated systems are delivered by mobile crane and ready for installation. This significantly lowers the risk of injuries during construction.

BIM enables the identification of potential hazards through digital simulations and clash detection, allowing safety risks to be addressed before construction begins. BIM simulations can help determine safe delivery routes for MiMEP modules and identify confined spaces that require special precautions. For example, BIM helped to modularize the double-deck AHU at EMSD Headquarters into 9 assembly-ready sections, which reduced the needs and risk for labour to work-at-height on site. The construction of BIM models and asset data input followed the BIM-AM 3.0 guideline. This ensured that the models were configured to include essential safety and operational data, which will support safer long-term asset management.

5. Technology Adoption

The project successful can be attributed to the adoption of BIM-AM and the openBIM.

5.1 BIM-AM Standards and Guidelines 3.0

In the BIM-AM Standards and Guidelines by the EMSD provides a structured framework for integrating BIM into asset management. [6] Its development stems from the need to standardize the lifecycle information requirements for E&M systems in Hong Kong, ensuring seamless transitions from design and construction to O&M. Initially introduced in 2017 and revised it the latest version 3.0 in September 2022, aligns with the BIM Harmonisation Guidelines by the Development Bureau (DEVB) and incorporates international standards such as ISO 19650 and CIC BIM Standards. This ensures that the guidelines remain relevant for future projects and are interoperable with global best practices.

The BIM-AM Standards and Guidelines introduces a define clear procedures and requirements for modeling, coding, and managing data related to E&M systems. It establishes conventions for BIM object creation, model setup, and asset coding, ensuring consistency and traceability throughout the lifecycle of a project. By specifying the Level of Information Need (LOIN), the standards balance geometric detail (LOD-G) and data richness (LOD-I) to meet operational needs effectively. Additionally, the guidelines integrate COBieLite data exchange formats and EMSD's AIMP to facilitate the handover of as-built models and associated asset information for long-term O&M use. These standards also emphasize interoperability by supporting openBIM principles and enabling the integration of BIM-AM systems with other platforms like IoT devices, RFID tags, and local Central Control and Monitoring Systems (CCMS).

Figure 3. Example of intelligent maintenance workflow using BIM-AM.

In the E&M asset life cycle management, the AIMP plays a pivotal role in enabling efficient asset management within the EMSD BIM-AM framework. It serves as a centralized, web-based system designed to manage and validate asset information, ensuring that all data generated during different stages is seamlessly transitioned into operational and maintenance workflows. AIMP also acts as a "third-party checker," verifying the completeness and accuracy of asset data by identifying missing information or incorrect formats.

Another AIMP's key functions is to facilitate the creation and maintenance of asset relationships, such as system topology, which defines the interconnections between E&M systems and their components. By using tools like COBieLite files and pre-defined templates, AIMP streamlines the input, organization, and mapping of asset data. It also enables contractors to upload documents and as-built BIM models into a structured folder system, automatically mapping them to corresponding systems and equipment. This structured approach ensures that asset information is organized, accessible, and linked to relevant documentation (e.g., operation manuals, testing records, and certificates).

5.2 openBIM standard adoption

The adoption of openBIM in the handover of RMAA projects and the asset management life cycle represents a transformative approach to addressing traditional challenges during project handovers. With integrated buildingSMART International (bSI) standards, including BIM Collaboration Format (BCF), buildingSMART Data Dictionary (bSDD), Information Delivery Specification (IDS), and Industry Foundation Classes (IFC), into workflows ensure seamless collaboration and data exchange across stakeholders. By leveraging these standards, BIM projects can transit from vendor-specific solutions to a vendor-neutral, interoperable framework, enabling efficient communication, reducing errors, and establishing a single source of truth for asset information throughout the project lifecycle.

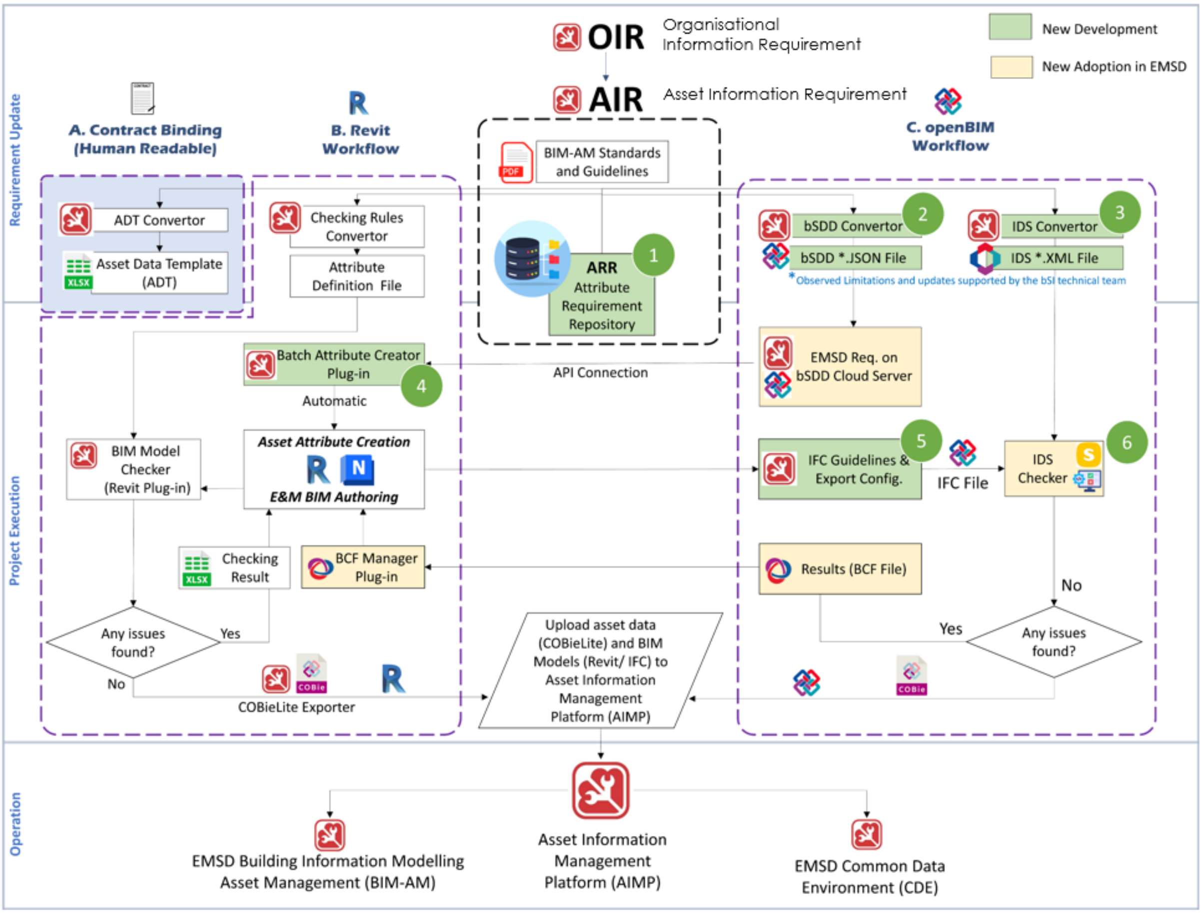

Figure 4. Process map of migration of BIM model into organization AIMP through openBIM.

Before adopting openBIM, new BIM model faced significant challenges related to data quality, inefficiencies in validation, and limited interoperability. Critical issues included missing or incorrect data (e.g., objects, attributes, and equipment types), data formatting errors, and misaligned or shifted objects during file format conversions, especially from native BIM formats to IFC. These errors often resulted in unreliable BIM models, which hindered the integration of asset data into downstream systems and created complications for O&M. Additionally, errors were frequently discovered after handover, leading to costly rework and delays. The reliance on vendor-specific BIM solutions further exacerbated these issues, as stakeholders needed expensive software to view, validate, and collaborate on different BIM submissions across disciplines.

The adoption of openBIM standards and workflows addressed these issues, enabling more efficient handovers and enhanced asset management. Key applications included the creation of an Attribute Requirement Repository (ARR), which serves as a centralized database for managing E&M-specific asset information requirements. These requirements were converted into bSDD-compatible formats and IDS schemas using in-house Python scripts, automating the validation process and saving over 90% of time compared to manual methods. Software plugins will be developed to automate the creation of attributes for asset types, ensuring consistent and accurate data. Additionally, data loss problem during IFC file conversions was addressed by developing tailored guides and tools to maintain data integrity, further lowering the entry barrier for using openBIM in project handovers.

6. Conclusion and Way Forward

The integration of MiMEP, BIM-AM, and openBIM standards represents a transformative approach to addressing challenges in the building RMAA projects as well as the O&M industry. These technologies address labour shortages, improve safety, and accelerate digital adoption, enabling more sustainable and efficient construction workflows. The pilot projects demonstrated the effectiveness, achieving significant reductions in on-site construction time, manpower requirements, and operational disruptions. By leveraging BIM-AM and openBIM standards, EMSD has set a system for seamless data exchange, lifecycle asset management, and interoperability across platforms, contributing to the advancement of sustainable and efficient asset management. With the possibility of further integration with other innovative technology, such as Artificial Intelligence, the O&M industry will be sustainable with the new quality productive forces and contribute to the building of smart city in Hong Kong.

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Net zero-carbon buildings and district

From fossil fuel Dependency to renewable Sufficiency: Predictive Energy Modelling for District Decarbonization Scenarios

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Abstract. This study demonstrates the use of the City Energy Analyst (CEA) tool as a powerful method for modelling decarbonization scenarios in urban districts, particularly those with historic and varied building types. By combining accurate building geometry modelling from CEA with a robust, adaptable building typology from literature, this approach enables detailed analysis of energy performance and decarbonization potential across diverse urban areas. Key analyses focus on transitioning from gas to district heating, implementing heat pumps and thermal renovation based on specific building geometries, orientations and compactness.

1. Introduction

Urban Building Energy Models (UBEMs) can act as Decision Support Systems (DSS) by providing assessments on the effectiveness of retrofitting measures for the stakeholders involved. However, practitioners are often faced with the challenge of limited information on the necessary parameters for UBEM simulations, subsequently the required early integration of energy planning in the district development is lacking [9,23]: Even if sufficient data is available and modelling possible, using district simulation models can be too resource-intensive to deploy early, as the planning will inevitably change in the process, rendering detailed simulation results invalid [26]. Furthermore, assuming building data based on shared characteristics is error-prone, has potentially low accuracy, which can sometimes be increased by clustering-based approaches [11,14,17,24].

Modeling cities as 3D "digital twins" promises to provide highly detailed information for planning processes at the building level through a model encompassing urban objects linked to various datasets, including population trends, energy usage, maintenance management, sensor and real-time information, EPCs and material building passports [6]. In practice, it is rarely achieved due to complexity and resource intensity [18,22,25] and in particular semantic interoperability [25]. Special formats such as CityGML were put forward to address this, but still suffer from barriers in Tooling and complex data structures, that are further exacerbated by the necessity for application domain extensions for use cases such as energy modelling [1,7,20].

Another issue lies in the lack of dynamic models for climate neutrality assessment of energy flexible districts with suitable timesteps [5], which is necessary to assess its flexible operation. Studies have stated the importance of suitable timesteps in assessing energy flexibility [12]. Most sources agree that stationary calculation of energy balances is insufficient due to its inability to resolve flexible control measures and interplay between district demand and onsite RES. High temporal resolutions on the other hand typically come with long compute times and resulting unwieldy models. The sweet spot for this application seems to be an hourly resolution on the scale of a full operational year [2,10].

City Energy Analyst (CEA) is an open source UBEM employing a bottom-up, physics-based RC model yielding hourly results [4], featuring open source databases on building typologies, which exist for Switzerland, Singapore, and recently Germany [3]. It uses building specific domain configurations as "types" to structure the input data required for irradiation, thermal and electrical energy balancing of heating, cooling, DHW, auxiliary and user electricity, as well as onsite renewable generation and operation properties of heating networks, which are well suited for re-use and re-arrangement of predefined types.

This study aims to **model decarbonization scenarios** for the case study of a dense urban vintage District in Vienna, Austria using the CEA software to investigate its potential as a DSS for municipal stakeholders. According to municipal decarbonization plans for 2040, a complete phase-out of gas heating is envisioned, not only for new buildings but also through comprehensive thermal and energy-efficient retrofitting of the existing building stock. The final energy consumption for heating, cooling, and hot water in buildings is to be reduced per capita by 20% by 2030 and by 30% by 2040, compared to the average value from 2005–2010. The associated CO_2 emissions are to decrease per capita by 55% by 2030 and reach net zero by 2040.

2. Methods and Data

The investigated district and its collected data on 76 existing buildings is shown Figure 1, indicating plausibility, energy supply, building condition and initial construction period as per municipal cadaster. Manual Data inspection based on site visits and satellite and Streetview

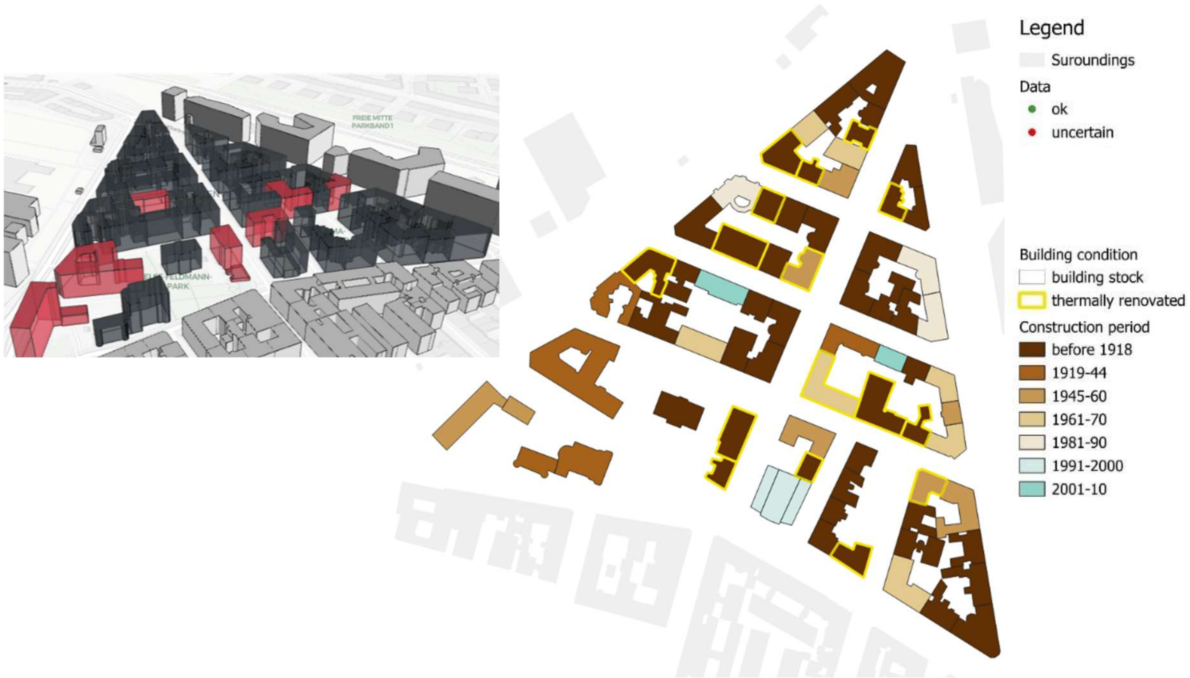

Figure 1. Left: 3D building geometry model in CEA, right: Collected district data for 76 buildings: Initial Construction Period, estimated Building Condition. Uncertainties in the initial dataset are shown as green/red dots

images indicated differences to the dataset such as unregistered window replacements and deviations in building heights, suggesting outdated or erroneous entries in the municipal cadaster, which were adjusted to the best of the authors' abilities. More than half of the 76 buildings in the district originated before 1918. About 30% of the buildings are mixed use with ground floor in non-residential use and the remaining district (69%) is residential. Currently, most of the district is fueled by natural gas, the remaining buildings are supplied by district heating and one lighthouse building renovation uses heat pumps sourced by ground water.

Four investigation scenarios were co-created with municipal stakeholders: **(0)** baseline conditions, **(1, BAU**) a phased, realistic retrofit approach representing business as usual with a 1.8%p.a. renovation rate, **(2, "Off-Gas")** targeting complete HVAC replacement of fossil Gas-Boilers to district heating and third **(3, "WAM")** a scenario representing the limit of feasibility with additional measures achieving nearly-zero-energy level Passive House standard in renovation for most buildings. Scenarios were simulated in CEA, and resulting heat demands validated by comparison with statistical top-down consumption data and secondary simulation results for individual buildings using an alternative single-zone RC-model [15,16]. The resulting energy end use for heating, cooling and DHW was extended with user plug loads from literature and separate hourly PV yield simulations and converted into primary energy and GHG emission equivalents for analysis and comparison with municipal goals.

2.1 Building energy modelling with CEA

Building modelling was carried out using open-source software City Energy Analyst (CEA), which requires definition of component and assembly types to be associated with each building geometry. The types were derived using three classifications consistent with existing structures in Austrian building code and literature: Construction period, building quality/renovation standard, and main energy supply, forming a consistent framework translated into CEA category types enabling compatibility and future scalability. The specifications and CEA type definition files can be found in the supplementary data.

Construction Period defines unchangeable building parameters such as window-to-wall ratios and building physics characteristics such as thermal mass. Based on the district data, seven types of Construction Periods are defined specifying baseline properties such as U-values, air

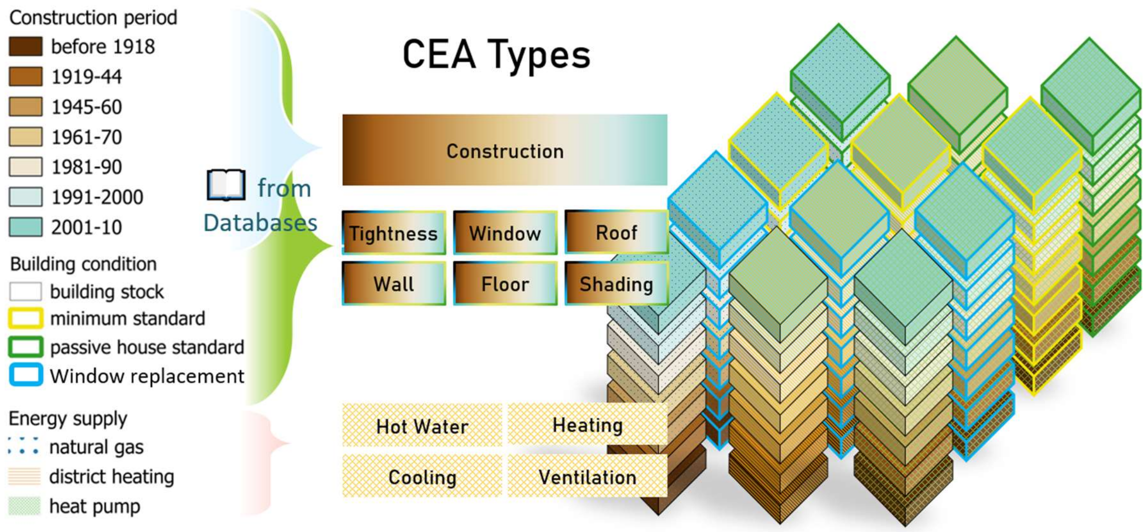

Figure 2. CEA Building Typology generation from available cadaster data (left), providing 84 unique building archetypes from 7 construction types, 4 building conditions/hull qualities and 3 energy supply systems. Specifications and CEA types can be found in the supplementary data.

tightness, and window-to-wall ratios according to Austrian building code classifications and other literature.

Building Condition determines the building physics properties and technical equipment features of the building, essentially characteristics subject to **potential change**. Five types were defined:

(1) **existing** condition of the building stock based on the EPISCOPE and Tabula [8,21]

(2) replacement of existing **windows** with SoA windows (thermal transmittance 1.1 W/m²K)

(3) **minimum** thermal renovations based on Austrian building code [13]

(4) highly efficient passive house standard compliant retrofits.

Energy Supply defines the energy carrier(s) and the primary conversion process for delivering final energy within the building. Three Systems are defined as CEA types for Hot Water, Heating, Cooling and Ventilation and models focus on energy carriers and system efficiency, with options limited to district heating, natural gas and heat pumps.

By combining these three categories, each building geometry can be modelled with **84 possible configurations**, reflecting diverse districts and decarbonisation scenarios. The resulting 6132 single building simulations were grouped into four groups of compactness for sensitivity analysis.

Usage: Building usage types were adopted from the default CEA types based on Swiss SIA building norms [19], as they are also used in the Austrian assessment standard of Climate Neutral Positive Energy Districts [15].

Due to the high uncertainty of the true renovation status of individual buildings, simulated results of assumed data have low individual predictive value. To better accommodate inquiries and additional data from stakeholders and inhabitants and offer a catalogue of potential building performances to choose a given hull and HVAC system from, all building geometries were also simulated with all other defined typologies of construction period, renovation measures and HVAC systems. The 6384 results for 76 geometries with 84 archetypes were clustered into four groups of geometry compactness: “very high”: <0.6, “high”: 0.6-0.8, “medium”: 0.8-1 and “low”: >1], which were calculated with formula (1):

$$(1)\ Compactness = \frac{thermal\ \ Hull}{Gross\ floor\ area} = \frac{A_{roof} + A_{base} + A_{Facade}}{A_{GFA}}$$

3. Results

Figure 3 shows the resulting specific heat demand of 76 building geometries on the y-axis, plotted against the compactness on the x-axis, modelled for six initial construction periods in separate subplots, indicated by their background color, and for all four types of renovation measures, indicated by marker color: original building stock (black), window replacement (blue), minimum renovation according to Austrian building code (yellow) and Passive house renovation (green). The effect of renovation measures decreases for newer buildings as they already are of a higher standard. As expected, the results strongly correlate with the compactness. It indicates the potential spread for each combination of construction type, thermal hull and compactness and facilitates quick referencing for interested stakeholders.

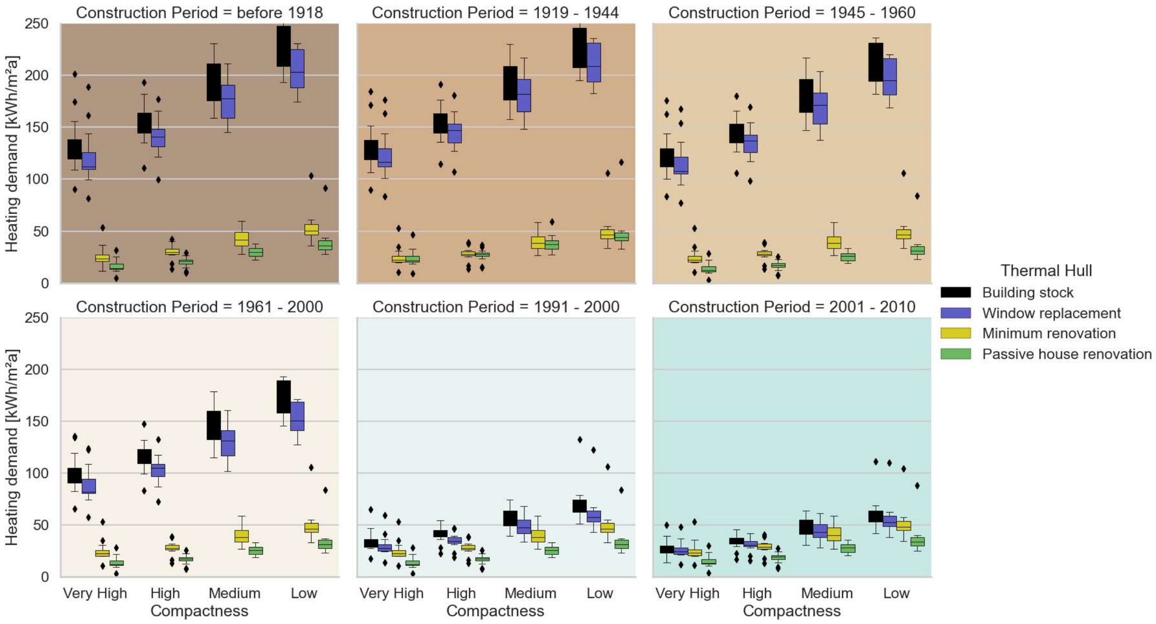

Figure 3. Heat demands for 6384 building configurations aggregated in four compactness categories as reference of potential savings for stakeholder and owners of individual buildings building archetypes from 7 constructions, 4 building conditions/hull qualities and 3 energy supply systems

Figure 4 shows the resulting heat demand, Primary Energy demand and GHG Emissions for building operation and use of the three investigated scenarios compared to the baseline. The aggregate specific heat demand, total primary energy demand and GHG emissions per gross floor area show that the municipal goal of reducing energy end use for heating by 30% until 2040 is achieved in all scenarios, including just business-as-usual (BAU) retrofitting rates, indicating lack of ambition. Note that the non-renewable primary energy and GHG emissions do not reach zero despite a complete switch to district heating in the rightmost two scenarios due to the use of current conversion factors as prescribed in [13]. The reduction in GHG emissions reaching net zero requires additional decarbonization of the surrounding electricity grid and district heating, which is not part of the building assessment in this framework.

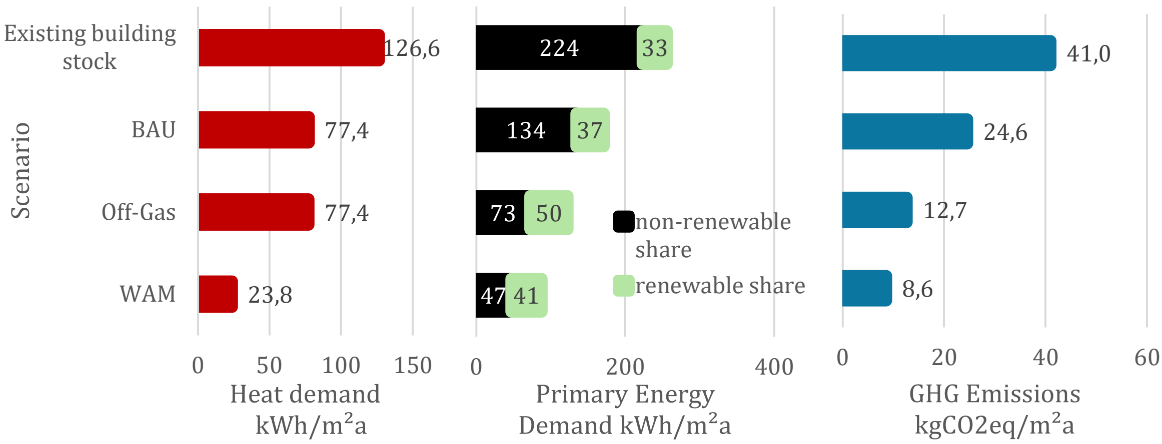

Figure 4. Heat demand, Primary Energy Demand and GHG Emissions of investigated Scenarios: Existing building stock, Business-as-usual (BAU), a complete HVAC switch to district heating ("Off-Gas") and a scenario with additional measures (WAM) and higher thermal retrofitting rates.

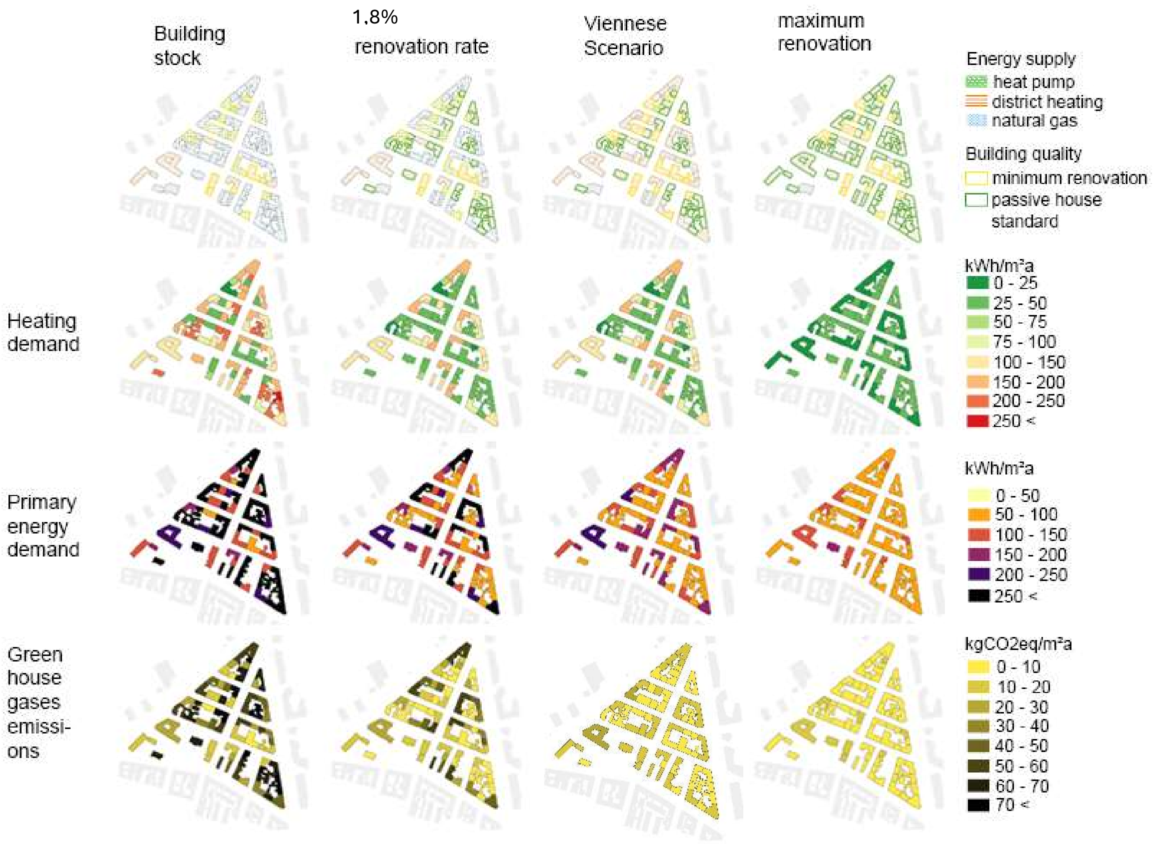

Figure 5. Scenario results per building: Heat demand, Primary Energy Demand and GHG Emissions (top to bottom) for scenarios: Existing building stock (left) , Business-as-usual (BAU, "2% renovation rate", middle-left), a complete HVAC switch to district heating ("Off-Gas", "Viennese scenario middle right) and a scenario with additional measures and higher thermal retrofitting rates ("WAM", "maximum renovation" right).

Figure 5 shows the assessment results in a GIS-based format per building and shows the potential of CEA as a DSS for municipal stakeholders. Since CEA inputs are GIS-based, the outputs too can be quickly analyzed and post-processed with common GIS-tools to navigate district scenarios and potential savings for individual buildings.

Discussion

District modelling and simulation with CEA

Using CEA, several uncertainties regarding the implementation of the model persist: First, changing ventilation type caused little change on the thermal energy balance, as indicated by the small difference between the minimal renovation and passive house renovation, where the former implements window ventilation and the latter a mechanical ventilation system with 75% heat recovery. Further analysis is needed.

Second, despite the principal possibility to simulate PV yields with CEA it was not employable in the study, as the system configurations cannot readily be changed to context-specific orientations considering real roof geometries.

Especially for highly efficient mixed-use buildings, CEA showed surprisingly low heat demands compared to similar simulation methods, potentially indicating overestimation of occupancy rates and subsequent higher internal gains and lower heat loss through ventilation or a combination of both. Further research and comparison with different district case studies is required. It should also be noted that the presented method makes use of building data compiled and parametrized with the purpose of modelling Viennese building stock, rendering it not immediately replicable in other cities.

Nevertheless, CEA's ability to readily provide accurate thermal hulls for available 3D building geometry – given its accuracy – and combine it with pre-defined building stock typologies leads to quicker modelling and simulation cycles.

Scope limitations to Climate Neutrality assessment

The presented study is limited to investigating building operation and use and is omitting other aspects such as mobility and embodied emissions. It is a first step in integrating detailed building data into district scale assessments for climate neutrality and is well suited for future extension with the pursued framework of Austrian climate-neutral Positive Energy Districts featuring three expanding functional system boundaries: (1) Operation and Use, (2) Motorized individual Mobility and (3) Embodied Energy and Emissions over the life cycle.

Conclusion

The study showcases the use of City Energy Analyst to explore vintage, heterogeneous district decarbonization pathways that can be used for municipal stakeholders in communicating and implementing the district decarbonization plan. It adds re-usable components to future UBEM studies with the defined 84 typologies.

The study found that the municipal goals for reducing energy use intensity in the built environment do not go significantly beyond what is already happening by current trends in retrofitting to code.

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Reusing Waste Heat from Data Centres

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Abstract. Data centres consume around 400 TWh of electricity annually. This accounts for around 2 % of the world's total electricity consumption. Energy efficiency of IT components and other technical systems in data centres have been addressed in the long term. Reusing waste heat is not that common in the data centre industry. With the new Czech law 469/2023 Sb. and update of 406/2000 Sb. data centre providers with an IT power greater than 1 MW must reuse their waste heat. The law states 3 options: on-site consumption, heat supply to a nearby consumer and heat supply to a district heating network.

This paper presents a case study of an existing DC and evaluates the effectiveness of reusing its waste heat in DHN. It concludes that the intention of reusing waste heat in district heating is technically viable. Various obstacles are being gradually solved so that more low potential heat sources may supply district heating networks. Individual approach is necessary, as reusing waste heat from DCs includes many specific factors in rentability such as the cooling system, size and distance to DHN, as well as its operational temperatures etc. In some cases, utilizing free cooling may be superior to extracting waste heat, especially in sites where waste heat cannot be utilized all year round.

Reusing waste heat from data centres is a way to add a stable source of heat and diversify heat sources in district heating networks as well as decarbonise and reduce primary non-renewable energy of district heating networks.

1. Current State

1.1 District heating in Europe

District heating is a network system that provides several participants with heat. The main components of the system include the heat source, the pipeline network and the user's heat exchanger station. This paper looks at each component of the network so that the whole can be optimized to recover waste heat from data centres that is considered a low potential heat source. The main parameters of DHNs are its size, power, piping distance and temperature gradient. These parameters are discussed in the following chapter. The European Union stands as one of the largest district heating markets with roughly 608 TWh of thermal energy annually (including United Kingdom). [1]

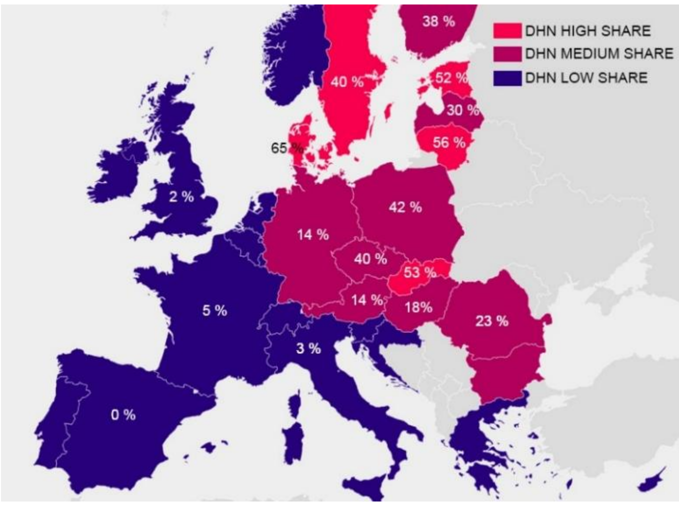

Figure 1. Ratio of district heating to the total share of heating sources [2]

1.2 District Heating in the Czech Republic

District heating in the Czech Republic is highly developed with a total of 25,7 TWh of transferred heat power, which accounts to around 40 % of the total domestic heat use. The total length of Czech district heating is around 7 500 km, with roughly 3 500 km installed as hot water pipeline and 4 000 as steam or high temperature hot water pipeline. [3][4]

The study brought forward by Boháč et el [3] has summarized the Czech DHS´s. The DH has been broken down into 6 typological models, based on DH total size, centralization of DH source and demand type. From their list, three models have been selected that are suitable for the implementation of waste heat from data centres. These are labelled as typological models 3 to 5 – Large/medium/small urban network with a combination of conventional and low emission centralised heat sources with a primary domestic consumption.

These three models supply a total of 30 % of Czech DH, which is around 7,7 TWh/a. These networks are relatively small (10-20 km) and the primary consumers are households. Due to these facts, the operator may be more flexible in connecting small heat sources as well as implementing modern applications, such as lower temperatures in the network. The primary sources of heat are gas and coal with a non-negligible amount of biomass, in contrast to large scale DHS, where the main sources are coal and waste heat from power plants.

The other models (model 1 and 2) are large scale industrial type waste heat with 100+ MW power, where small scale heat input becomes irrelevant and model 6 is a small-scale community network, which is not a typical position for data centres.

Table 1. Summary of district heating system in the Czech Republic

Typological model	III	IV	V
Size - Power (kW)	70	35	15
Heat supply (TJ/a)	270	180	135
Temperature (°C)	110/70	95/65	85/65
Size – length (km)	20	15	10
Heat loss (%)	15	10	8
Size - Power (kW)	70	35	15

All data above is abbreviated to average (typical) values of the given district heating system based on the typological models

1.3 Data Centres as a Source of Heat

Data centres can generally be considered as a very stable and constant heat source with a low output temperature. The output temperature depends on the cooling system. The basic types of cooling are air-cooled and liquid-cooled data centres. Standardized outlet temperatures are set by the ASHRAE technical committee. Typical values for air-cooled data centres are 30-35°C. For water cooling, it depends on the specific technology, where typical values are 25-45 °C, and maximum values are 60-70 °C.

Two data centres in the Czech Republic have been analysed, focusing on their cooling system and possible extracted heat. Both are air cooled data centres located in Prague. The graphs show that data centres produce heat steadily over time with little variation in heat output.

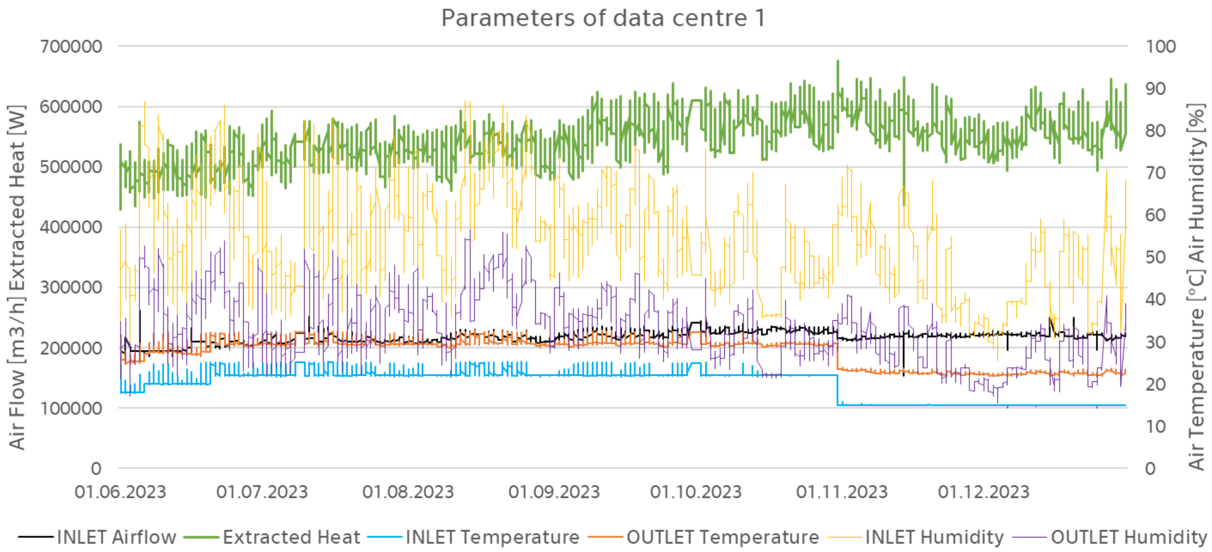

Figure 2. Parameters of the first analysed DC [5]

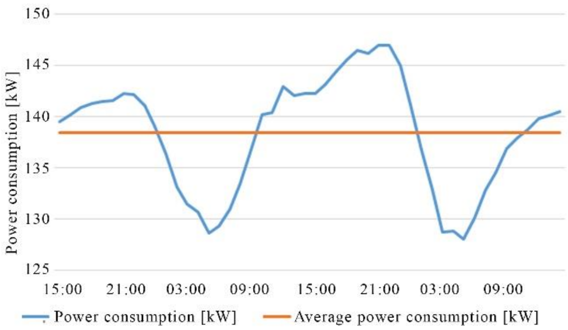

Figure 3. Power consumption of the 2nd analysed DC - typical server room [6]

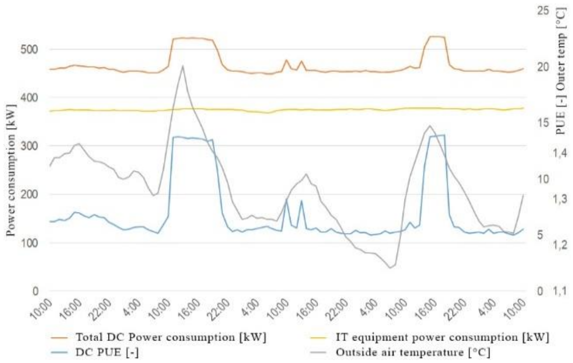

Figure 4. Parameters of the 2nd analysed DC. [6]

2. Technical Solution

2.1 Supplying Heat from DC to DHN

The main obstacle to tackle is the fact, that data centre waste heat is of low temperature output, whereas district heating still tends to operate on higher overall temperatures. The current trend in DH is constantly decreasing the temperature gradient due to lower temperatures in domestic heating systems, thanks to better building insulation and modern heating systems. This leads to higher efficiency of heat sources, lower losses and a possibility of cooperation with low potential heat sources. However, data centres will still need a heat upgrade, mainly using high temperature heat pumps. The demand for heat upgrade can be decreased if we supply heat into the return pipe, instead of the feed pipe.

In data centres with air cooling technology, chillers are often used to supply air handling units (CRAH) with chilled water. Warm water may be harvested on the condenser side. In some instances, direct expansion cooling is used, where condensers are often directly cooled by outside air. Here, special condenser units enabling heat recovery would have to be installed. Third alternative in air cooled DC are rare free air cooled DCs. In this instance, heat recovery is technically very problematic. The options are installing air/water exchanger or air/water heat pump at the air outlet from the hot aisle.

Data centres using water cooling technology are more suitable for reusing waste heat, as the primary coolant is water (or mixture) and there is no need for heat transfer between gas and liquids. Also, in many instances warm to hot water may be harvested directly from the DC. This allows for a smaller temperature upgrade in the high temperature heat pump, which is still necessary for supplying DHN. For direct in situ use, hot water from DC might have adequate temperature for heating and/or domestic hot water preparation.

A factor to overcome is the distance between the data centre and the district heating network. Naturally, longer distances reduce the economic rentability of the project. The investment costs are larger, heat loss must be considered as well as more powerful circulation pumps. Heat loss may be reduced by upgrading the heat closer to the DHN substation.

3. Case study

3.1 Objective of the Case Study

The case study has been performed on the first data centre, which is located in the semi-industrial outskirts of Prague. The surrounding consists mostly of warehouses with little heat demand. However, a small scale DHN (expected typological model - V) is located roughly 1 km from the data centre. This study aims to determine the increased energy demand while reusing waste heat from the data centre. These demands are electric energy for high temperature heat pump and circulation pumps and heat loss from long distance piping. At the same time, a simple analysis has been set to compare loss of potential free cooling vs heat pump needed for temperature upgrade.

3.2 Technical Solution

Currently, the data centre cooling system uses CRAH units to supply cold air to the cold/hot aisle. Chilled water is produced by chillers. Condenser water is cooled by dry coolers. During low outdoor temperatures free cooling technology is enacted (roughly 12 °C). Cooling scheme is displayed below. This solution is the standard used up to date in DCs and is used as a reference for energy consumption.

To obtain the required temperature in DHN a high temperature heat pump has been added to the current system. The evaporator operates at 51/45 °C and the condenser at 87/82 °C. The expected temperature reduction at the heat exchanger is 2 K, allowing for a heat upgrade in the DHN up to 85 °C.

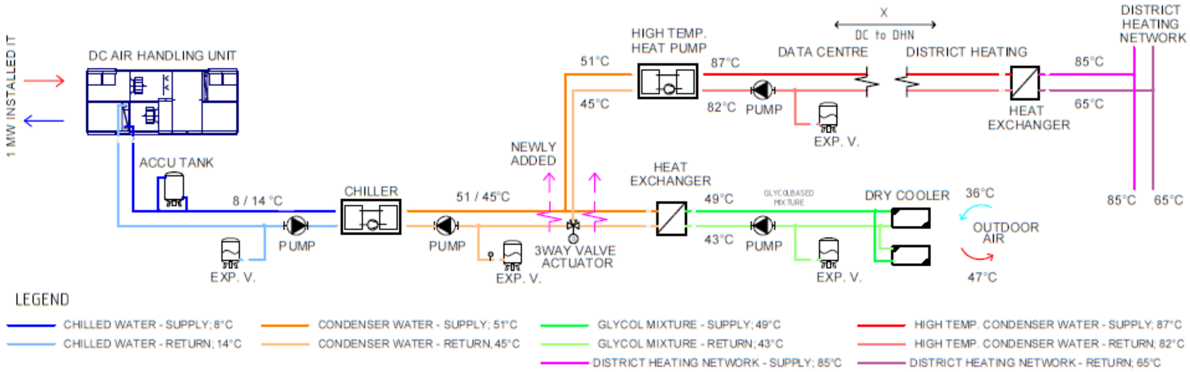

Figure 5. Technical solution of the DC used in the case study

3.2 Evaluation of the Case Study

The main objective was to compare a standardly operated DC with a model simulating reusing waste heat. By comparing the possible heat recovered and electric energy supplied, we may conclude potential project efficiency. In an ideal scenario, we may recover a total of 4 021 MWh with an increased electric cost of 1 167 MWh. This gives a "COP" of 3,45, which is a competitive value. However, if the DHN would only be capable of absorbing heat during winter season, the "COP" would drop to 2,0, which is economically questionable. This needs to be considered when considering heat recovery from DCs. Furthermore, reusing waste heat may reduce primary energy consumption rapidly, as seen in this example with a reduction of 40,7 %.

Results further show that electricity consumption for maintaining circulation pumps is ≈ 1 % and heat loss from piping between DC and DH substation is ≈ 3,5 %.

All evaluated parameters have been summarised in table 2. The time period is 7 months (1.6. – 31.12.2023) and respects the data obtained from the DC.

Table 2. Summary of case study results

Energy consumed	Standard data centre	With heat recovery
IT power (MW)	2 594	2 594
Cooling technology electricity consumption	552,9	1719,5
Air handling units	129,7	129,7
Chiller	354,8	648,5
Heat pump	0	926,4
Circulation pumps	4,4	14,8
Dry coolers	64,0	0
Heat supplied to DHN	0,0	4021,1
Heat Extracted	2594,0	4169,0
Heat lost	2594,0	147,9
Primary energy consumption* [MWh]	1437,5	4470,7
Primary energy saved in DHN [MWh]	0	3619,0
Primary energy sum [MWh]	1437,5	851,7
Potential heat supply during heating season ***	0	2329,4

All data above is referred to the time covered in the study – 7 months (1.6.2023 – 31.12.2023)
* Current conversion rate in the Czech Republic for electricity is 2,6. IT power is not included.
** Current conversion rate in the Czech Republic for efficient DHNs with <80 % renewable sources is 0,9.
*** Heating season is referred to as 1st September in accordance with Czech Decree of the Ministry of Industry and Trade No. 194/2007 Sb.

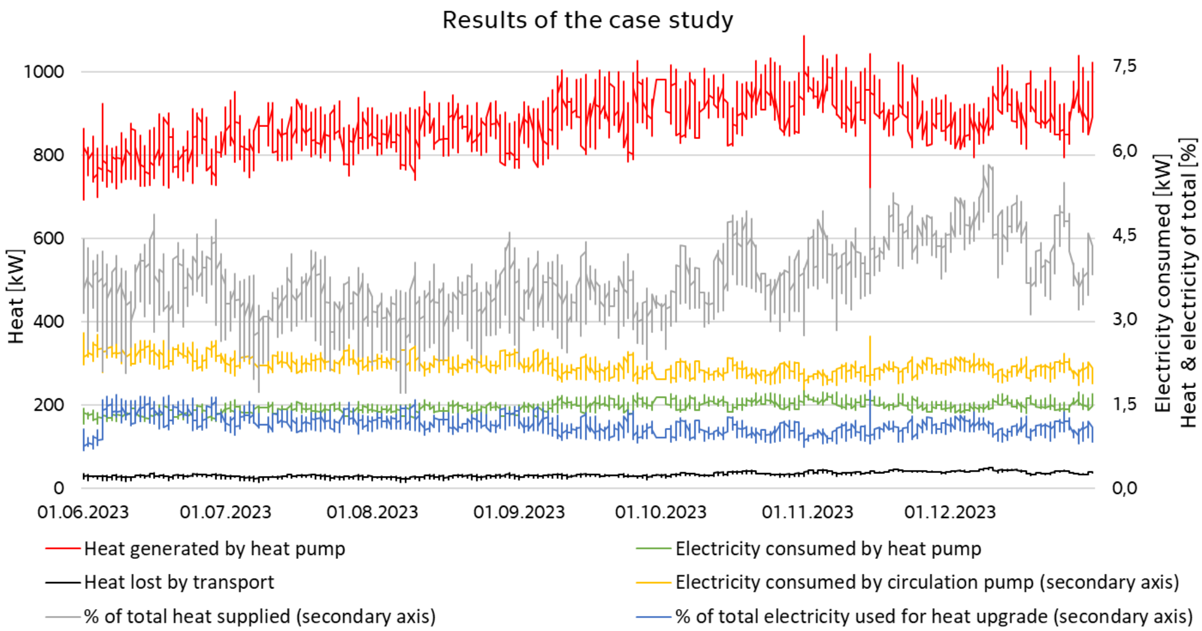

Figure 6. Results of the case study

4. Conclusion

Reusing low potential waste heat from data centres in district heating networks is a viable option in the foreseeable future. The main obstacle, high operational temperature in DHNs, is gradually being overcome with new developments in DHNs and by the reduction of energy consumption in buildings. There is a strong demand for green and renewable energy from both public and private institutions, which is a key role in overcoming high investment costs. These can be further reduced by government incentives, tax cuts or subsidies.

Reusing waste heat from data centres is not ideal in every scenario. It should be considered that modern trends in data centre cooling are taking advantage of free cooling, which is possible mostly during winter season. Free cooling is associated with very little investment costs and is not dependent on any third party. This is in stark contrast to reusing waste heat, since around 80 % of the demand is during winter and transition seasons. Therefore, waste heat recovery should be applied where it may be used efficiently. An ideal candidate is a large-scale DC using water or DX cooling technology with high temperature outputs and located close to a small to mid-size DHN with low operative temperature. It is also highly advisable, that the waste heat is reused all year round, as the warm season is critical in electricity consumption due to operating chillers instead of free cooling.

The last five years have witnessed a stark increase in new data centres, which goes hand in hand with the development of artificial intelligence. When constructing new large scale data centres, it is advisable to plan ahead in locations with possible waste heat reuse. Many DC are being built in warm climates or in industrial sites with little to no waste heat reuse potential. In the near future, city planners should think of suitable locations, not only for data centres, but other waste heat sites, which could be easily connected into district heating networks. An example of these sites are newly constructed living quarters with a modern DHN or an administrative site with “in situ” consumption.

Reusing waste heat from data centres is a way to add a stable source of heat and diversify heat sources in district heating networks as well as decarbonise and reduce primary non-renewable energy of district heating networks.

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Key success factors of PED Labs

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Abstract. Positive Energy Districts (PEDs) promise reduced climate impacts through surplus local renewable energy generation, yet their implementation remains complex. PED Labs–defined under JPI UE SET-Plan ACTION 3.2–function as "seeding grounds" to test innovative solutions in real urban conditions. This paper analyses existing PED Labs by examining scales (building to district), stakeholder engagement (public, private, research, community), and lifecycle phases (planning to operation). The findings highlight collaboration, transparent monitoring, and integrated planning as crucial success factors. They offer concrete guidance for policymakers, industry, and researchers seeking to replicate and scale PED solutions, for more resilient, sustainable urban districts.

1. Introduction

Positive Energy Districts (PEDs) are recognized as a promising approach to achieving energy efficiency and reducing the negative environmental impact of climate change through the surplus of local renewable energy generation [1]. Despite the potential, the implementation of PEDs faces several challenges. The main challenges are those related to governance, incentive, social, process, market, technology and context [3]. PED Labs, as have been defined by JPI UE in the SET-Plan ACTION n°3.2 Implementation Plan, can serve as «*seeding ground for new ideas, solutions and services, will be developed according to place-based needs and local context baselines. PED Labs will follow an integrative approach including technology, spatial, regulatory, financial, legal, social and economic perspectives*» [2]. The PED Labs provide an opportunity to find ways to address the inherent complexity of the implementation and learn how to overcome the challenges.

In line with this perspective, the COST Action PED-EU-NET positions the PED labs as a "*subset in the international debate on sustainable urban development, currently led, in Europe, to the two new concepts of Climate Neutral City and New European Bauhaus".* The PED labs serve as Testing Platforms driving Positive-Energy Living Laboratories. The insights gained from such urban labs, urban living labs, city laboratories and incubators guide the development of Positive Energy Districts [4]. The PED-LAB is simultaneously:

- *A concept referring to a small or medium-scale experimentation, in a risk-controlled environment - especially because it deals with experiments on real urban environments,* *which allows validating innovative solutions to be replicated later on a larger scale involving entire cities.*

- *A concept referring to the whole of the PED-prototypal experiments, which, by sharing good and bad practices, positive and negative results, constitute an extended laboratory in which integrated solutions are tested and validated in similar or different urban contexts.*

PED-Lab definition regarding the Strategic Energy Technology Plan (SET-Plan Action 3.2): *PED Labs will be pilot actions that provide opportunities to experiment with the planning and deployment of PEDs, as well as provide seeding ground for new ideas, solutions, and services to develop. PED Labs will follow an integrative approach, including technology, spatial, regulatory, financial, legal, social, and economic perspectives.*

1.1 Objectives

As part of this effort, this paper aims to consolidate the PED Labs definition based on analysis of implemented cases, by identifying the aspects (technical, social, financial regulatory) and how they influence both implementation and evaluation.

The paper will present the analysis of PED Labs and provide guidance on their design and implementation from technological, social, financial and regulatory perspectives. Leveraging this experience and the involvement in the implementation of PED Labs we aim at answering the following research questions:

- What framework is most suitable for implementing PED Labs?
- How can the relevant factors be organised across appropriate scales, lifecycle stages and stakeholder groups?
- What lessons learned can strengthen PED Lab implementation, particularly in existing districts?

2. Methodology

The methodology consisted of three main steps, each designed to provide a clear, structured view of PED Labs:

1. Develop framework for the PED Labs Analysis

A foundational framework was created to capture key PED characteristics and KPIs, emphasizing technological, social, financial, and regulatory perspectives. This serves as the basis for formulating a consolidated PED Lab definition and developing guidelines for their effective implementation.

2. PED Database Review

The PED Labs identified in the PED-EU-NET database were analysed according to the PED Database classification and aligned with Set Plan Action 3.2 [2] (https://pedeu.net/cast-studies-table-view/?ped_type=lab&phase=&project=). 'PED Labs' are pilot actions that provide opportunities to experiment with the planning and deployment of PEDs. Under this framework, PED labs operate as urban laboratories that test, model, and monitor proposals, technologies, and services reflective of place-based needs and local context baseline. They enable integrative solutions encompassing technology, spatial, regulatory, financial, legal, social, and economic dimensions.

3. Case Study Examination

Building on the developed framework, three specific PED Labs were examined in detail. The analysis focused on how four core aspects (technological, social, financial, regulatory) interrelate with three key dimensions: stakeholders, life-cycle phase, and scale.

2.1 PED Lab database

To systematically map the facilities, resources, and key attributes of existing laboratories, a structured set of classification questions was developed. Table 1 provides an overview of the PED Labs available in the database. As shown in Table 2 (Appendix 1), researchers from academia and R&I centers are the primary stakeholders, drawn by the focus on innovation, experimentation, and monitoring. However, both public and private sectors also demonstrate substantial interest, leveraging the controlled environment of PED Labs to pilot and refine novel solutions.

Currently, 10 cases in the database are designated as PED Labs. Each is undergoing detailed analysis within this task, guided by classification questions that capture the facilities, resources, and operational models unique to each laboratory [6].

2.3 PED Lab framework

A framework was developed to analyse the PED labs aims at including the technological, social, financial and regulatory perspectives. In this respect, mapping the key stakeholders, as well as on which scale and phase the decisions are made will be part of the analysis. As a result, the proposed framework provides a relation between the 4 key aspects: technological, social, financial and regulatory and the 3 dimensions: Stakeholders, Life-cycle phase and Scale.

The framework primarily focused on identifying the tools and is designed to not just assess technologies or KPIs in isolation, but rather to analyze the decisions made within the PED labs – focusing specifically on who makes the decision, when it is made, and at what scale the decision is being implemented [7]. With additional key performance indicators, it was then possible to validate the framework. We followed the methodology as follows:

Table 1. PED Labs in the PED-EU-NET database

PED Lab	from project	category
Évora, Portugal	POCITYF – A POsitive Energy CITY Transformation Framework	PED Relevant Case Study / PED Lab
Groningen, PED South	MAKING-CITY – Energy efficient pathway for the city transformation: enabling a positive future	PED Lab
Groningen, PED North	MAKING-CITY – Energy efficient pathway for the city transformation: enabling a positive future	PED Lab
Maia, Sobreiro Social Housing	SPARCS – Sustainable energy Positive & zero cARbon CommunitieS	PED Lab
Lubia (Soria), CEDER-CIEMAT		PED Lab
Tartu, City centre area	SmartEnCity – Towards Smart Zero CO2 Cities across Europe	PED Relevant Case Study / PED Lab
Barcelona, SEILAB & Energy SmartLab		PED Lab
OpenLab	EU Horizon project with living lab (to be added by Vito)	PED Lab
Vantaa, Aviapolis	NEUTRALPATH – Pathway towards Climate-Neutrality through low risky and fully replicable Positive Clean Energy Districts	PED Case Study / PED Relevant Case Study / PED Lab
Aarhus, Brabrand	BIPED – Building Intelligent Positive Energy Districts	PED Lab

1. Short analysis of the specific case
2. Stakeholders: their role objective and decision making
   - *Which were the main decision makers for the P'ED?*
   - *Which actor was responsible for implementing*
   - *Who was the key user of the PED and how the PED influenced their life quality?*
   - *Who has financial savings/benefits (value, revenue)?*
3. Life-cycle phase
   - *In which phase were the technical interventions decided?*
   - *Which phases were monitored and how were the outcomes used?*
   - *How and when will the investment pay back?*
   - *In which phase did the community engage?*
4. Scale
   - *At which scale was the technology implemented?*
   - *Which other scales did the technology influence/interacted with?*
   - *Which scale was the community engagement relevant for and in which capacity? For example, building/dwellings, urban developments, energy communities, etc.*

3. Results

3.1 Analysis of PED Labs

Based on the PED Labs (Table 4 in Appendix) its targets were compared (Tables 5 and 6 in Appendix) and further details of each PED Lab collected (Table 7 in Appendix). It investigated in depth how the three dimensions of stakeholders, project phase, and scale influenced the technical, financial, regulatory and social aspects of the PED Lab.

Table 2. Short analysis of the specific case

Name	Sobreiro Social Housing«×»	Lubia (Soria)	Genk PED Lab
Location	Maia	Lubia (Soria)	Genk, Belgium
PED Lab	Strategic	Strategic	Strategic
District size	84 buildings	6 buildings	27 buildings
Number of homes	498 homes	6 office buildings	27 homes
Fields of application	Energy efficiency, energy flexibility, energy production, E-mobility, urban comfort, digital technologies	Energy efficiency, energy flexibility, energy production, digital technologies, indoor air quality	Energy efficiency, energy flexibility, energy production, digital technologies, indoor air quality

1. Maia Sobreiro Social Housing

In Maia, the primary decision maker was the Municipality of Maia, led by the city's leadership and coordinated through it's Strategy Development and Innovation Office (NEDI), and working closely with the technical divisions like the Division of Energy and Mobility and partners such as AdEPorto (Energy Agency), EDP NEW R&D (Industry partner) and the University of Maia [8]. The

Municipality set the overall vision, aligned with the City Vision 2050 [9], and formulated policies driving the development [8].

Table 3. Overview of Maia PED Lab dimensions

Dimension	Technological	Social	Financial	Regulatory
Stakeholders	Technical partners (AdEPorto, EDP NEW R&D, University of Maia) provide feasibility studies, assessments, and integration tools.	Residents of the Sobreiro Social Housing District engage in co-design and REC formation, influencing comfort and quality of life.	Municipality and Espaço Municipal benefit from reduced energy bills; industry (e.g., Sonae) gains via enhanced sustainability.	Municipality sets policies and coordinates with national bodies to enable the REC model and ensure compliance.
Life-cycle Phase	During planning, feasibility studies define retrofit measures (e.g., PV installations, smart meter deployments); monitored through an energy management platform in operation.	Community engagement starts in the planning phase (public consultations, workshops) and continues through implementation and operation.	Investment decisions (e.g., outcome-based contracts) are made during planning; operational savings accumulate to achieve rapid payback.	Permitting and policy formulation occur in planning, with ongoing compliance monitoring during the operational phase.
Scale	Interventions are executed at the building level (individual social housing blocks and municipal buildings) and aggregated into a district-scale virtual PED.	Engagement occurs at the building/dwelling level and expands to neighbourhood-level via collective actions in the REC; results inform urban-scale replication.	Savings are realized at the communal level (public buildings, social housing) and scaled up through broader municipal investments.	The PED Lab operates within municipal and national regulatory frameworks that enable replication across different urban zones

Community engagement began in the early planning phases, through public consultations and co-design workshops and continued into operation via regular meetings and digital platforms. Technological interventions were applied mostly at the building level (social housing blocks and municipal buildings) and aggregated to eventually form a district scale virtual PED. These measures also influence the broader urban scale as part of the “Maia Positive City” vision. Community engagement operates at multiple scales, from individual dwellings to neighbourhood wide energy community efforts, ensuring both technical and social dimensions are addressed.

2. CEDER-CIEMAT PED Lab

The Centre for the Development of Renewable Energy (CEDER) [http://www.ceder.es/redes-inteligentes] is placed in the middle-north region of Spain (Soria) and it is specialized in applied research, development and promotion of renewable energy. This PED Lab is located in the CIEMAT facilities (Spanish public research center) and operates as an energy district, covering an area of 640 hectares. The district consists of six office buildings and two energy networks, one electrical (operational) and one thermal (under implementation). The electrical network integrates a 50 kW wind turbine, eight photovoltaic systems with a total generation capacity of 116 kW, a 100 kVA engine generator, a reversible hydraulic system and storage systems through batteries and flexible loads. The thermal network currently consists of two 300 kW biomass boilers and 90 kWh water tanks for thermal storage. However, this network is being expanded through the incorporation of a low temperature ring (90°C) and a high temperature ring (150°-250° C), both interconnected through an oil/water heat exchanger. Several thermal storage systems are also being incorporated through boreholes, phase change materials, geothermal exchange or the use of zeolites.

3. Genk PED Lab

oPEN Living Lab Genk is part of the project oPEN Lab which is funded under the European Union's Horizon 2020 Research and Innovation and will focus on identifying and demonstrating replicable, commercially viable solution packages enabling to achieve positive energy buildings and neighbourhoods. oPEN Living Lab Genk is located in Genk, Belgium in the suburban residential neighbourhood called "Waterschei". This neighbourhood consists of two distinct areas: a former miners' district constructed in the 1920s and a more recent social housing district called "Nieuw Texas" built in the 1990s. Together with the suburban context, a very high level of social housing ownership (85%) in Nieuw Texas, and the nearby presence of former mines, represent a unique opportunity for large-scale, real-life demonstrations of promising technology, renovation processes, and social innovation toward the creation of a Positive Energy Neighbourhood.

3.2 Identified gaps in PED Lab

Based on the above analysis, despite meaningful progress in demonstrating innovative pathways for sustainable urban development, several critical knowledge gaps must be addressed to accelerate the transition towards fully operational Positive Energy Districts (PEDs):

Standardized methodologies and metrics:

- There's a lack of standardized methodologies for assessing and comparing the performance of PEDs. This makes it difficult to benchmark progress and share best practices effectively.
- We need more comprehensive metrics that go beyond energy balance and consider other crucial aspects like environmental impact, social equity, and economic viability.

Long-Term performance and resilience:

- Most PEDs are relatively new, and there's limited data on their long-term performance, especially regarding energy efficiency, maintenance, and resilience to climate change.
- We need to better understand how PEDs can adapt to changing conditions, such as evolving energy technologies, climate patterns, and societal needs.

Integration and scalability:

- Optimizing energy performance at the district level is complex, requiring sophisticated modeling and simulation tools that consider interactions between buildings, energy systems, and infrastructure.
- Scaling up PED initiatives from pilot projects to widespread implementation poses significant challenges, requiring innovative business models, financing mechanisms, and policy frameworks.

Social and behavioral aspects:

- Understanding user behavior and engaging residents in PED initiatives is crucial for their success. We need more research on how to promote energy awareness, encourage sustainable practices, and ensure social acceptance of new technologies.
- It's important to ensure that the benefits of PEDs are distributed equitably across all segments of society, including vulnerable populations.

Technological innovation and integration:

4. We need to keep abreast of emerging technologies in areas like renewable energy, energy storage, smart grids, and building automation, and explore how they can be integrated into PEDs.
5. Integrating various technologies and systems at the district level requires advanced planning and coordination to ensure interoperability and optimize performance.

Policy and regulatory frameworks:

- Supportive policies and regulations are essential to create an enabling environment for PED development. We need to identify and address policy gaps and barriers that hinder the adoption of PEDs.
- Streamlining planning and permitting processes for PED projects can reduce costs and accelerate implementation.

4. Discussion

4.1 Framework

The aim was to provide a framework regarding PED characteristics and KPIs, considering technological, social, financial and regulatory perspectives. These different perspectives are essential to provide in a framework for PED Labs.

4.2 Dimensions in PED Labs

It became clearer that the framework must be embedded in the 3 dimensions: Stakeholders, Life-cycle phase and scale. In essence, with rooting decisions in their context, the framework serves as an analytical tool to dissect and understand decision making in PED Labs.

4.3 Learnings from PED Labs

When introducing PED Labs it is important to take into consideration:

- **Focus on PEDs:** Their core mission is to facilitate the creation of PEDs, which are areas or groups of buildings that generate more renewable energy than they consume annually.
- **Collaborative Approach:** They emphasize collaboration among diverse stakeholders, recognizing that achieving PEDs requires a holistic approach involving various perspectives and expertise.
- **Real-World Testing:** PED Labs involve real-world testing and demonstration of innovative technologies and solutions in actual urban settings. Coupled with monitoring and energy management platform, this allows for practical evaluation and refinement of these approaches.
- **Knowledge Sharing:** They serve as platforms for knowledge sharing and learning,

5. Conclusions

PED Labs act as critical “seeding grounds” where innovative ideas, technologies, and services can be tested and refined according to specific local contexts. This approach effectively captures the inherent complexity of Positive Energy District (PED) implementation, integrating technological, social, financial, and regulatory perspectives. The proposed framework—linking these four key aspects with three overarching dimensions (stakeholders, lifecycle phases, and scale)—clarifies essential success factors for PED Lab deployment, particularly the collaborative approaches and real-world context testing. Those factors are highlighted in the framework dimensions of stakeholders, implementation phase and scale.

Still, knowledge gaps remain, mainly in standardized methodologies and long-term resilience. Addressing them requires cohesive efforts from researchers, policymakers, industry, and local communities. By collaborating across sectors and investing in robust, integrative planning, we can accelerate the transition toward more sustainable, resilient cities through Positive Energy Districts. The framework aspects highlight needs for integrated approaches based on multi-disciplinarity.

As PED Labs continue to evolve and expand, developing standardized metrics and digital tools—such as advanced data-analytics platforms and collaborative modelling environments—will be essential for shared learning and broader replication. Equally important is the adoption of inclusive engagement strategies that empower local communities throughout planning, implementation, and monitoring. By maintaining close collaboration among stakeholders, continuously refining best practices, and fostering knowledge exchange, PED Labs can become indispensable drivers of urban innovation.

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***Appendix:* Tables 4-7 give an overview of different PED Labs included.**

Table 4. PED Labs analysed

Name	Vantaa	Aarhus	Évora	Groningen	Groningen	Maia, Sobreiro	Lubia (Soria)	Tartu	Barcelona
Location	Aviapolis	Brabrand	Portugal	PED South	PED North	Social Housing	CEDER-CIEMAT	City centre area	SEILAB & Energy SmartLab
PED case study	yes	yes	no	no	no	no	no	no	no
PED relevant case study	yes	yes	yes	no	no	no	no	yes	no
PED Lab.	yes	yes	yes	yes	yes	yes	yes	yes	yes

Table 5. Targets of the PED Lab

Name	Vantaa	Aarhus	Évora	Groningen	Groningen	Maia, Sobreiro	Lubia (Soria)	Tartu	Barcelona
Climate neutrality	yes	yes	no	yes	yes	yes	no	yes	no
Annual energy surplus	no	yes	yes	yes	yes	no	no	no	no
Energy community	no	yes	yes	yes	yes	no	no	no	yes
Circularity	yes	no	no	yes	yes	no	no	yes	no
Air quality and urban comfort	no	no	no	no	no	no	yes	no	no
Electrification	no	no	no	no	no	no	no	yes	yes
Net-zero energy cost	no	no	no	no	no	no	no	no	no
Net-zero emission	no	yes	no	yes	yes	no	yes	yes	yes
Self-sufficiency (energy autonomous)	no	no	no	no	no	no	yes	no	yes
Maximise self-sufficiency	no	no	no	no	no	yes	no	yes	no
Other	no	no	no	no	no	no	no	no	yes

Table 6. Further details of the PED Lab

	Vantaa, Aviapolis	Aarhus, Brabrand«×»	Évora, Portugal«×»	Groningen, PED South«×»	Groningen, PED North«×»	Maia, Sobreiro Social Housing«×»	Lubia (Soria), CEDER-CIEMAT«×»	Tartu, City centre area«×»	Barcelona, SEILAB & Energy SmartLab«×»
A1P005: Project Phase of PED Lab	Planning Phase	Planning Phase	Implementation Phase	Implementation Phase	Implementation Phase	Planning Phase	Implementation Phase	Implementation Phase	In operation
A1P009: Data availability	General statistical datasets, GIS open datasets	Open data city platform – different dashboards, General statistical datasets, GIS open datasets	Open data city platform – different dashboards	Monitoring data available within the districts, Open data city platform – different dashboards, GIS open datasets	Monitoring data available within the districts, Open data city platform – different dashboards, GIS open datasets	Monitoring data available within the districts, Open data city platform – different dashboards, Meteorological open data, General statistical datasets, GIS open datasets	General statistical datasets	Monitoring data available within the districts, Open data city platform – different dashboards	General statistical datasets
A1P016: Ownership of PED Lab:	Mixed	Mixed	Mixed	Mixed	Mixed	Public	Public	Private	Public
A1P022e: Financing - PUBLIC - National funding	no	no	no	yes	yes	yes	no	yes	no
A1P023: Economic Targets	Positive externalities, Boosting local businesses, Boosting local and sustainable production	Boosting local and sustainable production		Boosting local businesses, Boosting local and sustainable production	Boosting local businesses, Boosting local and sustainable production	Positive externalities, Boosting local and sustainable production	Boosting local and sustainable production, Boosting consumption of local and sustainable products	Positive externalities	Job creation, Boosting local and sustainable production

Table 7. Further details of the PED Lab

	Vantaa, Aviapolis	Aarhus, Brabrand«×»	Évora, Portugal«×»	Groningen, PED South«×»	Groningen, PED North«×»	Maia, Sobreiro Social Housing«×»	Lubia (Soria), CEDER-CIEMAT«×»	Tartu, City centre area«×»	Barcelona, SEILAB & Energy SmartLab«×»
B2P004: Operator of the installation	The City of Vantaa manages the lab, working closely with landowners and other stakeholders such as energy companies, solution providers, universities and citizens.			The Municipality of Groningen is Manager of the lab but works closely with other parties such as the university, university of applied sciences, research institute TNO and several other parties.		CM Maia, IPMAIA, NEW, AdEP.	CIEMAT. Data detail		IREC
B2P007: Motivation for developing the PED Lab	Strategic	Strategic		Civic		Strategic	Strategic	Strategic	Strategic, Private
B2P008: Lead partner that manages the PED Lab	Municipality	Research center/ University		Municipality		Municipality	Research center/ University	Municipality	Research center/ University
B2P011: Available facilities to test urban configurations in PED Lab			Buildings, Demand-side management, Prosumers, Renewable generation, Energy storage, Energy networks, Waste management, E-mobility, Social interactions, Circular economy models	Buildings, Demand-side management, Energy storage, Energy networks, Waste management, Lighting, E-mobility, Information and Communication Technologies (ICT), Social interactions, Business models		Buildings, Demand-side management, Prosumers, Renewable generation, Energy storage, Efficiency measures, Lighting, E-mobility, Information and Communication Technologies (ICT), Ambient measures, Social interactions	Buildings, Demand-side management, Prosumers, Renewable generation, Energy storage, Energy networks, Efficiency measures, Information and Communication Technologies (ICT), Ambient measures, Social interactions	Buildings, Prosumers, Renewable generation, Energy networks, Lighting, E-mobility, Green areas, User interaction/participation, Information and Communication Technologies (ICT)	Demand-side management, Energy storage, Energy networks, Efficiency measures, Information and Communication Technologies (ICT)
B2P012: Incubation capacities of PED Lab			Monitoring and evaluation infrastructure, Tools for prototyping and modelling, Tools, spaces, events for testing and validation	Tools for prototyping and modelling		Monitoring and evaluation infrastructure, Tools, spaces, events for testing and validation	Monitoring and evaluation infrastructure, Tools for prototyping and modelling	Monitoring and evaluation infrastructure, Pivoting and risk-mitigating measures	Monitoring and evaluation infrastructure, Tools for prototyping and modelling, Tools, spaces, events for testing and validation
B2P014: Monitoring measures				Execution plan, Available data, Type of measured data, Equipment, Level of access		Execution plan, Available data, Type of measured data	Equipment	Available data, Life Cycle Analysis	Equipment
B2P015: Key Performance indicators	Energy, Environmental, Social, Economical / Financial	Energy, Environmental, Sustainability, Social, Economical / Financial	Energy	Energy, Social, Economical / Financial		Energy, Environmental, Social, Economical / Financial	Energy, Environmental, Economical / Financial	Energy, Sustainability, Social, Economical / Financial	Energy, Environmental
B2P019: Available tools	Energy modelling	Energy modelling, Decision making models		Energy modelling, Social models, Business and financial models		Energy modelling, Social models, Business and financial models, Fundraising and accessing resources, Matching actors	Energy modelling	Social models	Energy modelling

Sustainable refurbishment of cultural and industrial heritage

An Active Rescue of Immovable Industrial Heritage in the Form of a New Use

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Abstract. The paper presents the results of the first phase of the ministerial research, NAKI III ("The immovable industrial heritage, the physical evidence of the industrial era, cultural heritage and national identity"), which is focused on mapping cultural and creative industries as a new function of former industrial buildings. The result of the mapping, evaluation criteria and statistics will be presented, which show the nature of these interventions. It is perceived to be the base of further possible consideration of the types of interventions in abandoned industrial buildings. This type of non-traditional functions (circus, climbing walls, temporary cultural activities, coworking), and proven functions as well (theatres, galleries, offices), helps often to preserve the buildings themselves without the need for monument protection. They also help to develop local communities and support the sustainability of industrial heritage in the locality. The NAKI project sees the adaptability of the building and its compatibility with the new function as the main criterion, so that the future use is truly sustainable.

1. Annotation

The text summarizes the ongoing research findings of the programmatic project "Active Preservation of Immovable Industrial Heritage through New Uses," funded by the Ministry of Culture of the Czech Republic under the NAKI III program (2023–2027) and conducted at the Faculty of Civil Engineering at the Czech Technical University in Prague. In the first phase (2023-2025) of the project, the focus is on the mapping reuse of cultural and creative industries within the neglected industrial buildings of the Czech Republic.

The aim of this filed of research is to portray as much diversity in cultural and creative undertakings as possible that are provided re-purposed industrial buildings. A total 350 former industrial structures have been catalogued based on their transformation processes, present activities, architectural alterations, proprietorship, and legal status. Results have been analyzed using statistical methods and will be further explored.

The aim of the project is to explore the role of implementing creative activities and cultural programs in derelict industrial structures in preserving industrial heritage while also offering opportunities for these activities to take place where there is a lack of suitable buildings for such purposes.

2. Introduction

2.1 Subject of investigation

The current tendency around the world is to create an economy that is built on creativity, innovation, a high level of qualified workforce, and business. The so-called cultural creative industries (hereinafter referred to as CCI) encompass those industries which are founded on cultural values of arts and other forms of individual or collective innovations. We take CCI definition in its general form as provided by Bilík-Nétek (Bilík, Nétek, TAČR, 2020) and subdivide it into three basic domains namely: the domain of traditional art (more publicly funded), the domain of cultural industries, and the domain of creative industries. Original creation which forms the core of CCI includes performing arts, music, visual arts, crafts, design, fashion, architecture, advertising, software, gaming, film and audiovisual, television and radio, new media, information technology services, publishing, education in the field of culture, and all culture producing innovations. Our analysis, however, goes beyond this boundary and includes, for instance, culinary art and, to some extent, sports, if they possess a cultural-communitarian dimension.

Several research projects and programs have been active for the past 15 years in describing, analyzing and assessing the impact of creative industries in Europe (see Creative Europe, New Bauhaus, etc.). The same applies for the Czech Republic (Creative Česko, CzechInvest), where the works of M. Cikánek's (Cikánek, 2013; Žáková, 2015) and Bilík-Nétek (Bilík, Nétek, TAČR, 2020) are relevant because they point out the still vague conceptualization of the CCI terms. The focus of the motifs has shifted from simply attempting to define the problem to one where there is a structured strategy to provide support towards establishing and sustaining this sector. This was seen in 2020 with the launch of the Creative Czech Republic platform by CzechInvest Agency, which aims at supporting creative cities, and regions. Despite these changes, there is a deficit in the thorough mapping of these locally oriented activities.

Simultaneously, those activities help to form a cultural and cultivated environment (Gehl, 2012), which shapes the behavior of society and life in the settlements, including the nurturing of urbanism (Kašpar, 2024). It is well documented that they substantially contribute to HDP formation (check Czechinvest statistics). However, the goal of our research was not the CCI theoretical essence scoping discussion, but rather mapping and describing creative activities that have crystallized over the last few years within the neglected industrial landscape. During a decline and demolition phase of former industrial sites, such activities seem to promise a vibrant future for industrial heritage by giving the neglected structures temporary protective uses, or even permanent new lives.

2. How does CCI relate with Industrial heritage?

Industrial structures, which include but are not limited to the extraction and processing of raw materials, construction, and storage, have emerged during the latter half of the 19th century and the early parts of the 20th century. It loosely includes railway structures, urban infrastructure as well as warehouses. (TICCIH Charter 2003, Doet, 2013, Matěj-Ryšková, 2018). Currently, there is a tendency to classify decayed structures from the second half of the 20th century as heritage sites, such as heating plants and transformer stations among other things. (Popelová, Šenberger, 2021). From a typological perspective, industrial buildings encompass all principal types of structures, whether it is generic, multi-purpose, multi-story ‘towers and halls’, unique single-purpose chemical plants, or combined breweries, boiler rooms, transformer stations and railway stations.

How can “industrial heritage” be connected to a contrary concept such as “cultural and creative industries”? The combination of social change, concern for the environment, emerging technology, and the substantial energy crisis that plagued Europe due to the transition from the “second industrial revolution” (defined as 2-0) to the “third industrial revolution” (3-0) during the beginning of the second half of the 20th century were major factors in transforming the continent’s technology and, therefore, the decline of Western heavy industry and any related sectors between the late 1960s and early 1970s. By this time, industries in the UK had already declined close to 70%.

The investigation into striking industrial architecture from the late 1960s led to the formation of TICCIH in 1973, recognizing industrial heritage as cultural heritage. Since the 1970s, many industrial buildings in the West have been repurposed with varying success in meeting modern urban needs. This was embraced by 'creative' efforts mainly from artists of various kinds who began to occupy these vacant spaces. This is where the two entities are still interrelated today. The new users of these spaces also come into play, which American theorist Richard Florida (Florida 2003, 2019) has dubbed ‘the creative class.’ He foresaw their emergence and growth as being vital to future innovation, increased GDP contribution, and the birth of a novel cultural and business scene. Realizing the significance of these activities, non-profit entities, and later public administrations, offered various forms of subsidies, especially to non-commercial entities. The spontaneous use of empty structures was also logical specially for creative work. It was, often, with no or little funding. These vacant structures addressed the shortfall but posed various challenges. Similar initiatives started in the West and had different socio-cultural foundations than the Czech Republic where it was influenced by illegal squatting, varying acceptance of leftist movements, and independent cultural and artistic life.

According to the findings of our research, little improvement has been observed until now, these activities are still largely directed to abandoned buildings. It is now evident that some artistic domains have fully integrated into the industrial space such as performing arts in the renowned Rondhouse in London as theatres are symbols of innovation. Theoretician J. Strong (Strong, 2010) defines the meaning of “industrial theatres” as spaces within industrial sites that have been repurposed into performance spaces (Poláček, Pokorný, 2015; Lapšanský, Popelová, 2016). Art studios, galleries, and artist residences now integrate into industrial spaces like Leipziger Baumwollspinnerei, Tate Modern, and Humpolcká 8MIČKA etc. Dance studios and schools, such as the Prague Dance Centre in the Branický brewery, are also part of this trend, especially in the West and the Czech Republic. It is now common for industrial spaces to be converted into photography studios, coworking spaces, and bars that make use of industrial chic as part of their branding (Poláček, Pokorný, 2015).

From the perspective of industrial heritage conservation, tourism related to the preservation of industrial heritage is gaining greater significance today with the aid of many networks such as ERIH, Technotrasa, Go to Brno, and others, including those of cross-border significance. Other networks unite professional circles such as ANTENA, Trans Europa Halls/TEH and others, and theorize their work (TEH, 2024).

The focus extends beyond individual initiatives to encompass entire locations, including creative clusters and creative cities. This has been studied in the Western world before, for example the Working Heritage Project (VCPD 2004), attempted to study and analyze the most advanced transforming areas in Birmingham, Roubeix, Schio, and even Prague. Currently, we include cities like Leipzig, Milan (Fossa, 2015), Łódź, Linz, Barcelona (Duarte, 2018), Košice, etc. Today, this phenomenon expands to include European Capitals of Culture (hereinafter referred to as ECoC). For the Western region, large-scale regeneration of previous industrial zones is quite common, as it is seen in the Silesia or Ruhr regions (IBA). In our region, rather smaller creative clusters are known, for instance, smaller ones like in Pražské Holešovice, creative cities like Pilsen 2015, and from large-scale interventions the Lower Vítkovice Area (DOV) in Ostrava, the reconfiguration of Zlín or the attempts for landscape interventions in the Most region. These phenomena require huge resources to be invested, to name a few, PLATO Ostrava and Automatické mlýny in Pardubice. (Merta et al., 2024). However, as our research shows, many CCIs in the industrial sector are far simpler, they are smaller, often low-cost projects and in the sense of Cikánek's words (Cikánek, 2013, p. 138), it is often socially engaged individuals who lead these transformation initiatives.

3. Concepts

Building upon the generally stated list of creative activities of cultural and creative industries, the research established basic categories in which the nature of the activity is primarily monitored in relation to spatial (typological) requirements, dominant period of use, and requirements for public contact or visitors. After evaluation, we selected two primary types of sectors: First, production, which is an activity in which outputs of a tangible nature that can be marketed are produced deemed by the creativity of the makers (creative industries). Second, presentation, which thanks to a more flexible definition includes Cultural Sector – an activity in which artistic performances, works of art, different collections, as well as books or archives are presented (cultural industry). The last element covers education as a fundamental type of cultural activity and one form of access to the above industrial building.

The phrase ‘re-use/conversion’ is used in regard with the level of structural intervention as well as the scope of adaptability (Šenberger, 2023). The conversion is viewed as maintaining the structural substance of the original industrial building by inserting a new function (TICCIH, 2003; Matěj, Ryšková, 2018,). The degree of intervention to the original structure relies on the adaptability of the converted structure, type of new program, and even the creativity of the architect.

4. Results and preliminary interpretation of the research - selected statistical items

A total of 350 industrial sites were assessed in the study, with statistical data collected as of December 31, 2024. The evaluation focused on key attributes and specific characteristics of each site, including: location (categorized by region and settlement type), locality (urban center, suburban area, rural setting), building type, and current function (classified into primary and secondary uses, as well as monofunctional or multifunctional spaces). Additionally, the study examined the anticipated duration of use (temporary or permanent), the type of cultural institution (independent, established, or hybrid), and the extent of intervention (minor, moderate, or major). Further factors included ownership structure (private, public, or mixed), project initiation (led by private entities, public entities, or a combination), and heritage protection status (protected or unprotected). Finally, the research recorded data on grant funding, overall costs, and financial support mechanisms associated with each project.

From the items analyzed so far, we select:

Region

The number of conversions of industrial buildings relies heavily on the concentration of the creative cultural class in economically powerful areas. Prague, with 62 creative cultural sites which accounts to 18.1% of the total industrial fabric, and the Central Bohemian region, with 48 sites (14.0%), account for the highest share of recorded conversions because this is where cultural and economic activity is centered. A second key factor is the ethnographic allocation of industry in the Czech Republic, with some regions having a strong industrial legacy, leading to higher rates of adaptive reuse. The Moravian-Silesian Region, with 35 sites (10.2%), ranks third benefiting from its industrial heritage and strong local support for large-scale conversions, particularly in Ostrava. Other historically industrial regions, such as Ústí nad Labem, with 29 sites (8.5%), Liberec, Zlín, and Pilsen, with equal number of sites at 23 each (6.7%), also exhibit conversion activity, though at significantly lower levels. Pilsen, for instance, has received support through initiatives like the European Capital of Culture 2015. On the other hand, agricultural regions like South Moravian and Karlovy Vary with 18 sites (5.3%) each, as well as Hradec Králové with 17 sites (5.0%), have recorded minimal CCI-related conversions, which indicates a minimum demand and less available industrial structures to be utilized. South Bohemian Region recorded 16 sites (4.7%), while Olomouc Region recorded 12 sites (3.5%). On the lower end of the spectrum, the Pardubice Region has 9 sites (2.6%), while, appearing to have much lower volumes of engagement, Vysočina Region has only 8 sites (2.3%).

Location (urban center, suburban area, rural setting)

The positioning of industrial structures greatly affects their potential adaptability to a new purpose as well as the choice of the purpose itself. The activities in question are quite often directly associated with a sufficient number of "users" which is directly connected to the site of the building. 56.7% (194 buildings) of the CCI mapped projects are found in the central area of the settlements which once again pays back to support that CC are in more central areas of the cities where the demand and supply is highest. Nonetheless, the number of buildings that could be repurposed as CCI are constrained and restricted by many factors (scale, temporal range of use, land value, etc.). In central locations, there is often the phenomenon of temporary use of buildings, which are ready for demolition, for more commercial use of the land.

Moreover, 37.7% (129 buildings) of the sample studied reside within the boundaries of the suburban areas of the settlements where industry was historically situated - and this area possesses great benefits (dispersal zones, integrating with the natural environment, greater spatial scale) but also has some downsides (commuting problems, barriers to the city – fortification walls, watercourses, etc.). Only 4.7% (16 buildings) are found in rural areas, where they are often repurposed for tourism, recreation, or specialized cultural uses. A small portion, 0.9% (3 buildings), remains unclassified.

Buildings types

In the first part of the research, we examine general groups (in the subsequent phase, specific industries). Usually, only a portion is utilized of the mixed-use structures, which are the most common and offer the afore mentioned diversity of use. The new users here tend to encounter problems of variety and particularity of different spaces within the premises which may pose challenges to a project's effectiveness and sustainability if the goals are unspecified. (e.g. breweries). Based on the typology of the 350 repurposed industrial buildings characterized in this study, the most common were combined-use buildings (18.1%), followed closely by halls

(17.3%), which is rather an astonishing finding if we perceive multi-storey buildings as being more difficult to convert due to having greater cubic capacity, need to interconnect several levels, etc. Multi-story industrial buildings come third with (16.7%), offering flexible spaces for reuse. Special buildings are also converted as expected, (16.1%), but once more they pose a greater range of challenges, as do larger building complexes (9.9%), such as mining areas. Railway stations with (8.8%), and smaller industrial buildings with also (8.8%) were transformed into CCI use as well. A small portion fell under other categories (3.8%), and 0.6% unspecified. What is particularly interesting here is the phenomenon, which we know for instance from Kulturbanhof network in Germany, of repurposing neglected railway infrastructure that also came to Czechia. (Šenberger, Popelová et al., Hájek, 2018).

New predominate function

The study analyzed the primary functions of repurposed industrial buildings, highlighting their transformation into spaces for production and presentation activities. Cultural and heritage collections (27.5%) represent the most common reuse, followed by exhibition spaces (20.8%) and performance venues (14.9%), which accounts to 63.5% of the sample analyzed as presentation functions. The level of private collection activities, and also public institutions, such as traditional museums, is surprising for research and demonstrates a great interest in preserving traditional values through providing accessibility to neglected industrial structures. The trend of contemporary independent galleries, and collections is also astounding. Meanwhile, other functions like gastronomy are usually affiliated. Performing arts use that is set within this environment follows, such as theatres, stages in general, new circus, recording studios or other cultural halls, dance halls, disco clubs and cultural centers, which also reflect the emerging social trend of the time. Office spaces, artist studios (13.2%) come third along with gastronomy-related uses (13.2%), and workshops and creative studios with (9.1%), which account to approximately one third of the sample representing production. The most common functions are gastronomy, offices, creative workshops, studios, and the very trendy nowadays coworking spaces that focus on innovation, for instance, the TechTower in Plzen and Robota Zlin. Hence, the assumption that abandoned industrial buildings are more important centers for technological innovation has not been fulfilled. On the other hand, (1.5%) remains unclassified.

Figure 1. Karlovy Vary Heating Plant - an example of community use. Photo: Dyzajnpark archive.
Figure 2. The new Phoenix sports hall in the former station check-in hall of the Havířov railway station. Multifunctional use. Photo: Aleš Luzar.

Single-Multi use

Looking at the analysis results regarding the single-multi use of repurposed buildings, over half of the structures (56.7% i.e. 194 buildings) are of multiple use and multifunctional in nature with culture, commerce or community activities constructively woven together in one space. According to Mírek and Lényi (Mírek, 2019; Lényi, 2014), multifunctional is better as it contributes to the stability and life of projects. Often, projects that were centered on a single function at genesis tend to broaden their scope over time or even change it flexibly, and this is also related to the professionalization of operations which tend to start at an amateur level (Mírek, 2019). On the other hand, only 42.7% of the buildings (146 structures) can be classified as monofunctional or single purpose buildings, usually food services or something like exhibitions. Unclassified structures only make up a tiny percentage of this figure, precisely 0.6% (2 buildings). This diversity is beneficial for the given communities and is often the result of their collective discourse of the projects (Kašpar, 2024).

5. Conclusion

The relationship between IH and CCI is rather tenuous. If it is not directly speaking about museum's functions, it has to do with the decline of the latter and the absence of appropriate structures and spaces for CCI. Currently, there is not enough construction taking place that reflects the demands of the given communities and individuals who are looking for a space for their activities. CCI employees are not predominantly motivated by the will to conserve industrial heritage as it is. In some cases it could be secondary or a side effect, or even unintended side effect. Preliminary results suggest that over half of the structures are started and held by private individuals in some kind of partnership with the public sphere to a limited extent. Future consideration of support in this direction is appropriate. (Plevoets, Van Cleempoel, 2019; Sidorová, 2020). We can restate that the monitored CCIs functions have fostered employment even during economic crises, excluding the impact of Covid, when, for example cultural facilities were closed, they repeatedly tend to employ youth, display a high dependence on welfare grants, and are to a lesser degree impacted by the outsourcing of labor or the introduction of intelligence automation. Having regard to the fact that they account for 4.5 percent of the EU GDP (Kreativní Česko, n.d), they have ample reasons to be properly funded.

Clearly, the interrelationship between the adaptability of an industrial building and the demands of the new use is one of the most important factors of success in the conversion. The extent and nature of the necessary interventions, triggered by the need for adaptation for new functions, especially for listed industrial buildings, must be a topic of discussion between creators (architects) and conservationists (monuments), owners, and the community. With very low levels of investment, CCIs are able to facilitate the reuse and possible safeguarding of abandoned buildings by providing access to them, which can create the basis for more permanent use in the future.

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Environmental Impact of Reutilising Large Retail Properties: A Case Study from Germany

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Abstract. The existing building stock plays a crucial role in achieving climate protection targets within the construction sector. At the same time, many large retail properties built between the 1950s and 1970s in German city centres are now vacant due to decreasing demands. Repurposing these buildings presents significant opportunities for both social and environmental urban development. From an environmental perspective, life cycle assessments (LCA) provide a comprehensive evaluation of refurbishment measures by accounting for material- and energy-based environmental impacts throughout the extended life cycle of the refurbished building. Recent research has developed methodologies and indicators that highlight the benefits of continued material use compared to demolition and new construction, proving the potential for reducing embodied emissions. Reducing these emissions by retaining existing materials is essential in minimizing the overall emissions associated with buildings. This paper examines the energy- and resource-efficient transformation of large retail properties in German city centres from an environmental perspective. Two vacant inner-city shopping centres serve as case studies, illustrating refurbishment and repurposing concepts. In addition, the environmental impact of refurbishment is compared with a continued use scenario highlighting the importance of energy-efficient refurbishment.

1. Introduction

The refurbishment of existing buildings has been acknowledged by the EU as a pivotal measure in mitigating climate change within the construction sector [1]. At the same time, inner cities face the challenge of adapting to the shifting requirements of urban areas. Major retail properties are particularly relevant due to their size and location and often provide enormous potential for further use in diverse purposes. Due to the loss of the economic necessity of large physical retail spaces in cities, many of these large properties are currently abandoned, yet hold great architectural and identity value for inner cities [2].

Energy-efficient refurbishment results in a reduction in operating energy and thus a reduction in CO_2 emissions during building operation. Moreover, existing materials are largely retained, ensuing a lower material consumption as well as a lower embodied emissions to produce additional materials [3]. Given the extensive amount of waste generated in the construction sector, refurbishment measures can further help to minimize the amount of new waste produced.

The objective of this paper is the systematic assessment of emission savings through energy-efficient refurbishment with the help of an adapted LCA for existing buildings and the systematic assessment of advantages in continued use of materials. Subsequently, the exemplary buildings examined for the paper are presented. By analysing refurbishment scenarios alongside continued use in two case studies, we highlight the potential for emission reductions and savings through refurbishment measures, encompassing both operational energy use and materials perspective.

2. Existing Building LCA

For buildings, LCA has become an established method for quantifying environmental impacts. Standardization following EN 15978 provides the calculation methodologies necessary for evaluating the environmental impact of buildings over their life cycle. Adopting the methodology for new buildings, the life cycle is outlined from material production (Module A), through the use phase (Module B), and concluding with the end-of-life phase (Module C). Additional information outside the life cycle is covered in Module D [4].

When assessing environmental impacts of existing buildings, the life cycle modules described above must be adapted. Continued use of parts of the building as well as the dismantling measures required to carry out refurbishment measures result in impacts which no longer correspond to the standardized new construction approach. Nor is it possible to demonstrate the advantage of continuing to use parts of the building without adapting the life cycle concept. Numerous scientific publications have worked on a variety of approaches for the assessment and environmental evaluation of refurbishment measures in existing buildings. [5–14]

In recent research the advantages of continued use of materials have been described in terms of the Avoidance Potential (AP) and the Sustained Emissions (SE) [3]. The AP defines the maximum possible savings in material emissions achieved through the continued use of an existing building. It results from the sum of the emissions required in Module A for the new construction of an equivalent building and the environmental impacts in Module C for the demolition of the existing building. Both the postponement of demolition emissions and the emissions from constructing a new equivalent building are considered in the AP. Thus, it serves to assign an environmental value to an existing building and is a decision-making tool for dealing with stock buildings. However, its value is theoretical and does not reflect the actual avoided environmental impacts [3, 14].

SE refer to the environmental impacts associated with the production and disposal of materials remaining in the building after a refurbishment. Although the calculation is like the AP, the SE only accounts for the materials that remain in the building after refurbishment. Depending on the degree of refurbishment, different shares of the AP may remain as SE. In the case of demolition and new construction, these emissions are omitted, whereas in the case of energy-efficient refurbishment, a large proportion of the AP is recognized as SE. Consequently, the environmental impact of different refurbishment approaches can be compared.

3. Analysed Objects

To examine the energy- and resource-efficient transformation of large retail properties in German city centres two buildings were environmentally assessed. The two buildings are former department stores that were built in major West German cities in the early 1960s. The buildings have five storeys above ground and two or one basement storey. They are designed as reinforced concrete skeleton constructions. The gross floor areas are 17,500 square metres and 20,525 square metres respectively, the net floor areas are 15,730 square metres and 18,248 square metres respectively.

For decades, both buildings played an important role in a central location in the respective city centre as a shopping location, social meeting point and reference point within the city. Changing consumer habits led to a decline of department stores and lower demand for retail space in city centres. As a result, the longstanding vacancy of the two buildings analysed in this study could only be ended through conversion. Extensive changes had to be made in both buildings as part of the conversion work to mixed-use properties.

This included separating the storeys to allow for different uses on each floor. In both cases, the central stairwells were removed, and stairwells and lifts were created at the edges of the buildings. In addition, large atriums were designed to provide the building with more daylight and fresh air. The foundations and external walls could largely be reused, although external walls had to be replaced on the upper floors of both buildings. Load-bearing columns and interior walls were largely retained and, in some places, reinforced or added to. More than ten thousand square metres of new interior walls were installed to allow a new use in both buildings. The ceiling panelling and floor coverings were renewed, and the old windows were replaced with larger, modern ones. Differences can be seen in the façades and the measures taken to improve the energy efficiency of the buildings. The first object is a listed building, which meant that the characteristic façade elements had to be retained and only thinner insulation without reaching an energetic standard was possible. In the second building, more than twice the insulation thickness could be achieved, and parts of the façade were greened. Both the supporting structure and the roof coverings had to be at least partially renewed in both buildings. The technical building equipment had to be completely renewed to meet the requirements of the new utilisation.

4. LCA Results

To calculate the LCA results, a life cycle inventory was drawn up for both buildings once the objective and scope of the study had been defined. For both buildings, with six and seven storeys respectively and a total net floor area of over 30,000 square metres, all building components were analysed. Thus, the parts which were demolished as part of the measure, those parts which retained in the building and the newly installed parts had to be assessed in detail, resulting in hundreds of hours of labour. All building components were then transferred to the LEGEP software [15], in which the impact assessment was conducted. Due to the size and complexity of the buildings, more than 800 elements were required to fully describe each building. The results of the impact assessment are based on the life cycle inventory and the German Ökobaudat serves as the data basis for the environmental impacts of the elements. Based on a system developed by the Federal Ministry of Housing, Urban Development and Building and within the framework of the German Assessment System for Sustainable Building (BNB), the service life of the components is assumed. [16] All results are calculated on the indicator global warming potential (GWP-fossil), the net floor area of each building and a life cycle of 50 years.

4.1 LCA Results for Material Emissions

Initially, the LCA results of the material emissions of the construction measures are presented, this serves to illustrate the SE and the AP. For this purpose, the left-hand side of Figure 1 shows the Sustained Emissions, meaning the material emissions that remain in the building due to the continued use of building parts in both Modules A and C. The right-hand side shows the incurred material emissions as the actual material emissions from deconstruction (Module C_0), the production of the refurbishment measure (Module A_0), the emissions generated over the life cycle for the replacement of materials (Module B4) and the total deconstruction after 50 years (Module C_{50}). The sustained emissions of around 3.6 and 4.1 kg CO_2-eq/m^2a are higher than the material emissions from the production of the refurbishment measures. The deconstruction emissions in C_0 and C_{50} are significantly lower than the production of materials. The figure illustrates the significance of the potential savings in grey emissions by continuing to use parts of the building.

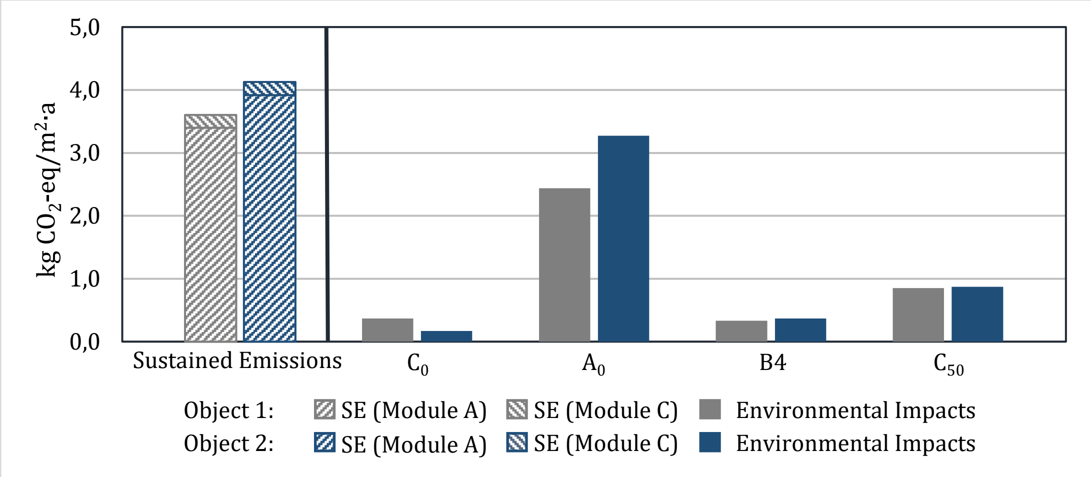

Figure 1. Material emissions - comparison of actual emissions with sustained emissions

To illustrate the AP, Figure 2 shows how the potential changes over the construction process in terms of emissions. Firstly, the existing avoidance potential of the buildings before the refurbishment measure was analysed, which is given as a reference value of 100%. Large parts of the buildings were demolished to conduct the refurbishment, meaning that a lower AP remained in the building during the project as illustrated in Figure 2. The SE correspond to around 59% of the earlier potential for Building 1 and around 66% for Building 2. The refurbishment adds materials to the building system and the resulting AP of the buildings is higher than the potential before the measure. For Building 1, the AP increases to 110% compared to the initial state and for Building 2 to 129%. The difference in both analyses is attributed, among other factors, to the better energy standard of Building 2.

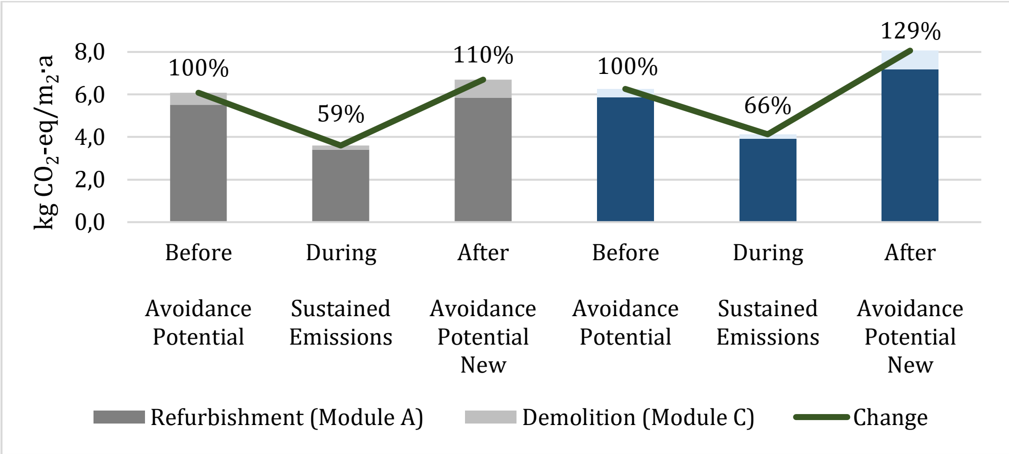

Figure 2. Development of avoidance potential and sustained emissions over the course of construction

A further assessment is the analysis of material emissions at component level. Figure 3 shows the emissions from the individual components of the buildings. This shows that different levels of emissions occur in different building components for both buildings. For example, the total emissions for the external walls in Building 2 are significantly higher than in Building 1, while the floorings in Building 1 trigger significantly higher emissions than in Building 2. Internal walls generate the highest emissions in both buildings, which are explained by the changes in use and the creation of new room layouts.

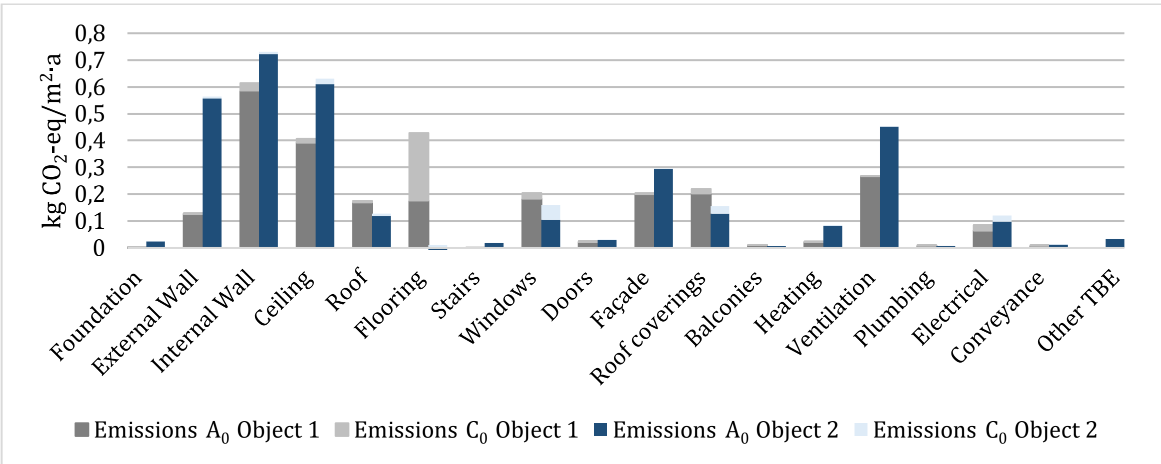

Figure 3. Comparison of material emissions for building components

4.2 LCA Results including operational energy

In addition to analysing material emissions, the reduction of operational energy consumption in life cycle assessments continues to be the greatest potential for reducing overall emissions. For this purpose, the operating emissions were determined for both buildings over an observation period of 50 years and added to the material emissions. Figure 4 displays the total emissions of the life cycle modules analysed, whereby the size of the circles shows the total emissions. For both buildings, the operational energy use (module B6) generates the largest proportion of the total emissions, generating 91% for building 1 and 78% for building 2. Most notably, the reduction in total emissions is linked to the quality of the energy-efficient refurbishment, while the share of material emissions increases with the optimization of energetic performance.

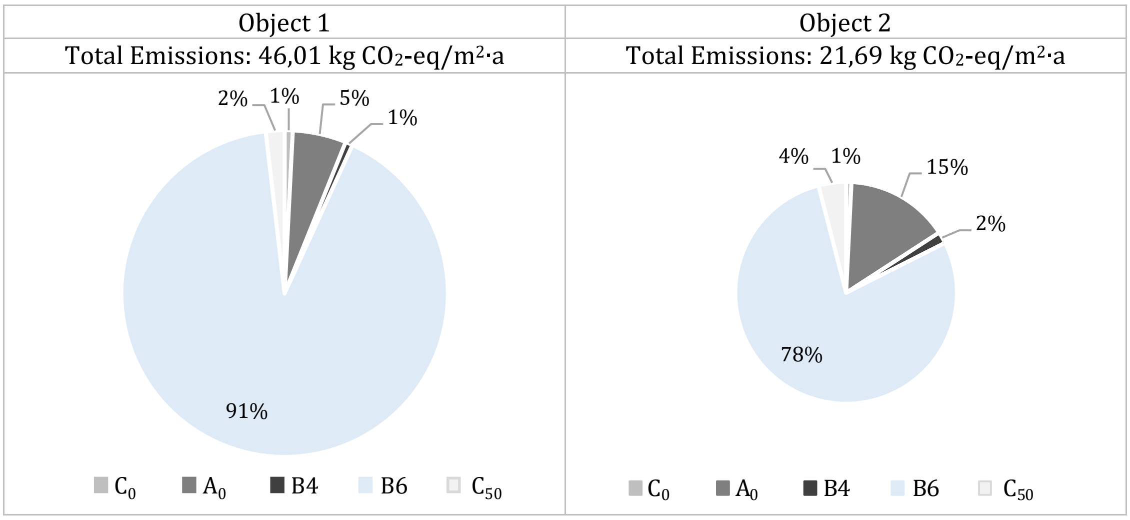

Figure 4. Comparison of total emissions for both objects over the life cycle

In a further calculation, Figure 5 shows the cumulative emissions from material emissions and operating emissions of the buildings over the life cycle. Further, variants of a continued use without refurbishment are also shown for both buildings. The material emissions from the production of the refurbishment measure are amortised environmentally after around 1.76 years for Building 1 and 1.80 years for Building 2. From this point onwards, more operating emissions are saved than the material emissions generated for the entire refurbishment measure. Over the life cycle, assuming continued use, around 122 kg CO_2-eq/m^2·a are released for Building 1, while the refurbished variant releases around 46 kgCO_2/m^2·a. The difference is even greater for Building 2, where 111 kg CO_2-eq/m^2·a are triggered for continued use and 21.7 kg CO_2-eq/m^2·a for the refurbished variant. This reiterates the critical role of refurbishment, emphasizing both the necessity of refurbishment itself and the potential for further emission reductions by minimizing operational energy consumption.

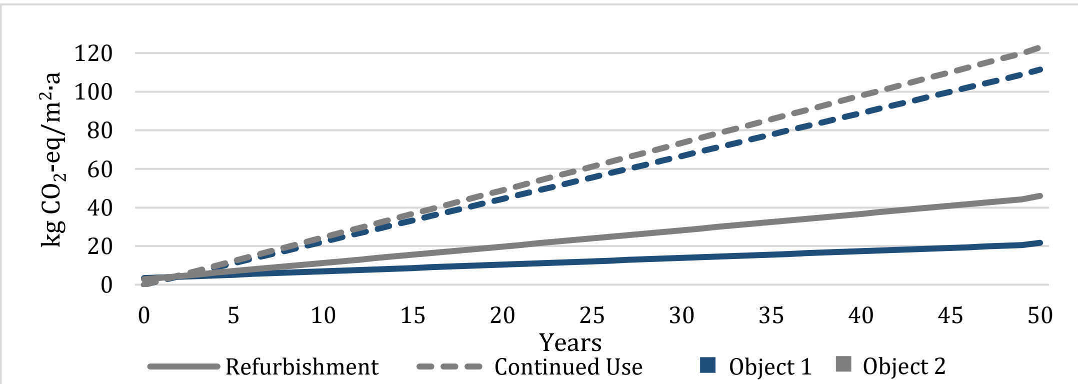

Figure 5. Cumulative emissions over the life cycle of the realised refurbishment measures

5. Conclusion

The findings of this study highlight the critical importance of sustained emissions (SE) for the comprehensive evaluation of the building stock, particularly in the context of refurbishment and revitalization buildings. SE enable a consistent, life-cycle-based comparison of alternative development strategies and are especially relevant for assessing the environmental implications of continued use versus demolition and new construction. Incorporating SE into the assessment framework thus enables a more comprehensive and quantifiable comparison between renovation and demolition followed by new construction.

While new buildings meet high energy efficiency standards, their environmental benefits are often offset by emissions associated with material production and construction. In contrast, deep refurbishment significantly extends the service life of existing buildings and reduces embodied and operational emissions while minimizing new material inputs. This is particularly relevant for vacant large-scale retail properties in inner-city areas, where early and comprehensive refurbishment proves advantageous from both environmental and urban development perspectives. These structures often carry historical and spatial significance within the urban fabric; thus, adaptive reuse emerges as a key strategy to reduce ecological and economic burdens while maintaining urban continuity.

However, significant methodological challenges remain when comparing renovation with demolition and new construction, particularly in contexts with heritage constraints or limited refurbishment options. Nonetheless, studies such as [3, 5, 8] consistently highlight the environmental benefits of refurbishment, primarily due to lower operational energy demands (B6), which substantially reduce life cycle emissions compared to new buildings. To generalize findings across the broader building stock, further research is required, considering construction methods, usage profiles, and energy standards.

The proposed methodologies support the systematic assessment of refurbishment impacts and facilitate comparability of LCA results across different cases. They are not limited to specific building types and can be applied more broadly. Additional investigations are planned to evaluate their applicability to diverse building typologies, including both residential and non-residential buildings.

Acknowledgments

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Digital Building Logbook Technology: Insights from the BUILDCHAIN EU project

Decentralized Knowledge Graph for construction data management

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Abstract. The construction industry produces large volumes of diverse data, making effective management and seamless interoperability among stakeholders essential. Conventional centralized data management methods often lead to data silos, reduced transparency, and limited traceability. This paper examines the use of the OriginTrail Decentralized Knowledge Graph for managing construction data, incorporating blockchain and linked data principles to enhance data integrity, provenance, and accessibility. The architecture of a Decentralized Knowledge Graph-based system is outlined, its benefits for improving collaboration are discussed, and the ways in which semantic data integration can support better decision-making are explored. A case study is included to illustrate the practicality of this approach, with advancements in data interoperability, security, and automation demonstrated. The findings indicate that significant potential is held by Decentralized Knowledge Graph to drive the digital transformation of the construction industry, fostering a more transparent, verifiable, and efficient data ecosystem.

1. Introduction

The construction sector is inherently complex, involving multiple stakeholders who generate and manage large volumes of data. Traditional centralized data management systems often lead to inefficiencies, data fragmentation, and a lack of transparency, which ultimately leads to data ownership issues and can hinder collaboration and decision-making. The potential for new services based on holistic data management through the “big picture” approach allows for much new value to be unlocked if these problems can be overcome or mitigated.[7], [8], [9]

This paper investigates the role of Decentralized Knowledge Graph in tackling these challenges by enabling secure, verifiable, and interoperable data management. Synergizing knowledge graphs as symbolic AI with neural AI and blockchain technology, the Decentralized Knowledge Graph ensures data integrity while facilitating seamless collaboration. The paper presents an architectural framework for a Decentralized Knowledge Graph-based construction data management system and evaluates its impact through a case study.

2. Challenges in construction data management

2.1 Data fragmentation

One of the challenges in construction data management is the presence of isolated information repositories across various stakeholders. Different entities involved in the construction process – such as architects, engineers, contractors, suppliers, and building owners – often maintain their own separate databases or systems for storing and managing data. These isolated repositories can lead to significant inefficiencies, as information becomes fragmented and difficult to access or synchronize. This fragmentation creates inconsistencies, as each party may be working with outdated or incomplete data, which can result in miscommunication, delays, and costly errors. Furthermore, without a unified system for data sharing, it becomes challenging to ensure that all stakeholders are working from a common source of truth, undermining collaboration and the overall success of the project. The lack of seamless data exchange between these silos prevents the realization of the full potential of digital tools and technologies that could improve project efficiency, reduce risks, and enhance decision-making across the lifecycle of a building.[2], [3], [10]

2.2 Limited transparency

Many traditional data management systems in the construction industry lack built-in mechanisms for ensuring transparency and tracking the provenance of data. As a result, it becomes challenging to verify the authenticity and integrity of data and information, which can lead to significant issues such as miscommunication, data manipulation, and disputes among stakeholders. Without clear visibility into where data originated from, who modified it, and when, stakeholders may struggle to trust the information being shared. This lack of transparency can result in conflicting interpretations of project requirements, delays in decision-making, errors in execution and any possible other negative impacts during design, development and operation. Furthermore, when changes to data are not properly tracked or documented, the risk of unauthorized alterations or inconsistencies increases, making it difficult to determine accountability and undermining the reliability of the data. In the absence of a robust system for tracking data provenance, disagreements over accountability and responsibility can arise, complicating project management and increasing the potential for legal or financial disputes. Ensuring transparency and a clear audit trail of all data modifications is crucial for fostering trust, collaboration, and efficient resolution of issues across the construction project lifecycle.[2], [3], [11]

2.3 Challenging traceability

Tracking changes and verifying the history of data modifications is crucial for ensuring compliance and maintaining quality control in construction projects. Regulatory standards, safety codes, and contractual requirements often demand that all aspects of a project be meticulously documented and traceable. This includes changes to designs, materials, inspection results, and any updates made throughout the construction process. However, conventional data management systems often fall short in providing a comprehensive and immutable record of these modifications. Many traditional systems are not equipped to automatically log or audit changes, which means that important details—such as who made a change, when it was made, or the rationale behind the modification—may be overlooked or lost. This lack of a clear, tamper-proof record makes it difficult to verify whether all necessary changes were made in compliance with relevant regulations and project specifications. It also opens the door for potential errors or disputes regarding responsibility and accountability. Without a reliable and transparent system for tracking data history, construction projects face increased risks related to compliance, quality control, and potential legal or financial liabilities. Therefore, it is essential to implement systems that not only track changes but also ensure that all modifications are securely logged, verifiable, and resistant to tampering.[2], [3], [12]

2.4 Security risks

Security remains a major concern in the construction industry, especially when handling sensitive project information such as building designs, procurement records, contracts, bill of material and cost estimates, and other proprietary data. This type of information is not only critical to the successful execution of a project but also highly valuable, making it an attractive target for competition. Unauthorized access to sensitive data can result in data breaches, intellectual property theft, or the manipulation of key project details, which could have severe consequences on project outcomes. Cyber threats such as hacking, phishing attacks, or ransomware can further compromise the integrity of project data, leading to financial losses, delays, and even damage to a company's reputation. In addition to external threats, there is also the risk of internal breaches, where authorized individuals may misuse or improperly access sensitive information. Given the increasingly digital nature of construction projects and the vast amounts of data being shared among multiple stakeholders, ensuring robust cybersecurity measures is crucial. A failure to safeguard project data can lead to compromised decisions, delays in the construction process, or non-compliance with regulations, ultimately affecting the project's success and the safety of the final structure. As construction projects become more complex and interconnected, securing sensitive project information must be a top priority to preserve data integrity, protect stakeholder interests, and ensure the safe and efficient delivery of the project.[2], [3]

3. Decentralized Knowledge Graph

3.1 Overview and key concepts

A Decentralized Knowledge Graph is a distributed data structure that combines the advantages of knowledge graphs and blockchain. It enables structured data representation while maintaining security, accessibility, and trust. OriginTrail Decentralized Knowledge Graph presents a global, open data structure composed of interlinked Knowledge Assets structured in a Resource Description Framework (RDF) knowledge graph hosted on an open, permissionless decentralized network of Decentralized Knowledge Graph nodes.[1]

The Decentralized Knowledge Graph consists of three layers. The Decentralized Knowledge Graph layer stores the knowledge graph data, distributed across the network in separate graph database instances. The blockchain layer interfaces with various blockchains, such as NeuroWeb on Polkadot, Base, and Gnosis to manage node relations and implement trustless protocols. Lastly, the application layer includes both Artificial Intelligence (AI) driven and traditional applications that use the OriginTrail Decentralized Knowledge Graph in their data processes. OriginTrail Decentralized Knowledge Graph architecture is presented in Figure 1.[1]

The Decentralized Knowledge Graph (DKG) supports both, public and private knowledge. The public graph is replicated across all network nodes, allowing data discoverability through a decentralized index and enabling search queries. Private graphs are hosted by individual nodes and connected to the public graph. Once information is discovered in private graphs, data exchange protocols, like a data marketplace protocol, facilitate data retrieval.[1]

The protocol actors in the OriginTrail Decentralized Knowledge Graph (DKG) consist of knowledge publishers, who publish knowledge; data holders that help uphold the DKG and are incentivized with tokens; and knowledge users, who query and utilize the knowledge. Both knowledge publishers and knowledge users can be humans or AI agents, enabling a more dynamic and intelligent exchange of information within the network.[1]

Datasets published to the Decentralized Knowledge Graph (DKG) are called Knowledge Assets and are associated with cryptographic identities (DID) of the publishers, stored on the blockchain. Knowledge Assets are structured as graph-linked data, have cryptographic fingerprints (Merkle roots) on the blockchain, are timestamped, and are replicated across peers. This ensures that each graph vertex or edge can be verifiably linked to its publisher DID and dataset, enabling data source and integrity verification.[1]

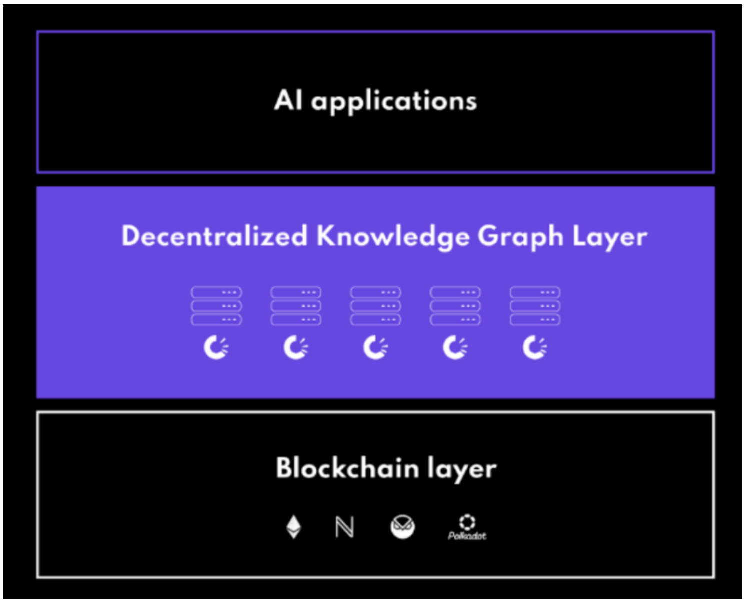

Figure 1. Decentralized Knowledge Graph architecture

3.2 Role of blockchain

Blockchain technology is integrated into Decentralized Knowledge Graph to enhance data provenance and immutability, ensuring each piece of knowledge can be verified in terms of source. Smart contracts regulate data access and updates, ensuring trust and security among stakeholders. Blockchains are trust networks established to enable reliable computation through decentralized consensus, operating as a global, dependable computer.[1]

3.3 Role of knowledge graphs

Knowledge Graphs are structured representations of real-world entities and their relationships. They enable the linking of diverse data sources, making information more accessible and contextually meaningful. By utilizing ontologies and semantic relationships, Knowledge Graphs support advanced querying, reasoning, and automation, improving decision-making and data interoperability in construction management.[1]

4. Core components of the architecture for a construction data management system powered by a Decentralized Knowledge Graph

4.1. Knowledge Assets

A Knowledge Asset is an ownable entity in the Decentralized Knowledge Graph (DKG) with verifiable provenance, representing any object, concept, or entity. It is identified by a unique Uniform Asset Locator (UAL) and consists of graph data, cryptographic proofs, and a non-fungible token (NFT) on the blockchain. Knowledge Assets can be public or private, with public data replicated across the network and private data stored within the asset owner's domain. Assertions within Knowledge Assets are cryptographically verifiable on the blockchain.[4]

4.2. Edge Nodes

Edge Nodes facilitate diverse decentralized AI applications within the DKG. They provide configurable components for the creation and publication of Knowledge Assets, secure private data storage, and the development of Decentralized Retrieval Augmented Generation (dRAG) pipelines to retrieve and utilize verifiable knowledge from the DKG, leveraging various AI models. With flexible configurations, Edge Nodes accommodate a wide range of technologies and user interfaces, facilitating advanced neuro-symbolic AI projects and solutions.[5]

4.3. Core Nodes

Core Nodes ensure reliable access to the DKG and maintain network stability. Full participation requires staking 50,000 TRAC tokens, with larger stakes leading to higher chances of earning rewards. Core Nodes may also serve as Gateway Nodes, publishing data to the DKG. These nodes offer services for a fee, with competitive pricing mechanisms encouraging active contributions. This balance of incentives ensures a stable and equitable ecosystem for the DKG.[6]

5. Case study: Implementing Decentralized Knowledge Graph in BUILDCHAIN project

5.1 Project background

BUILDCHAIN is a project focused on enhancing the management and sustainability of the construction industry through the development of a Digital Building Ledger (DBL). This system brings together a wide range of building data, including administrative details, performance metrics, and environmental impact, ensuring transparency and efficiency across the building's lifecycle. By integrating interoperable platforms, BUILDCHAIN supports data sharing, facilitates real-time monitoring, and advances the EU's climate-neutral targets for 2050. Its emphasis on data integrity, security, and usability enables better decision-making, fostering sustainability in the built environment.

5.2 Implementation steps

The implementation of the BUILDCHAIN project follows a structured approach, divided into several phases that ensure scalability, flexibility, and seamless integration of decentralized technologies. The core of this implementation revolves around the integration of the Decentralized Knowledge Graph (DKG) to manage building data and enhance interoperability across stakeholders.

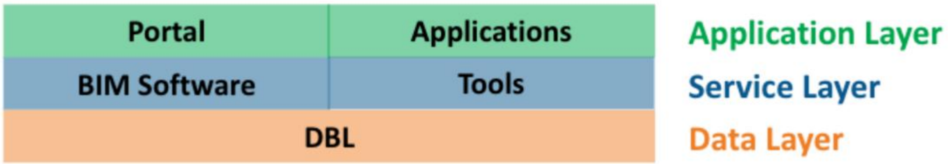

Figure 2. Three-layered high level BUILDCHAIN architecture

The process begins with defining a flexible and scalable system architecture composed of three primary layers: the Application, Service, and DBL Layers. This approach ensures long-term sustainability and easy integration of new tools. The DBL Layer incorporates the Decentralized Knowledge Graph (DKG) to organize building data into knowledge banks, providing a secure, decentralized data management system. APIs are then developed to connect the DKG with external data sources, allowing for seamless, real-time data flow that supports informed decision-making. The Service Layer leverages APIs, smart oracles, and other tools to optimize building performance, ensure compliance, and incorporate real-time external data. Blockchain integration guarantees data integrity and security, with multichain functionality enhancing scalability and resilience. The user interface in the Application Layer is designed to be intuitive, allowing stakeholders easy access to relevant data and services. Rigorous validation and testing are carried out to ensure the system's functionality, performance, and scalability across various use cases. Finally, the system is designed for continuous evolution, allowing for regular updates and integration of new data types to remain adaptable to the changing needs of the construction industry.

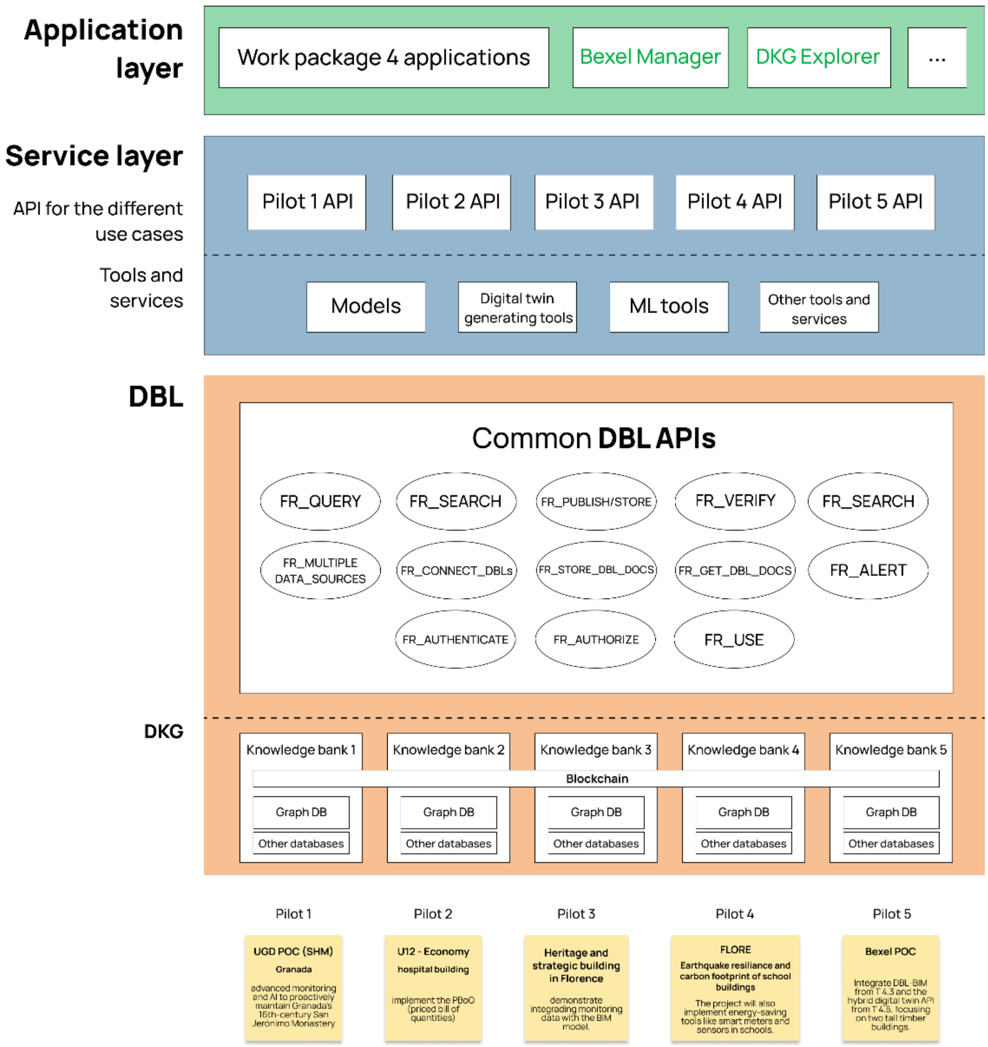

Figure 3. BUILDCHAIN high-level architecture with a blockchain supported DKG DBL foundation

5.3 Key outcomes

5.3.1. Improved data interoperability

The integration of the OriginTrail Decentralized Knowledge Graph facilitated smooth data exchange among all stakeholders involved in the building lifecycle. This integration ensured that data from various sources—such as architects, contractors, owners, and regulators—was unified and connected. The DKG provided a consistent, standardized view of building data, eliminating data silos and making information readily available and reliable for all parties. This approach enhanced collaboration and decision-making, allowing for more efficient workflows and reducing errors due to miscommunication.

5.3.2. Enhanced data security

Leveraging blockchain technology, the DKG implemented a robust verification system that secured the integrity of building data. By fingerprinting data cryptographically, blockchain ensured that information could not be tampered with or altered without detection. This tamper-proof feature provided a secure, transparent mechanism for storing and sharing sensitive data, such as building designs, material lists, and compliance documentation. As a result, all stakeholders could trust the authenticity and accuracy of the data throughout the building's lifecycle, minimizing risks associated with unauthorized access or data corruption.

5.3.3. Optimized predictive maintenance

By combining neural AI into the DKG for a neuro-symbolic approach, the system could analyze both historical and real-time data to identify patterns and predict potential issues. Predictive models provided valuable insights into the condition of the building, enabling proactive maintenance planning. This helped to detect early signs of wear and tear or operational inefficiencies, allowing building managers to address issues before they became critical. As a result, maintenance activities were better planned, leading to reduced downtime, extended building lifespans, and optimized resource usage, ultimately contributing to cost savings and improved building performance.

5.3.4. Streamlined compliance monitoring

The DKG also simplified compliance checks by organizing all relevant regulatory data in a standardized format. Real-time access to this data allowed regulators and project stakeholders to easily monitor compliance with building codes, safety standards, and environmental regulations. This standardized approach reduced errors and delays in compliance verification, ensuring that buildings met all required standards throughout their lifecycle. The transparency provided by the DKG fostered trust among stakeholders, as it ensured that all necessary regulatory information was readily accessible and up to date.

6. Conclusion

This study highlights the significant advantages of integrating Decentralized Knowledge Graph in construction data management. The OriginTrail DKG facilitates seamless data interoperability by unifying diverse data sources into a single, connected knowledge base, enhancing collaboration among stakeholders and improving decision-making. By incorporating blockchain technology, the DKG ensured robust data security, offering tamper-proof verification and fostering trust in the accuracy and integrity of critical building data. The integration of AI and machine learning enabled predictive maintenance, reducing downtime and extending the lifespan of buildings. The DKG also streamlined compliance monitoring by organizing regulatory data in a standardized format, simplifying the verification process. Although challenges remain, the findings from this case study demonstrate the potential of DKGs to drive digital transformation in the construction sector, offering opportunities for enhanced efficiency, security, and sustainability in building management.

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The BUILDCHAIN platform for trustable knowledge management in construction – Use Cases, Architecture and Design

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Abstract. The Architecture, Engineering, and Construction (AEC) sector faces persistent challenges—including data fragmentation, insufficient trust mechanisms, interoperability hurdles, and inefficiencies in tracking building lifecycle information. Although Digital Building Logbooks (DBLs) have emerged to address these issues, they often suffer from incomplete, inconsistent, and unverifiable data, complicating decision-making for diverse stakeholders such as property owners, facility managers, policymakers, and investors. Furthermore, the lack of standardized, secure data exchange impedes collaboration and automation throughout the various stages of a building's lifecycle.

In response, the Horizon Europe–funded BUILDCHAIN project proposes a secure, decentralized, and interoperable platform that leverages blockchain and decentralized knowledge graph (DKG) technologies to establish a tamper-proof, verifiable, and semantically structured repository of building-related data. This aligns with both the European Green Deal and ISO 19650 standards, ensuring regulatory compliance and enhancing data-driven decision-making. The platform's integrated components include blockchain for immutable records, smart contracts for automated compliance, and DKG for semantic interoperability. Additionally, blockchain smart contracts enable privacy-preserving authentication and access control, while a Smart Oracle Network solution validates and integrates real-time IoT sensor data and external data sources for reliable on-chain information, thereby supporting data-driven sustainability targets throughout the building lifecycle.

This paper presents the BUILDCHAIN platform, it's use cases, multi-layered architecture, and data management approach, covering functional and non-functional requirements, ontology mapping, and a decentralized infrastructure for transparent DBL management. It also explores the platform's smart contract logic, and oracle implementation, concluding with insights on its impact for building lifecycle management, sustainability, and innovation in the construction sector.

1 Introduction

The Architecture, Engineering, and Construction (AEC) sectors often face challenges with data fragmentation, lack of trust, interoperability issues, and inefficiencies in tracking building lifecycle information. The Digital Building Logbooks (DBL) initiative aims to enhance data verifiability and strengthen collaboration among stakeholders—including property owners, facility managers, policymakers, and investors—to support informed decisions on energy efficiency, sustainability, and regulatory compliance. However, DBLs still face challenges with incomplete and inconsistent data, limiting their full potential to drive meaningful improvements across the building lifecycle. Furthermore, the absence of standardized and secure data exchange mechanisms restricts collaboration and automation at various stages of a building's lifecycle. To address these challenges, the BUILDCHAIN project, funded under the Horizon Europe research and innovation program, envisions a secure, decentralized, and interoperable platform that enhances trust, automation, and efficiency in managing building data. The project aims to integrate blockchain and decentralized knowledge graph (DKG) technologies to create a tamper-proof, verifiable, and semantically structured repository of building-related data. This vision aligns with the broader goals of the European Green Deal and ISO 19650 standards, ensuring regulatory compliance and data-driven decision-making. By providing real-time visibility into material usage and lifecycle impacts, BUILDCHAIN empowers stakeholders to make more sustainable choices, reducing waste and overall environmental footprints in the construction sector.

This paper introduces the BUILDCHAIN platform, detailing its use cases, multi-layered architecture, and data management approach. The role of blockchain-based solutions in enhancing privacy-preserving authentication and access control will be discussed. Furthermore, the proposed Smart Oracle Network solution will be discussed, which validates and integrates real-time IoT sensor data and external data sources to provide reliable and trustworthy on-chain data. BUILDCHAIN approach aims to streamline building lifecycle management, support sustainability efforts, and drive innovation in the construction sector. As a result, the platform fosters more holistic resource utilization throughout the building lifecycle.

The structure of the paper is as follows. In Section 2, the Use Cases of the BUILDCHAIN Project are presented, while in Section 3, the Functional and Non-Functional Requirements of the Use Cases are presented. Section 4 presents the data management approach, followed by the ontology mapping explanation in Section 5. Section 6 presents the decentralized infrastructure of the DBL, followed by the platform's architecture in Section 7. The software engineering approach for the BUILDCHAIN platform is presented in Section 8 while the smart contract role is presented in Section 9, followed by the BUILDCHAIN's oracle implementation that is presented in Section 10. Lastly, Section 11 concludes the paper.

2 Use Cases of the BUILDCHAIN Project

The BUILDCHAIN project is built around twelve specific use cases, each tackling a key challenge in the digital management of buildings. Together, they showcase how the platform leverages blockchain, DKGs, and AI-driven analytics to enhance interoperability, efficiency, and security within AEC industry.

Life-Cycle Analysis (LCA) and Carbon Footprint Calculations emphasizes the importance of transparent environmental reporting by integrating Life-Cycle Analysis (LCA) methodologies with blockchain and DKG technologies. By ensuring that material data, energy consumption metrics, and emissions records are both traceable and immutable, BUILDCHAIN empowers stakeholders—ranging from project owners to regulatory bodies—to make responsible sustainability decisions. The result is an end-to-end overview of a building's carbon footprint, which streamlines the adoption of eco-friendly materials and processes.

Reasoning Architecture for Large-Scale Building Management employs advanced data analytics and predictive modeling to reduce operational costs and extend asset lifespans. By integrating real-time monitoring with smart contracts, this approach streamlines maintenance processes, automates resource allocation, and promotes proactive problem-solving. Property owners and facility managers benefit from a unified view of multiple buildings, allowing them to address potential issues before they escalate and improving overall efficiency and occupant satisfaction.

Structural Health Monitoring (SHM) and Anomaly Detection is central to safety and longevity in the built environment. In this use case, AI-driven sensor fusion combines data from various sources—such as vibration, temperature, and strain sensors—to paint a comprehensive picture of a structure's condition. By recording and validating all sensor outputs on a blockchain, BUILDCHAIN guarantees reliability and transparency. Automated anomaly detection further strengthens preventive maintenance strategies, minimizing service disruptions and guarding against catastrophic failures.

Earthquake and Climate Resilience Digital Twin merges digital twin technology with predictive AI models to mitigate the persistent threats posed by earthquakes and extreme weather events to buildings and infrastructure. By generating dynamic replicas that simulate climate scenarios and seismic activity, BUILDCHAIN leverages real-time sensor data and historical records stored on a blockchain, providing verifiable proof of structural performance and informing preparedness measures. This proactive strategy is vital for safeguarding occupants and the broader urban environment as climate patterns continue to evolve.

Smart Heritage Building Monitoring employs the BUILDCHAIN framework to preserve the unique character and structural integrity of historic and cultural heritage sites by tracking environmental conditions, detecting changes in structural health, and managing restoration processes securely. Decentralized identity management ensures only authorized personnel can access sensitive data, with every modification fully traceable—enabling conservation teams to collaborate confidently. This approach provides a robust digital archive that safeguards these sites for future generations.

Bayesian Updating in Design Processes enables modern building designs to adapt iteratively to new requirements or insights. By employing Bayesian updating within decentralized knowledge graphs, BUILDCHAIN ensures each design revision is tracked and informed by data-driven probabilities rather than guesswork. As a result, stakeholders can spot design errors and inefficiencies early, leading to streamlined, cost-effective construction. This transparent approach encourages cross-disciplinary collaboration and ultimately delivers better-performing buildings.

Self-Attentive Sensing addresses the challenges of indiscriminate sensor data collection, which can cause information overload, high storage costs, and analytical blind spots. In this use case, BUILDCHAIN integrates decentralized AI decision-making models to determine when and where data should be captured, prioritizing critical insights over raw data volume. This selective approach allows building management teams to maintain high-fidelity monitoring, reduce operational expenses, and enhance the clarity and actionability of recorded information.

Flood Control and Precipitation Monitoring addresses the immediate hazards and long-term infrastructure strain posed by urban flooding. In this use case, BUILDCHAIN employs IoT-enabled rainfall and hydrological sensors to collect timely, accurate data that is securely stored on the blockchain. Predictive analytics then support informed decisions on water diversion, drainage, and emergency response strategies. As a result, municipalities benefit from a verifiable foundation for flood control measures, enhancing overall resilience.

Post-Catastrophic Intervention System ensures swift and well-coordinated recovery when catastrophic events occur. This BUILDCHAIN feature maintains an immutable record of post-disaster assessments, documenting building damage, repair schedules, and resource allocation. By automating the verification of key recovery steps, stakeholders can rely on accurate, tamper-proof data to guide their decisions. Such transparency and coordination significantly expedite rebuilding efforts and reduce overall recovery costs.

Construction Economics and Cost Estimation Accurately estimating and managing construction costs is challenging in any project, let alone on a large scale. Through real-time data captured on the blockchain, BUILDCHAIN provides an auditable, reliable cost analysis from design through completion. Smart contracts facilitate secure, automated transactions—preventing fraud and ensuring clear financial accountability. Contractors, investors, and other interested parties gain continuous insight into budget allocations and potential savings.

Deep Renovation Workflows often involve multiple stakeholders and intricate logistical chains. In response, BUILDCHAIN's platform securely tracks material usage, verifies compliance at each milestone, and transparently records progress. By automating approvals and payments through smart contracts, administrative burdens are reduced and potential disputes minimized. This centralized-yet-decentralized model facilitates effective collaboration, ensuring large-scale retrofit projects stay on schedule and within budget.

Increasing Operational Energy Efficiency is a pivotal factor in both operational costs and environmental impact. By integrating IoT-based energy management systems with blockchain validation, BUILDCHAIN supports continuous monitoring and optimization of energy usage. The platform's analytics help identify inefficiencies—like equipment left running off-hours or suboptimal HVAC settings—enabling timely interventions. These insights align with regulatory standards and foster long-term sustainability, creating greener and more cost-effective buildings.

3 Functional and Non-Functional Requirements of the Use Cases

Each use case within the BUILDCHAIN project has specific functional and non-functional requirements that ensure its successful implementation (See Table 1). Functional requirements (FR) define the essential operations and behaviors expected from the system, setting clear objectives for data collection, information processing, and decision-making mechanisms. Non-functional requirements (NFR) describe the quality attributes—such as performance, security, and scalability—that the platform must maintain to operate reliably under varying conditions. These requirements also influence system architecture choices, technology stacks, and resource allocation strategies, ensuring that solutions are robust enough to handle the diverse and evolving demands of large-scale building and infrastructure management.

Use Case	**FR**	**NFR**
LCA and Carbon Footprint	Secure logging of material data, emissions tracking, automated reporting	High accuracy, compliance with sustainability regulations
Large-Scale Building Management	Real-time monitoring, predictive analytics, automated maintenance scheduling	High availability, scalability, fault tolerance
Structural Health Monitoring (SHM)	AI-driven anomaly detection, blockchain-based logging	Low latency, real-time data processing
Earthquake and Climate Resilience Digital Twin	Digital twin modeling, integration with climate data sources	High computational performance, real-time analysis
Smart Heritage Building Monitoring	Secure conservation data storage, controlled access permissions	Data integrity, secure identity management
Bayesian Updating in Design Processes	Probabilistic modeling, iterative design improvements	Efficient data handling, compliance with ISO standards
Self-Attentive Sensing	AI-driven filtering of sensor data, smart alerting mechanisms	Efficient data storage, AI model interpretability
Flood Control and Precipitation Monitoring	IoT sensor integration, automated warning systems	Resilient infrastructure, reliable sensor connectivity
Post-Catastrophic Intervention System	Damage assessment logging, resource allocation automation	Disaster resilience, fault tolerance
Construction Economics and Cost Estimation	Real-time cost tracking, automated financial reporting	Financial accuracy, data security
Deep Renovation Workflows	Progress tracking, milestone validation using smart contracts	Process automation, secure auditing
Increasing Operational Energy Efficiency	AI-driven energy optimization, smart metering	Energy-efficient data processing, compliance with green standards

Table 1: Functional and Non-Functional Requirements for Various Use Cases

4 Ontology and Data Management Approach for BUILDCHAIN

To achieve seamless interoperability and trust in digital building data management, the BUILDCHAIN project employs an ontology-driven approach integrated with blockchain and DKGs. The ontology framework provides a structured and standardized method for data representation, ensuring compatibility with established Building Information Modeling (BIM) standards, including Industry Foundation Classes (IFC) [1] and ISO 19650 [2].

The ontology facilitates semantic data integration, enabling different stakeholders to query and retrieve relevant building data across multiple platforms. This approach supports context-aware decision-making by linking diverse datasets such as structural health monitoring records, lifecycle emissions data, and regulatory compliance documentation [3, 4].

The DKG serves as the backbone of BUILDCHAIN's data management strategy, allowing for trustless data exchange and verifiable provenance. Data integrity is maintained using blockchain-based immutability, ensuring that all modifications and access requests are transparently recorded. Additionally, smart contracts provide secure authentication and role-based access control, preventing unauthorized modifications while maintaining data privacy.

The ontology also supports automated compliance checking, enabling real-time validation of building regulations and sustainability standards. By integrating AI-driven analytics, stakeholders can derive insights from building performance data, facilitating predictive maintenance and optimizing energy efficiency. The combination of ontology-driven data structuring, blockchain security, and decentralized governance establishes BUILDCHAIN as a pioneering platform for future-proof digital building logbook management.

5 Ontology Mapping in BUILDCHAIN

Ontology mapping in BUILDCHAIN ensures seamless interoperability and data consistency across different sources and stakeholders within the DBL ecosystem. The system integrates multiple domain-specific ontologies, including IFC, Brick Schema, Building Topology Ontology (BOT), Semantic Sensor Network (SSN), and Smart Applications REFerence Ontology (SAREF). Each of these ontologies addresses a specific aspect of building information management, such as structural components, energy efficiency, sensor data, and digital twin integration.

To enable semantic interoperability, BUILDCHAIN employs ontology alignment and reasoning mechanisms that allow mapping between IFC-based BIM models and knowledge graph representations. For instance, a structural element in IFC can be mapped to BOT ontology concepts, allowing enriched semantic queries across different building management systems. Similarly, energy efficiency data collected via IoT sensors is modeled using SSN and SAREF ontologies, ensuring that all performance metrics are standardized and comparable. The DKG plays a key role in semantic integration, allowing different data sources to be linked and queried using RDF (Resource Description Framework) and Linked Data principles. This approach enables automated reasoning, which enhances data discoverability and usability. For example, when querying a building's carbon footprint, the system can infer energy consumption trends, link them to sustainability benchmarks, and automatically trigger alerts if inefficiencies are detected.

Ontology mapping also facilitates regulatory compliance checks. By aligning BUILDCHAIN's data with ISO 19650 and BuildingSMART standards [5], the system ensures that construction and renovation activities meet both local and international sustainability criteria. These mappings make it possible to automate sustainability reporting, reducing manual workload for engineers and auditors.

6 Decentralized Infrastructure for Transparent Digital Building Logbook Management

BUILDCHAIN introduces a decentralized infrastructure that enables transparent, verifiable, and immutable management of DBLs. This infrastructure is built upon blockchain technology and DKG ensuring secure data access, enhanced traceability, and seamless interoperability between stakeholders in the AEC industry.

The blockchain layer functions as the immutable foundation of the BUILDCHAIN platform, storing hashed records of all building-related transactions. Smart contracts automate critical processes such as certification verification, compliance enforcement, and contract execution, minimizing manual interventions and improving efficiency. The blockchain smart contracts enable decentralized identity verification enabling stakeholders to securely authenticate and maintain control over the data [6, 7].

The DKG extends the capabilities of traditional DBLs by providing context-aware semantic integration. This enables stakeholders to query and retrieve structured building data, ensuring interoperability across heterogeneous data sources, including IoT sensors, digital twins, and environmental impact assessments. The DKG also facilitates dynamic linking of data entities, allowing for real-time updates and knowledge sharing without centralization.

Together, these decentralized components form a transparent, scalable, and secure infrastructure for managing DBLs, reducing fraud, increasing efficiency, and fostering trust in digital building data management.

7 Architecture of the BUILDCHAIN Platform

The BUILDCHAIN platform is designed using a modular, multi-layered architecture to address both functional and non-functional requirements while ensuring scalability, security, and interoperability. The architecture consists of three primary layers as depicted in Figure 1.

Data Layer: This layer handles data acquisition and storage, integrating BIM, IoT sensor networks, environmental data, and structured metadata. It employs DKG to organize data in a semantic, machine-readable format. The blockchain-based ledger ensures that all data modifications are immutable and verifiable.

Processing and Computation Layer: This layer is responsible for executing smart contracts, running AI-driven analytics, and managing decentralized identity authentication. Smart contracts automate certification validation, regulatory compliance, and transaction execution across multiple stakeholders. AI-driven models process real-time sensor data, enabling predictive maintenance and anomaly detection in structural health monitoring and energy efficiency management.

Application and User Interface Layer: This layer provides interfaces for stakeholders, including building owners, policymakers, engineers, and regulators. The user interface integrates data dashboards, compliance monitoring tools, and AI-based recommendations for energy optimization and risk assessment. Role-based access control (RBAC) ensures secure and efficient user authentication.

By adopting this layered approach, the BUILDCHAIN platform provides a transparent, secure, and scalable digital building logbook solution that enhances efficiency, ensures compliance, and fosters trust in the AEC industry. The technological design considerations ensure high availability, fault tolerance, and interoperability. The modular architecture allows for seamless integration with existing BIM platforms and regulatory databases, ensuring compliance with ISO 19650 standards. Security is enforced through blockchain immutability, cryptographic data signatures, and distributed ledger consensus mechanisms.

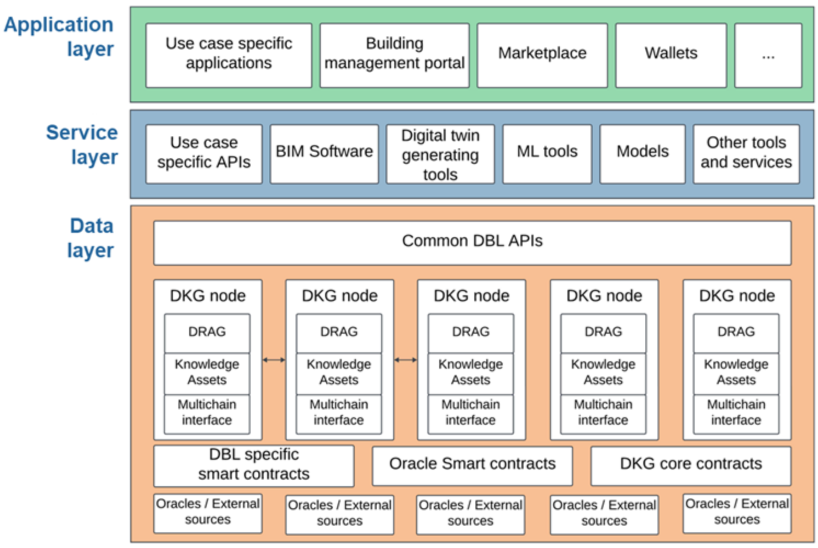

Figure 1: BUILDCHAIN layered architecture

8 Software engineering approach for the BUILDCHAIN platform

The BUILDCHAIN's three-layered architecture ensures flexibility and scalability while maintaining decentralized data integrity. The Application Layer provides user-facing applications for interacting with DBLs, while the Service Layer includes APIs, tools, and smart oracles for seamless data processing. At the core lies the DBL Layer, which hosts the DKG and a blockchain network to support data integrity and interoperability.

Ontologies play a crucial role by providing structured knowledge representation that enables semantic interoperability among stakeholders. Several ontologies are integrated into the system, including IFC for BIM data exchange, Brick Schema for metadata representation of smart buildings, and BOT for structuring building components. These ontologies support the DKG, which serves as a repository for Knowledge Assets (KAs)—digital representations of buildings, materials, environmental impact data, and structural health monitoring (SHM) information. The DKG incorporates Decentralized Identifiers (DIDs) to uniquely identify buildings while leveraging Verifiable Credentials (VCs) to store building certifications and compliance records securely [8].

The smart contracts implemented in BUILDCHAIN automate and enforce agreements between stakeholders, ensuring data integrity verification, automated compliance checks, and enabling a tokenized economy for construction data exchange. Smart contracts validate environmental impact data, log carbon footprint reports in the DBL, and streamline digital tendering and procurement processes using NFT-based credentials stored on the blockchain. These contracts help establish trust in construction projects by providing immutable, verifiable records of compliance with regulatory frameworks such as ISO 19650.

Smart oracles function as trusted data providers, bridging off-chain and on-chain data sources. They play a key role in fetching real-time IoT sensor data related to structural integrity, energy consumption, and environmental parameters. Oracles continuously update the DBL with validated data, enabling predictive maintenance, risk assessment, and real-time decision-making. This integration ensures that BUILDCHAIN remains adaptive to changing conditions, such as weather variations, seismic activity, and material degradation.

The BUILDCHAIN platform offers several advantages over traditional construction data management systems. It enhances interoperability by ensuring standardized data formats and ontologies, guarantees immutable and verifiable records through blockchain-based DBLs, and automates compliance verification through smart contracts. Additionally, its decentralized governance model, facilitated by DIDs and oracles, removes the reliance on central authorities for data validation. These features collectively drive greater efficiency, transparency, and security in the construction sector, making BUILDCHAIN a transformative solution for sustainable and intelligent building lifecycle management.

9 Smart Contract Logic in BUILDCHAIN

Smart contracts in BUILDCHAIN automate transactions and enforce agreements between different stakeholders, ensuring data integrity, security, and efficiency. These contracts are deployed on a blockchain network and interact with DBL records, IoT sensor data, and external regulatory frameworks to provide tamper-proof verification mechanisms. One of the core applications of smart contracts in BUILDCHAIN is automated compliance verification. When new construction materials, energy performance data, or maintenance records are logged in the DBL, a smart contract validates the data against predefined rules and standards (e.g., EU Energy Performance of Buildings Directive (EPBD), LEED certification, and BIM interoperability guidelines). If the data meets compliance requirements, the smart contract automatically certifies it and stores a verifiable proof on the blockchain. If it fails, the system flags the entry for review, preventing non-compliant materials or processes from being integrated into construction workflows.

Another key functionality of smart contracts is digital tendering and procurement. BUILDCHAIN enables a tokenized economy where construction services, certifications, and digital assets (e.g., BIM models, IoT data, and environmental reports) are represented as Non-Fungible Tokens (NFTs) or VCs. Contractors can submit bids on projects, and once an agreement is reached, a smart contract executes payments, tracks deliverables, and records milestones in a transparent and auditable manner. Additionally, automated warranty management is another significant application. Smart contracts are used to track the lifecycle of building components, ensuring that warranties remain valid until pre-specified conditions (e.g., structural safety thresholds or energy performance guarantees) are met. If an issue arises (such as sensor-detected structural degradation), the smart contract automatically triggers a maintenance request and notifies relevant stakeholders. The use of multichain compatibility allows BUILDCHAIN to integrate Ethereum-based smart contracts (ERC-20, ERC-3643, ERC-721, ERC-1155) while ensuring cross-chain interoperability with private Hyperledger Fabric networks for enterprise-level governance and compliance tracking.

10 Oracle Implementation in BUILDCHAIN

In BUILDCHAIN, a Smart Oracle Network that ensures data integrity and quality assurance is designed, implemented and deployed, to enable smooth interoperability between off-chain and on-chain logged data. Our Decentralized Oracle Network (DON) aggregates multiple data sources to provide reliable and trustworthy on-chain data, integrating seamlessly with the BUILDCHAIN ecosystem. This approach advances the state-of-the-art by including an innovative reputation-based consensus mechanism that incorporates subjective criteria, focusing on Quality of Experience (QoE). The proposed method evaluates the performance of Data Aggregators and Oracle nodes based on context-specific needs of smart contract consumers. Our focus so far is on two categories: a) weather and climate data, and b) building element costs. Regarding the latter, we foresee significant market potential for such new data feeds, extending the current oracle networks.

Our implementation integrates oracle data and IoT sensor data into a decentralized framework, ensuring proof of delivery and optimizing cost efficiency by means of InterPlanetary File System (IPFS)-based off-chain storage, which provides a flexible and agnostic approach for diverse use cases. The architecture supports continuous IoT data streaming on-chain, enabling automated control mechanisms and maintaining blockchain transparency and security. The system retrieves and verifies oracle data, resulting from aggregation from multiple providers and stores it in IPFS. Additionally, real-time streaming of IoT sensor data is stored in IPFS for cost-effectiveness and tamper-resistance. An external adapter retrieves these data, queries smart contracts for control parameters, and executes control decisions based on predefined conditions, ensuring compliance with smart contract rules.

An example that demonstrates the use of DONs in BUILDCHAIN is the enhancement of energy efficiency in buildings and the improvement of occupant comfort. Sensor data is collected with respect to energy consumption, occupancy, and temperature. Oracle data is collected with respect to environmental conditions, and is validated by the DON. Oracle and sensor data is stored in the DKG and blockchain to ensure accuracy. This data feeds the Digital Twin of the building, and thus contributes to the optimization of the energy use while maintaining occupant comfort by adjusting the system in real-time. The proposed solution can support the DBL economy by incorporating green certificates and digital product passports for buildings, promoting sustainability and ensuring compliance with environmental standards.

11 Conclusion

The BUILDCHAIN platform represents a transformative approach to addressing critical challenges in the AEC sector through innovative integration of blockchain, DKGs, smart contracts, and AI-driven analytics. By creating a secure, decentralized, and interoperable ecosystem, BUILDCHAIN ensures reliable data management, enhances collaboration, and streamlines decision-making across various stages of a building's lifecycle.

The twelve targeted use cases clearly illustrate the diverse capabilities of the platform, from enhancing sustainability and reducing carbon footprints to ensuring structural safety and operational efficiency. The integration of ontology mapping guarantees semantic interoperability across diverse data sources, enabling precise, context-aware data retrieval and real-time automated compliance checks aligned with industry standards such as ISO 19650. Smart contracts further enhance the platform's robustness by automating regulatory compliance, procurement processes, warranty management, and facilitating secure financial transactions. Additionally, the advanced implementation of oracles ensures continuous integration and validation of real-time data streams, bolstering predictive analytics for structural health monitoring, energy management, and risk assessment.

Ultimately, BUILDCHAIN sets a new benchmark for transparency, efficiency, and trustworthiness in building lifecycle management, aligning with broader sustainability goals and regulatory frameworks like the European Green Deal. Through its comprehensive technological infrastructure, BUILDCHAIN significantly reduces manual inefficiencies and errors, thereby accelerating innovation and fostering a more resilient, efficient, and sustainable built environment.

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Revolutionizing Construction Economics: A BIM-Based Framework Utilizing Decentralized Knowledge Graph, Smart Contracts and Oracles

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Abstract. The BUILDCHAIN study for construction economics aims to transform cost estimation and project planning in the construction industry by integrating advanced technologies, including Building Information Modelling (BIM), Decentralized Knowledge Graph (DKG), smart contracts and oracles. This study highlights the need for a detailed cost database covering various building elements at different stages of the project, using both real and estimated data from reliable sources. It aims to increase the accuracy of cost estimation, improve risk management and facilitate better collaboration between stakeholders. Traditionally, the construction industry relied on manual and expert cost estimation methods, often leading to inefficiencies and inaccuracies. The adoption of BIM technology, driven by the European Directive 2014/24/EU, has opened up new possibilities for data-driven project planning, significantly improving visualization, collaboration and resource optimization. The proposed methodology leverages the capabilities of BEXEL Manager for cost management, including DKG for data transparency. Oracles enhance this system by providing real-time, verified data, ensuring that cost estimates are up-to-date and in line with market trends. This integrated approach improves the accuracy and reliability of cost data and supports EU sustainability and energy efficiency goals. Future research will focus on developing standardized practices for data collection and management, advancing data ontologies, and further refining the innovative reputation mechanism in the Smart Oracle Network. By addressing these challenges, the BUILDCHAIN project aims to create a more transparent, efficient and sustainable construction industry, ultimately leading to improved project outcomes and increased trust between stakeholders.

1. Introduction

In the BUILDCHAIN for construction economics study (1), we aim to enhance the accuracy of cost estimation throughout various phases of building construction projects. It involves the establishment and use of a comprehensive cost database for building elements across different project types and stages, incorporating real and calculated values obtained from authoritative sources, such as national construction cost standards within the EU (e.g., DIN 276, ÖNORM B 1801, NEN 2699), the European Construction Cost Information System (Eurostat), verified supplier quotations, and anonymized historical project data validated through BIM-based analysis.. The functionalities include accessing detailed information on installed materials and building elements, obtaining and storing elements code list, and generating a detailed bill of quantities (BoQ) to facilitate precise cost estimation and project planning.

The proposed methodology integrates advanced cost management functionalities provided by BEXEL Manager—a comprehensive BIM-based tool developed by one of the consortium partners—with modern technologies such as the Decentralized Knowledge Graph, Smart Contracts, and Oracles.

2. State of the Art (Background on Construction Economics, Decentralized Knowledge Graph, Smart Contracts, Oracles)

2.1 Background on Construction Economics

The construction industry presents a key economic sector for the national economy. In addition to its direct contribution to gross domestic product (GDP), it also plays an important role in the development of infrastructure such as roads, railways, buildings and energy facilities, which provides multiplier effect to other sectors of the economy. For the last 5 years the construction sector in Europe consistently generated from 9,5 to 11,1% of the EU27 GDP per year (2).

Historically, cost estimations in the construction industry have depended on manual calculations, considering referenced projects and historical data and the expertise of the individuals. This approach is often time-consuming and dependent on the specialist’s availability on the market as well as verified information about the prices on materials and workforce. As a result, multiple errors and incontinences in prices affected the overall result and caused budget overruns or delays.

Introduction of Building Information Modelling (BIM) has impacted the economics of construction by improving efficiency and cost management. BIM in general contributes to better visualization of projects, more effective collaboration between stakeholders and more accurate cost estimation, allowing for an optimal use of resources and a reduction in the overall project cost. In some cases, utilization of BIM in construction projects reduced time needed for cost estimation up to 80% (3). Besides this BIM technology helps to visualize the project better and facilitates the efficient collaboration of all parties that leads, at the end, to reducing time, solution optimization and overall cost reduction.

2.2 Role of the Quantity Surveyor in BIM-Driven Cost Estimation and Management

The adoption of BIM technology stimulated by the European Directive 2014/24/EU (4), has created new possibilities and horizons for construction professionals, and particularly quantity and cost surveyors. The shift towards the digital and data-driven approach in project planning and execution empowered quantity surveyors to utilize project data that before were unavailable or incomplete, and the overall processes slow and resource-intense.

The role of quantity surveyors in construction has developed significantly throughout the last decades. It is critical for the successful management of construction projects in many ways: managing costs, minimizing discrepancies between estimated and actual costs, providing information for tendering and procurement, optimizing project costs and identifying potential financial risks for the project. All these tasks are very sensitive to any mistakes.

The first task is to obtain reliable and complete data from the project that right now takes the biggest part of the time designated for project cost estimation. At the end it is compiled of BIM model, drawings in different formats, text and table documents as well as documents in non-machine-readable formats. To verify all this huge pile of information takes time and experience as well as patience and precision.

The next critical task of quantity surveyor is to compare cost estimation to the market level and to verify that prices are not significantly different from market levels. One way to overcome information incompleteness and verify project cost estimation is to use historical data or verified data from other projects. Therefore, construction companies collect and preserve construction data for future references and to be able to provide a more cost accurate estimation. And this is where transparency is missing. Every company has part of the data for specific types of projects or a particular region they are operating, but no one has a clear picture of prices on the global or at least regional level. The development of a reliable and robust database can make the construction market more transparent and will help to reveal hidden construction costs where they appear.

2.3 Decentralized Knowledge Graph

Knowledge graph is a way of organizing complex information that helps track connections between different pieces of information in various domains such as search engines, natural language processing, health, life science, and supply chain management, enhancing search results and data analysis (5). Unlike traditional Knowledge Graph , which are typically centralized and managed by a single authority, the Decentralized Knowledge Graph (DKG) operates without a central authority. It is maintained by multiple network participants who contribute to trust and data integrity through blockchain-based consensus mechanisms. Data is distributed across a global network of decentralized nodes, enabling secure, transparent, and efficient sharing and utilization of knowledge among diverse stakeholders..

The DKG's graph structure enables the system to establish a sophisticated network of data points, interlinking various events and triggers with semantic standards that ensure meaningful data interoperability. This structure, backed by a public decentralized ledger, records all events, making them verifiable and trustworthy. Events like updating the structural integrity data or implementing energy-saving measures are not just internal system functions but are also entries on the DKG, creating a rich, query-able web of information.

The innovation part of the DKG will embed the DBL design integration that is highly likely to meet BIM interoperability and ISO/GS1 standardization requirements. The comprehensive ontology and data collection can provide further advances in innovation aspects that are currently not yet envisaged (both in the area of tokenomics and new value generation from the overall embedded data in the DKG).

2.4 Smart Contracts

A smart contract is a self-executing digital agreement with the terms directly written into code. Smart contracts are stored and managed on blockchain networks, which ensures that they are transparent, immutable, and automatically enforceable once the specified conditions are met. Smart contracts facilitating project management together with improvement trust among stakeholders. This technology has a potential use in such areas as tendering and bidding processes, where system reduces the risk of bid manipulation, in supply chain management to track delivery, cost and quantity of the materials, for reporting automation and data security and integrity (6).

2.5 Oracles

Oracles facilitate querying, verifying, and relaying external data into the blockchain ledger and smart contracts. They process both structured and unstructured data to achieve consensus and connect with external databases. Oracles can function on-chain or off-chain, with off-chain state channels ensuring fast, secure, and cost-effective data transfers. ChainLink is a hybrid Decentralized Oracle Network (DON) that combines on-chain and off-chain elements for DeFi applications, using an aggregation-based consensus algorithm and requiring specific hardware for nodes (7). ChainLink is the preferred choice for BUILDCHAIN due to its decentralized, hybrid on and off-chain capabilities, and integration with Trusted Execution Environments (TEEs), ensuring secure and authenticated data feeds. However, it has some limitations, such as the lack of filtering among data providers and potential vulnerabilities in its staking method. A reputation mechanism could address these issues by filtering data providers and enhancing data reliability. Research in the field of oracles and reputation mechanisms is expanding (8), with current approaches focusing on oracle-level reputation, while they lack reputation on data aggregators and metrics involving Quality of Experience (QoE) (9).

3. Proposed Approach (DKG, BIM, Smart Contracts, Oracles)

3.1 DKG

While construction economics focuses on cost optimization and efficient resource allocation to maintain high performance, the DKG offers a trusted, decentralized infrastructure that empowers stakeholders across the construction value chain. By enabling seamless access to verifiable historical data—such as expenses, budgets, and performance metrics—the DKG facilitates peer-to-peer analysis, informed decision-making, and improved collaboration.

Whenever a dataset, financial record, or any other relevant metric is generated—such as through tools like BEXEL Manager—it is published on the DKG. This ensures that validated, tamper-proof information is immediately accessible for future cost calculations and planning. As more data is added, the DKG evolves into a growing, decentralized foundation of knowledge, supporting increasingly precise and efficient construction economics over time.

3.2. BIM

The proposed methodology integrates advanced cost management of BEXEL Manager, a comprehensive BIM-based tool, with DKG, Smart Contracts and Oracles. This integration enables an efficient and structured approach to cost analysis by leveraging existing BIM data and automating key processes. The work flow capitalizes on BEXEL Manager’s ability to manage and structure information about building elements from the BIM model, serving as a foundation for further data enrichment and analysis. The proposed approach utilizes a Digital Building Logbook (DBL) framework that is aiming to collect a comprehensive data throughout the building lifespan.

To enable the proposed work flow, dedicated APIs have been developed within the BUILDCHAIN project, to establish seamless interoperability between BEXEL Manager, DKG, Smart Contracts and Oracles.

In the beginning, a specialist enters the BEXEL Manager through an intuitive user interface (UI), and import cost classifications from the DKG. From the other side cost resources are collected via Smart Contracts and Oracles, as presented in Figure 1.

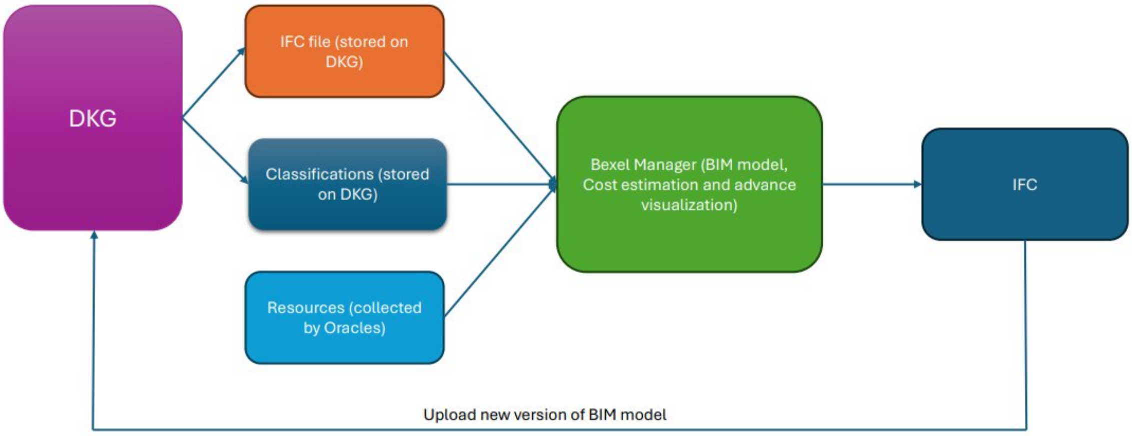

Figure 1. Data flow

Using existing BEXEL Manager functionalities, the next step involves advanced cost calculations based on imported classifications and mapped cost resources, as shown in Figure 2. Costs are then automatically assigned to BIM elements, enabling color-coded visualizations and interactive dashboards. The updated BIM model, exported as an IFC file, is securely stored on the DKG via a dedicated API.

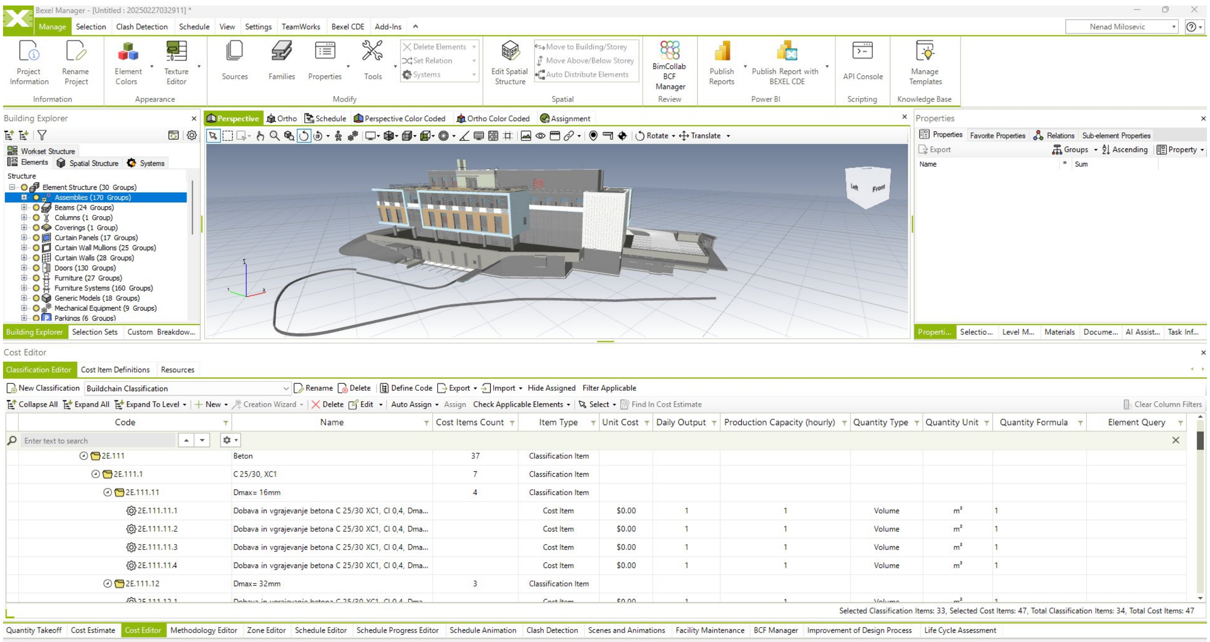

Figure 2. Imported Cost Classification from DKG

BEXEL Manager connects to both DKG and Oracles as part of the integration layer. From DKG, it fetches cost classification data through a JSON-based API, which is transformed into cost models for the BEXEL Manager Cost module. Oracles, on the other hand, provide real-time cost data from various databases, accessed via HTTPS requests from IPFS. These integrations ensure that BEXEL Manager uses accurate, up-to-date data for analysis. Upon completing the cost analysis, results are embedded in the IFC file and published to DKG as a new version through the available API endpoint.

3.3 Smart contracts and Oracles

We anticipate strong market demand for new data feeds and the growth of decentralized applications (dApps) in the marketplace. Our proposed solution integrates oracles that provide real-time cost data for building elements—currently absent from existing Oracle Networks—enhancing transparency and accessibility in construction-related financial insights. In BUILDCHAIN we propose a novel Smart Oracle Network solution extending the state of the art. Specifically, we build on top of ChainLink implementing a novel reputation mechanism that includes data aggregators and involves subjective criteria (e.g., QoE) in the reputation mechanism. This would allow the inclusion of various data types in the Oracle network for future purposes (such as text, images, maps and other forms). Furthermore, we extend ChainLink by integrating an automated data retrieval and storage mechanism that utilizes Oracle External Adapters to fetch pricing data from various external providers. This data is processed, structured into a human readable file (e.g. JSON, .csv and other formats), and stored on IPFS for decentralized and immutable access. The SC initiates the process by providing a country code parameter, which triggers the retrieval of pricing data from external providers through Oracle External Adapters.

Accordingly, we assess the performance of Data Aggregators and associated Oracle nodes based on the quality of user experience they provide to Smart Contract (SC) consumers, by introducing a "QoE score" for building-related cost data (i.e. price data), a subjective metric provided by each SC consumer, based on precision, completeness, and value for money. The QoE score acts as a comprehensive tool reflecting the SC consumer experience. This solution contributes to improved cost-effectiveness, circularity, and climate resilience in the construction sector by providing transparency, security, and immutability in contractual management, automating SLAs, facilitating seamless data integration, and improving stakeholder satisfaction. Moreover, our proposed solution extends the DBL economy as it can support the generation of green certificates and digital product passports for buildings, promoting sustainability and compliance. The complete information flow is depicted in Figure 3.

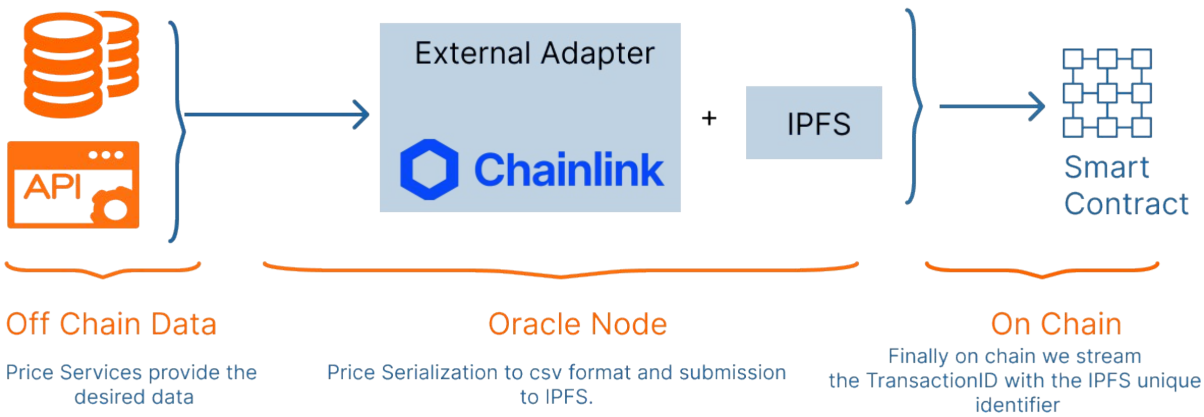

Figure 3: Information Flow of Price Data

4. Conclusions and Future Work

The integration of advanced BIM tools, such as BEXEL Manager, with emerging technologies—including blockchain, DKG, Smart Contracts, and Oracles—marks a significant advancement in the evolution of construction economics. This integrated approach has the potential to substantially enhance the accuracy and efficiency of cost estimation, resource intensity, project planning, and risk management throughout the construction lifecycle. By leveraging standardized and verified data from BIM models, combined with the data governance and automation capabilities provided by DKG, Smart Contracts, and Oracles, the system offers a transparent and reliable platform for informed decision-making.

The growing importance of BIM-based quantity surveying and cost estimation, particularly in alignment with the European Directive 2014/24/EU, underscores the urgent need for digital transformation within the construction sector. However, transitioning from traditional, often manual practices, to a fully digitalized and interoperable ecosystem, remains a persistent challenge. The implementation of Smart Contracts can streamline project management, tendering, and procurement processes, mitigating risk and fostering greater trust among stakeholders. Concurrently, the integration of Oracles and DKG enables the use of real-time, validated cost data, which reduces market discrepancies and helps to control cost overruns.

Future research should prioritize the continued development of the Smart Oracle Network, with particular attention to refining its innovative reputation mechanism. Equally critical is the development of standardized code lists, data collection protocols, and data management frameworks, alongside robust data ontologies that ensure semantic consistency across platforms.

Establishing these standards will lay the foundation for an industry-wide framework that enables stakeholders to seamlessly exchange and validate project budgets. In turn, this will contribute to greater economic efficiency, reducing costs, penalties, and inefficiencies resulting from poorly managed processes or inaccurately estimated expenses—ultimately improving social welfare across the construction ecosystem.

Looking forward, the creation of standardized practices for data interoperability will be pivotal for the broader digital transformation of the construction industry. In this context, the Digital Building Logbook (DBL) will play a foundational role in fostering a unified data environment that aligns with BIM interoperability requirements and international standards such as ISO and/or GS1. Moreover, the establishment of robust legal and regulatory frameworks will be essential to ensure the effective implementation, governance, and long-term sustainability of these digital innovations.

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Digital Tool for Managing Deep Renovation Disruptions – *A Use Case from the BUILDCHAIN Project*

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Abstract. The transition towards energy-efficient and sustainable renovations in the built environment poses considerable challenges in managing disruptions for occupants and end users. This abstract introduces Use Case 11 from the BUILDCHAIN project, which focuses on implementing a Service Disruption Assessment Tool designed to evaluate, mitigate, and optimize deep renovation workflows. The study specifically analyses renovation interventions in heritage school buildings located in Florence.

The tool integrates data-driven simulations to assess key disruption categories, including utility outages, internal environmental impact, and physical space constraints. By leveraging quantity data, structured renovation schedules, and real-time impact assessments, the system supports project managers, facility managers, and final users in planning, monitoring, and adjusting renovation processes to minimize operational disruptions. The tool is particularly valuable during the preliminary design stages, as it enables stakeholders to visualize renovation timelines and anticipate the potential impacts on end users during construction.

A pilot demonstration at the "Vittorio Veneto" elementary school in Florence, Italy, used the tool to analyze preliminary renovation activities. The results show the tool effectively optimizes scheduling, predicts operational disturbances, and provides actionable recommendations. Project managers can access full disruption reports and quantitative data to inform end users about upcoming renovation work.

The findings from this case provide insights into how to assist final users during deep renovation projects. This aims to improve data interoperability, knowledge sharing, and reproducibility in the construction sector. The work highlights the role of digital tools in facilitating energy-efficient renovations while considering

1. Introduction

The transition towards energy-efficient and sustainable renovations in educational buildings presents significant challenges in minimizing disruptions for occupants and building operators. The Deep Renovation Workflow Management Tool, further developed within the BUILDCHAIN project, provides a structured digital approach to assess and optimize renovation planning while mitigating disruption impacts.

This study presents Use Case 11, applying the tool at the Vittorio Veneto School in Florence, Italy. The tool enables the simulation of renovation activities, estimates disruption impacts, and supports decision-making for project managers, facility managers, and final user

2. Case Study: Vittorio Veneto School in Florence

As written in the Italian "Codice dei Beni Culturali – D.Lgs 42/2004 Art. 3 Comm. 1" for the protection of cultural heritage, conservation consists of activities based on adequate knowledge of the building to identify cultural heritage assets and ensure their protection for public use. For this reason, maintenance in historical buildings requires a deep understanding of all construction phases and historical periods to respect the pre-existences.

2.1. Case Study History

The first step for the maintenance project starts with a careful study of the documentation available concerning the building's past and recent history consulting archive sources [2]. Vittorio Veneto is a complex of historical buildings located in Via San Giuseppe 9-11 in the Santa Croce district in Florence. According to archive sources, these building has been constructed in the XVI century as private rustic houses used to storage agricultural tools and products, with a garden on the back for vegetable growing. Some years later the owner decided to transform these buildings into a unified aristocratic residence.

In the 1915 the big residence passing into the Municipality property who decided to transform it as Technical Female School. For the conclusion of the contract, the Municipality drew up a statement of consistency with plants and numbered rooms that represent the first graphic technical documentation of the building. The same plants are taken back in 1916 for another private evaluation of property accompanied by a general plan of the area and cadastral maps. From the plan it is understood that the structures present at the time were exactly those currently existing, unless the connection between the two blocks of the building. After the 1966 flood, the City of Florence plans to rehabilitate the Santa Croce district and drew up a series of maps from which it is possible to deduce that the school structure, excluding just one part, is already notified as a historical asset.

In fact, it had already been bound on 08/07/1936 according to the law of 20 June 1909 n. 364, that it is one of the first Italian laws on the protection of cultural heritage. This law established the protection of buildings of historical and artistic value, preventing their modification or demolition without authorization. In the 1970s, the Municipality of Florence decided to renovate all existing buildings to host the schools Città Pestalozzi, Vittorio Veneto and Tommaseo. The consistent restauration and consolidation work began some years later and ended at the end of 1990. In recent years other work has been done to improve insulation and structural consolidation of roofs.

2.2 Case study Description

The previous and following information of the school have been taken from an old collaboration between the Department of Civil and Industrial Engineering in Pisa and the Municipality of Florence. Vittorio Veneto school complex was created by combining several separate buildings and it is therefore possible and useful to separate it into blocks to analyse and describe as best as possible. The subdivision is based on a comprehensive structural knowledge of the entire building and respects almost entirely those which are the historical and present functional limits.

Test material and essay has been conducted during a survey campaign on buildings to better understand the vertical and horizontal structure. The vertical structures are mainly made of rough stone masonry mixed with solid bricks, with irregular texture and covered with plaster on both sides. However, block 2C was made with a regular-texture split stone masonry, while the internal walls made at a later stage were made of solid bricks and perforated bricks.

The horizontal structures are different to each other from shape (e.g. slabe floor, timber floor, vault) and materials (e.g. wood, steel, brick and cement). It is possible to understand the complexity of the historical buildings due to the different phase construction and materials. This led once more to underline the need of studying the buildings before planning of new maintenance operations.

2.3 Building Overview

This sub section presents an overview about the case study including the location, building owner and among other aspects needed to identify the school.

- Project Name: BUILDCHAIN - Elementary School "Vittorio Veneto"
- Type of Building: Educational (Heritage Building)
- Building Owner: Municipality of Florence
- Project Location: Via San Giuseppe, 9-11, Florence, Italy
- Project Start Date: 06/03/2025
- Building History: Originally constructed in the early 1500s, later transformed into a school in 1915, with multiple renovations over the centuries.
- Current Challenges: Structural weaknesses, unreinforced vaults, outdated insulation, and inefficient energy performance.

2.3 Renovation Objectives

This sub sections identifies the renovation objectives for the case study which were chosen with the Municipality of Florence.

- Enhance energy efficiency through insulation improvements.
- Minimize disruptions to students, teachers, and staff.
- Preserve the historical integrity of the building.
- Improve occupant comfort and safety through structural reinforcements.

3. Methodology

3.1 Tool Overview

The Deep Renovation Workflow Management Tool follows a structured workflow, integrating insights from previous studies on renovation disruptions such as Tzortzopoulos et al. (2016) [4] and Kassem et al. (2015) [1] . These studies highlight the importance of structured digital methodologies for reducing renovation-related disruptions and optimizing planning strategies.

The tool was developed to simulate renovation disruption impacts across multiple building areas, support decision-making for project managers (PMs), facility managers (FMs), and final users (FUs), and provide quantitative assessments on disruption categories, including utility outages, physical space constraints, and internal environment changes.

The methodology for this study is structured around the application and evaluation of the Deep Renovation Workflow Management Tool within the renovation process of Vittorio Veneto Elementary School under the BUILDCHAIN project.

This approach follows a structured workflow, integrating insights from previous studies on renovation disruptions such as Building Information Modelling to Cut Disruption in Housing Retrofit [4]and BIM in Facilities Management Applications [3] These studies emphasize the importance of structured digital methodologies for reducing renovation-related disruptions and optimizing planning strategies.

The Deep Renovation Workflow Management Tool was developed to simulate the impacts of renovation disruptions across various building areas. It supports decision-making for project managers, facility managers, and end users. The tool provides quantitative assessments on disruption categories, including utilities outages, physical space constraints, and internal environment changes.

3.2. Disruption categories include:

The disruption categories have mentioned above has been taken from previous research but also from internal knowledge from projects and disruption that can happen during a renovation.

- Utilities: interruptions in water, electricity, heating, and gas
- Physical Space: movement limitations, storage constraints
- Internal Environment: noise, dust, air quality, visual discomfort
- Traffic: restricted internal circulation

3.3. Data Setup & Scenarios

Initial setup involved defining renovation scope, building data, and expected disruptions. Two scenarios were considered:

Scenario 1: Site preparation, roof insulation, window/door reinforcements, façade insulation, window/door replacements

Scenario 2: All activities from Scenario 1, plus additional structural reinforcements

3.4. Outputs

The outputs from the tool are the followings:

- Disruption heatmaps
- Severity scores (1 = low, 4 = high)
- Renovation timelines

3.5. Processing Disruption was evaluated based on

The process to evaluate each activity are considered with the following criteria, in which background internal research have been done from RINA's industrial projects activities. Some aspects involved are:

- Activity duration
- Affected building areas
- Sensitivity of building use
- Disruption weights

4. Results

The tool provided insights into disruption severity, activity scheduling, and mitigation. Given that Vittorio Veneto is a functioning kindergarten and primary school, minimizing disruption is critical. Simulations enabled proactive planning to maintain educational quality and protect heritage features.

4.1 Scenarios Simulation

The simulation performed with the Deep Renovation Workflow Management Tool for Vittorio Veneto Elementary School offers valuable insights into the renovation's impact, scheduling efficiency, and mitigation strategies. The tool provided a structured approach for predicting disruptions, enabling stakeholders to enhace renovation phases while minimizing inconvenience to building occupants.

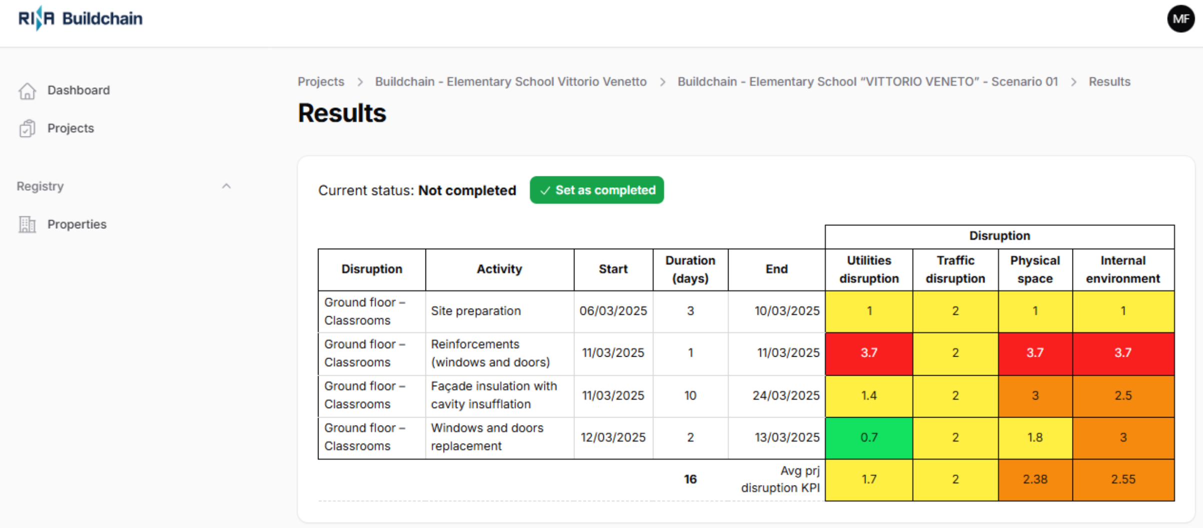
The simulation analysed renovation activities across multiple areas of the building, assigning disruption impact values based on work duration, affected zones, and intensity of disturbance. As with many historical buildings in Italy, the structure under study has been adapted for public use and currently functions as a kindergarten and primary school. This dual role demands high standards of energy efficiency and structural performance but also introduces challenges for municipalities in planning renovation activities.

Historical school buildings require particular attention not only due to their architectural and cultural importance but also because of the need to carefully organize construction activities to avoid significant disruption. Renovation works can easily interfere with school operations, leading to a deterioration in the quality of teaching. Although municipalities can mitigate some of these impacts by scheduling works during school holidays, a structured method for managing and controlling activities is still necessary.

In this context, the Deep Renovation Workflow Management Tool proves to be highly valuable. By demonstrating scheduling optimization, predicting operational disturbances, and providing actionable recommendations, it offers an effective support system for public authorities facing the complexities involved in renovating historical educational buildings.

4.1 Scenarios Simulation

- Scenario 1:
  - Most Disruptive Activities: reinforcements for windows and doors, (dust, noise), flat roof insulation (accessibility issues).
  - Impact Metrics: Utilities (1.7), Traffic (2), Physical Space (2.38), Internal Environment (2.55).


RI$R Buildchain

Dashboard
Projects
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Projects > Buildchain - Elementary School Vittorio Venetto > Buildchain - Elementary School "VITTORIO VENETO" - Scenario 01 > Results

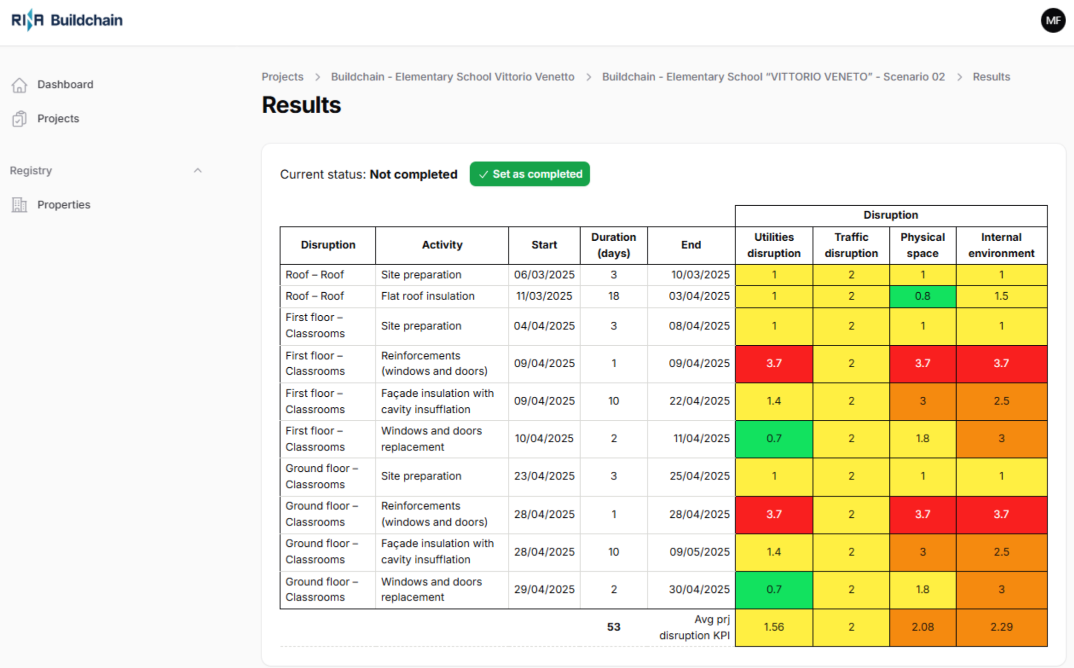
Results

Current status: Not completed ✓ Set as completed

Disruption	Activity	Start	Duration (days)	End	Disruption: Utilities disruption	Disruption: Traffic disruption	Disruption: Physical space	Disruption: Internal environment
Ground floor – Classrooms	Site preparation	06/03/2025	3	10/03/2025	1	2	1	1
Ground floor – Classrooms	Reinforcements (windows and doors)	11/03/2025	1	11/03/2025	3.7	2	3.7	3.7
Ground floor – Classrooms	Façade insulation with cavity insufflation	11/03/2025	10	24/03/2025	1.4	2	3	2.5
Ground floor – Classrooms	Windows and doors replacement	12/03/2025	2	13/03/2025	0.7	2	1.8	3
			16	Avg prj disruption KPI	1.7	2	2.38	2.55

Figure 1. Scenario 1 – Vittorio Veneto - Deep Renovation tool - BUILDCHAIN

- Scenario 2:
  - Most Disruptive Activities: Structural reinforcements, reinforcements for windows and doors.
  - Impact Metrics: Utilities (1.56), Traffic (2), Physical Space (2.08), Internal Environment (2.29).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Projects > Buildchain - Elementary School Vittorio Venetto > Buildchain - Elementary School "VITTORIO VENETO" - Scenario 02 > Results

Results

Current status: Not completed ✓ Set as completed

Disruption	Activity	Start	Duration (days)	End	Disruption: Utilities disruption	Disruption: Traffic disruption	Disruption: Physical space	Disruption: Internal environment
Roof – Roof	Site preparation	06/03/2025	3	10/03/2025	1	2	1	1
Roof – Roof	Flat roof insulation	11/03/2025	18	03/04/2025	1	2	0.8	1.5
First floor – Classrooms	Site preparation	04/04/2025	3	08/04/2025	1	2	1	1
First floor – Classrooms	Reinforcements (windows and doors)	09/04/2025	1	09/04/2025	3.7	2	3.7	3.7
First floor – Classrooms	Façade insulation with cavity insufflation	09/04/2025	10	22/04/2025	1.4	2	3	2.5
First floor – Classrooms	Windows and doors replacement	10/04/2025	2	11/04/2025	0.7	2	1.8	3
Ground floor – Classrooms	Site preparation	23/04/2025	3	25/04/2025	1	2	1	1
Ground floor – Classrooms	Reinforcements (windows and doors)	28/04/2025	1	28/04/2025	3.7	2	3.7	3.7
Ground floor – Classrooms	Façade insulation with cavity insufflation	28/04/2025	10	09/05/2025	1.4	2	3	2.5
Ground floor – Classrooms	Windows and doors replacement	29/04/2025	2	30/04/2025	0.7	2	1.8	3
			53	Avg prj disruption KPI	1.56	2	2.08	2.29

Figure 2. Scenario 2 – Vittorio Veneto - Deep Renovation tool - BUILDCHAIN

4.2 Recommended Mitigation Strategies

Inside the tool, there is a section that explains the recommendation to user according to the activities. This allows the users to: schedule disruptive activities during school holidays, use noise and dust barriers to improve air quality, stagger utility interruptions to prevent complete outages and ensure clear communication among project managers, facility managers, and school staff.

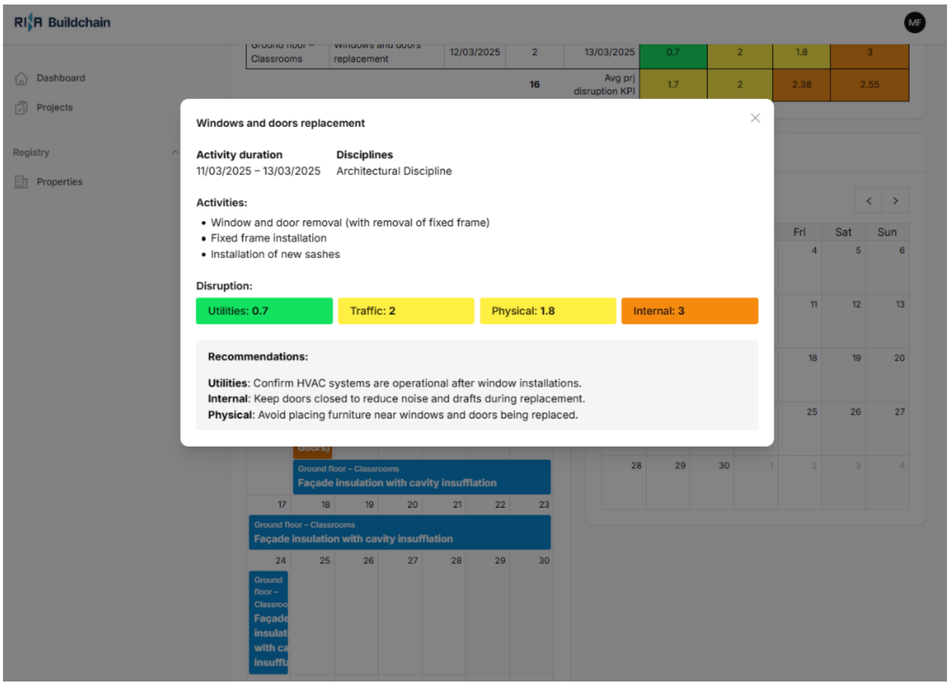

Figure 3. Scenario 1- activities, disruption KPIs – Vittorio Veneto - Deep Renovation tool - BUILDCHAIN

5. Discussions

The implementation of the Deep Renovation Workflow Management Tool at Vittorio Veneto School has provided valuable insights into the potential of structured renovation planning in minimizing disruption and improving project efficiency. The tool successfully simulated renovation activities, allowing stakeholders to visualize their impact and implement mitigation strategies.

5.1 Key Findings

The tool enabled a quantitative assessment of disruptions related to deep renovation activities, categorizing them into utilities, physical space, internal environment, and traffic impacts. It employed scenario-based simulation, allowing decision-makers to evaluate various renovation strategies before implementation. This approach enhanced communication among stakeholders, ensuring that project managers, facility managers, and end users were informed of potential disruptions and mitigation measures

The tool's current limitations include the need for enhanced scheduling functionality, as it is still being developed to provide a more precise estimation of activity durations for better planning and optimization of renovation timelines. Future updates will focus on integrating real-time monitoring by incorporating IoT-based environmental sensors to validate simulation results against actual site conditions.

Additionally, user feedback mechanisms will be refined to include structured feedback loops, allowing facility managers and occupants to report real-time disruption experiences to improve future simulations.

5.2 Comparison with Existing Literature

This approach aligns with Tzortzopoulos et al. (2016), who emphasized the role of structured digital methodologies in reducing renovation-related disruptions. Additionally, Kassem et al. (2015) highlighted the importance of structured workflows in renovation projects, reinforcing the need for accurate impact assessment tools.

Unlike traditional BIM-centered methodologies, which rely heavily on pre-existing models, this tool introduces a workflow-based approach that can be applied even in historical buildings where BIM models may not be readily available

5.3 Future Outlook

The next phase of development will focus on refining the tool's capabilities, including:

Smart contract-based access control, ensuring role-based access to renovation data.

- AI-driven disruption prediction models, improving scheduling accuracy based on historical renovation data.
- Decentralized knowledge graph (DKG) integration, allowing seamless data exchange and long-term knowledge retention.

While the current study has demonstrated the tool's feasibility in a heritage school renovation, further case studies across different building typologies will be necessary to validate its robustness and adaptability to varying renovation contexts

6. Conclusion

The application of the Deep Renovation Workflow Management Tool at Vittorio Veneto School demonstrated its effectiveness in:

- Simulating renovation workflows and visualizing impact levels.
- Providing data-driven recommendations to minimize disruption.
- Enhancing coordination between stakeholders and contractors.

This methodology integrates previous research on renovation disruption modelling with a practical, simulation-based approach for managing deep renovations in heritage educational buildings. Future work will enhance real-time monitoring, integrate smart contracts for access control, and expand data interoperability within the BUILDCHAIN platform.

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Streamlining Life Cycle Analysis through Decentralized Knowledge Graph Technology

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Abstract. Life Cycle Analysis (LCA) has been at the forefront of environmental impact assessment for products in general and construction in particular. Specific parameters derived by LCA have been the de-facto benchmark to quantify the effects and drive policy change, with primacy given to but not limited by global warming potential (GWP) indicator. However, the process of LCA involves numerous intricate steps, most of which underutilize emerging digital technologies or do so in only limited ways. Artificial intelligence, blockchains and even less recent BIM or even digitalization in general are still not well integrated in LCA. This paper briefly outlines the limitations of the current "digitally poor" approach and introduces a novel framework that integrates Building Information Modelling (BIM) with a blockchain-based Decentralized Knowledge Graph (DKG) technology to streamline the calculation of whole building Life Cycle Analysis (WBLCA). The proposed framework was developed as part of the BUILDCHAIN project, and the resulting tool is currently undergoing testing through a digitally enhanced LCA applied to a hospital building design in Slovenia.

1. Introduction to an LCA problem

To define the scope of this study, we focus on a specific problem encountered by experts in the field of LCA for buildings [1],[2],[3]. This limitation is necessary because the broad scope of LCA encompasses a wide range of challenges [4]. Accordingly, this article addresses data availability, particularly the complexities of data collection and the challenges associated with acquiring input data [4], specifically: (i) obtaining a list of components/materials for the whole building including quantities in adequate units, (ii) finding publicly available EPDs for each component or material in the building on online platforms for EPDs, (iii) matching functional units from EPDs to units in which architects can provide data about components/materials, (iv) filling data gaps when a building material or component lacks a high-quality EPD, requiring manual LCA calculations, (v) the manual calculation itself, when an LCA practitioner needs very detailed information about the product (exact materials used, mass) usually for complex components of a building that do not have an EPD online, (vi) expanding the system boundary to Use phase of the building, needing a new set of input data about the consumption of energy and water, and how to obtain it, in order to ensure good quality data, even if the consumption changes for various reasons during the use phase of the building

Data collection for a building LCA typically begins when the architect provides the expert with a Bill of Quantities (BoQ), usually in Excel format. This document outlines the materials and components included in the building, often categorized in groups like structural elements, building envelope, dry construction works, metalworking, finishing works etc. The LCA expert then reviews the data, consolidates repeated materials across applications to reduce entries, checks online platforms for EPDs, and verifies whether the EPDs comply with the EN 15804 standard [5] and match the units provided by the architect with units used in EPD. If all steps above are successfully completed, the LCA practitioner takes the LCA results from the EPD and multiplies them by the amount of the material installed in the building. However, if any of the steps above are not completed successfully, an LCA practitioner can face a formidable set of problems: mass units in plans are not available or do not match the units of EPDs, exact compositions of components are not known, EPDs are not available or are of too low quality…

These challenges are typically complex and resource-intensive to address and nearly always require substantial manual data collection and input, thus slowing down the process. And in case of expanding system boundaries (e.g. adding a "use phase" of a building) the whole set of problems arises anew, with LCA analyst having to consider and add data not included in the building component's EPDs like consumption of water, electricity and other energy.

These challenges are often complex and resource-intensive, typically requiring substantial manual data collection and input, which significantly slows the process. There are many possibilities for misunderstandings and errors, and they grow with the number of inputs. When an LCA is required for the whole building that also has very specific requirements, for example a hospital [3], the complexity can rise even further. This complexity underscores the need for an approach that can streamline the process with digitalization.

2. Proposed streamlining

This section presents a basic framework for addressing the common challenges faced by LCA experts, as outlined in the introduction. It also discusses implementation details, and the challenges encountered during development.

The proposed framework was designed to meet the following key requirements for streamlining the LCA process:

- Minimize time and effort required,
- Reuse existing models or plans wherever possible,
- Leverage digitalization, including integration with existing databases,
- Ensure scalability in terms of both resources processed and user roles (personas),
- It needs to be flexible enough so future processes can be added.

To fulfil these diverse requirements, we envisioned a system utilising a fusion of technology solutions. At the core of the system is an LCA process conducted by and expert with specialised software, addressing the challenges outlined in the previous section. For this framework, we propose simplifying data input by using Building Information Modelling (BIM) [6] to represent the building. By relying on such a model, we can quickly input data and utilise a standardized Industry Foundation Classes (IFC) data exchange scheme [7], that will be facilitate distribution of data within our system. Secondly, we will want to input environmental data for various materials used, by importing EN 15804 [5] compliant Environmental Product Declarations (EPD) published on reputable databases (examples include Eco platform, EPD International, EPD-online, ÖKOBAUDAT), which ensures a high level of quality control. Finally, a unified data exchange mechanism is required to ensure compatibility, enable access control, and support scalability for additional resources, users, or processes (e.g. LCA report marketplace or calculating with embedded sensor data). To allow for all this, a Distributed Knowledge Graph (DKG) technology [8] was selected as a solution.

By combining these technologies, it is anticipated that this approach will yield significant benefits by digitalization and streamlining of the LCA process. The following section examines some possible specific software solutions that can bring these platform independent technologies together.

2.1 BIM input and visualization

The proposed methodology integrates the advanced data management capabilities of BEXEL Manager - a comprehensive BIM-based tool - with Distributed Knowledge Graph (DKG) technology and the EPD-M database from the ECO Platform. This integration enables an efficient and structured approach to life cycle assessment (LCA) by leveraging existing BIM data and automating key processes. The workflow leverages BEXEL Manager's ability to manage and structure information about building elements from the BIM model, serving as a foundation for further data enrichment and analysis.

To enable the proposed workflow, dedicated APIs have been developed within the BUILDCHAIN project, to establish seamless interoperability between BEXEL Manager, DKG, and the ECO platform which provides Environmental Product Declarations (EPD).

Through an intuitive user interface, specialists can efficiently map building elements and products from the BIM model to available EPDs (Figure 1). Once mapping is complete, the developed interface initiates BEXEL Manager BIM model enrichment process, automatically importing relevant environmental data, ensuring the necessary inputs for comprehensive LCA calculations.

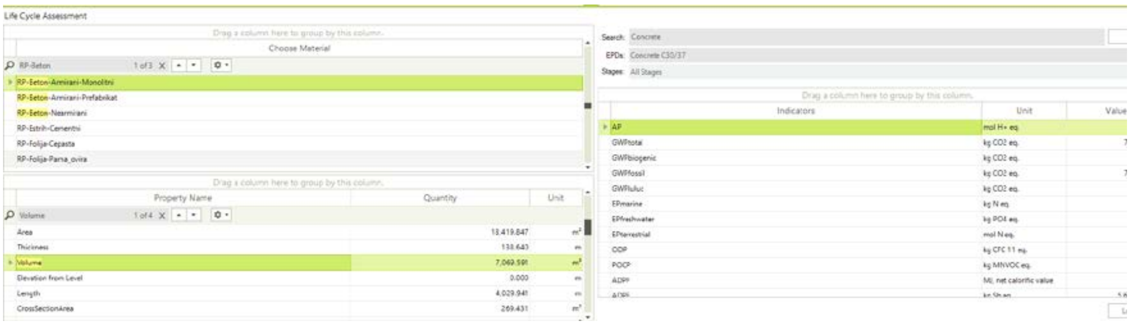

Figure 1. BEXEL Manager Add-in - Material to EPD matching process

Using existing functionalities of BEXEL Manager, the next step in the workflow involves quantifying materials and products within the BIM model. The enriched unit environmental data is then systematically applied to these quantities, generating accurate calculations for whole-building LCA analysis. By automating data extraction, mapping, and computation, this methodology significantly enhances the efficiency and accuracy of LCA processes, drastically reducing the time required for assessment while ensuring data consistency and reliability.

Furthermore, advanced color-coded visualizations highlight building elements and products with the highest environmental impact, as assessed by individual parameters. Interactive BIM dashboards provide additional insights into the environmental efficiency of the proposed design, enabling specialists to further optimize it and improve WBLCA results.

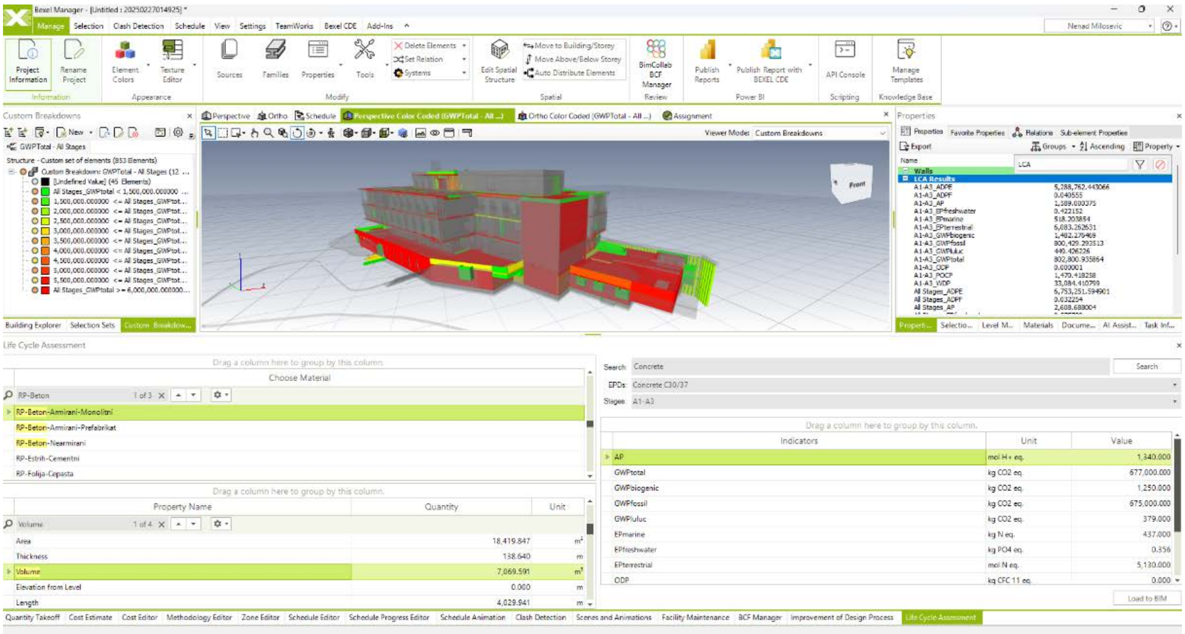

Figure 2. Advanced colour-coded visualizations based on GWP-Total indicator

2.2 Decentralized Knowledge Graph (DKG)

The primary advantages of decentralized knowledge graphs are connectivity and scalability. Working over blockchain, it is a collection of nodes arranged in a decentralized network. The core resources are knowledge assets and knowledge services. These graphs have become an important tool for sharing and connecting research or industry information and contacts enabling access, use and publication of data as a distributed system.

Within the BUILDCHAIN project [9], a specific domain—called the Digital Building Logbook (DBL)—was developed. However, no single standardized approach to data collection, management or interoperability is currently adopted within DBL domain. In fact, these elements were tailored to specific use cases, one of which deals with the streamlining of LCA. The innovation aspect of the DKG includes DBL design integration, which is expected to comply with BIM interoperability and ISO/GS1 standardization requirements – specifically (IFC) [7]. In the future, the comprehensive ontology and data collected through this effort may support further innovations, including applications in tokenomics [10] and new value generation from the embedded data within the DKG.

For the case of LCA analysis, specific API was prepared to allow for data importing (in IFC format), connecting BIM manager (BEXEL) over the DKG network with appropriate authentication procedure (personas). In the end, the same API can be used to link the end results of the analysis, in the form of WBLCA as a new knowledge asset in the DKG – this can of course again be accessed with appropriate authorization.

While this is merely a specific proof-of-concept working on a single use case, it is expected that DBL will assist in the development of a standardized approach for data collection, data management and interoperability and its legal framework. BUILDCHAIN project will help with the development of guidelines for linking existing databases related to environmental aspects including carbon footprint of the construction sector and show DBL concepts and its implementation on pilot buildings.

LCA thus serves as an example of multi-disciplinary data evaluation with a strong focus on verification and quality assurance. DBL is expected to function as a standardized approach for gathering, distributing and overseeing data, guaranteeing both interoperability, authenticity and transparency throughout the entire process. Meanwhile, BUILDCHAIN will assist in creating guidelines to connect and link either new or pre-existing databases via the DBL domain.

2.3 Additional LCA modules and considerations

It is pertinent to note that our solution ultimately stems from our application requirements, namely making a whole building LCA for a pilot hospital as required in the BUILDCHAIN project. In our approach, any LCA can be extended using dedicated software—specifically, “LCA for Experts” by Sphera. This is particularly useful for addressing data gaps and ensuring a comprehensive assessment in cases where EPDs are unavailable or when simplified calculations are insufficient. In doing so, it becomes evident that the approach is designed around specific technological platforms. For example, utilizing BIM is advantageous in our case, as the structures are designed using BIM software. However, this approach may be less suitable for existing buildings, renovations, or buildings that do not have a BIM model: In such cases, a BIM model would need to be created first as an extra step, followed by digital extraction of material quantities and subsequent linkage to EPDs. Similar arguments can be made for other parts of our solution.

These considerations are valid, but they do present a trade-off. Although initial setup may require additional effort (using BIM model, linking databases, setting up a DKG…) the proposed solution offers substantial long-term benefits. For instance, this approach is considered particularly beneficial when adding LCA modules B [5] to the analysis, dealing with usage of the building: A basic BIM model can be updated with building equipment and installations data (heating, AC, recuperation…) and thus used as input to WBLCA, reliably checked and authorized through DKG, especially for modules B6 and B7. Also, as module B is very dependent on different scenarios used, flexibility and visualization capabilities of BIM managers can provide a good overview of the process – one can see where the “hot-spots” are in Figure 2, and this can be similarly expanded to module B, if the underlying BIM model is enriched. Additionally, the LCA process can also be enriched in other ways that align well with this approach.

In the BUILDCHAIN project, structural health monitoring (SHM) sensors were installed and included in the BIM model. Such data, collected before or during the building’s lifetime, can be integrated into the LCA process for optimization or specific applications, such as recalculating LCA results based on measured data. It is feasible to envision how input from other sensors (water meters, power consumption…) can be similarly included, linked and verified by DKG, and further used in WBLCA. Such data can add valuable insight when calculating or checking resource usage during the lifetime of the building. These cases show how our solution can be flexible and scalable to include other data resources and processes and even be able to monitor environmental impacts of a building’s use in real time, potentially even recalculating environmental burden with “live data”.

But in its basic form this fusion of proposed technologies in this iteration includes input data in IFC form, input data from an environmental database (ECO platform), a BIM tool (BEXEL) for handling and visualisation, supplemental dedicated LCA software (“LCA for Experts” by Sphera), and DKG technology utilizing application user interface (API) to link it all together, with authorization privileges shown as personas. The overview of the proposed framework is best described by a flowchart outlining the solution and each of its components.

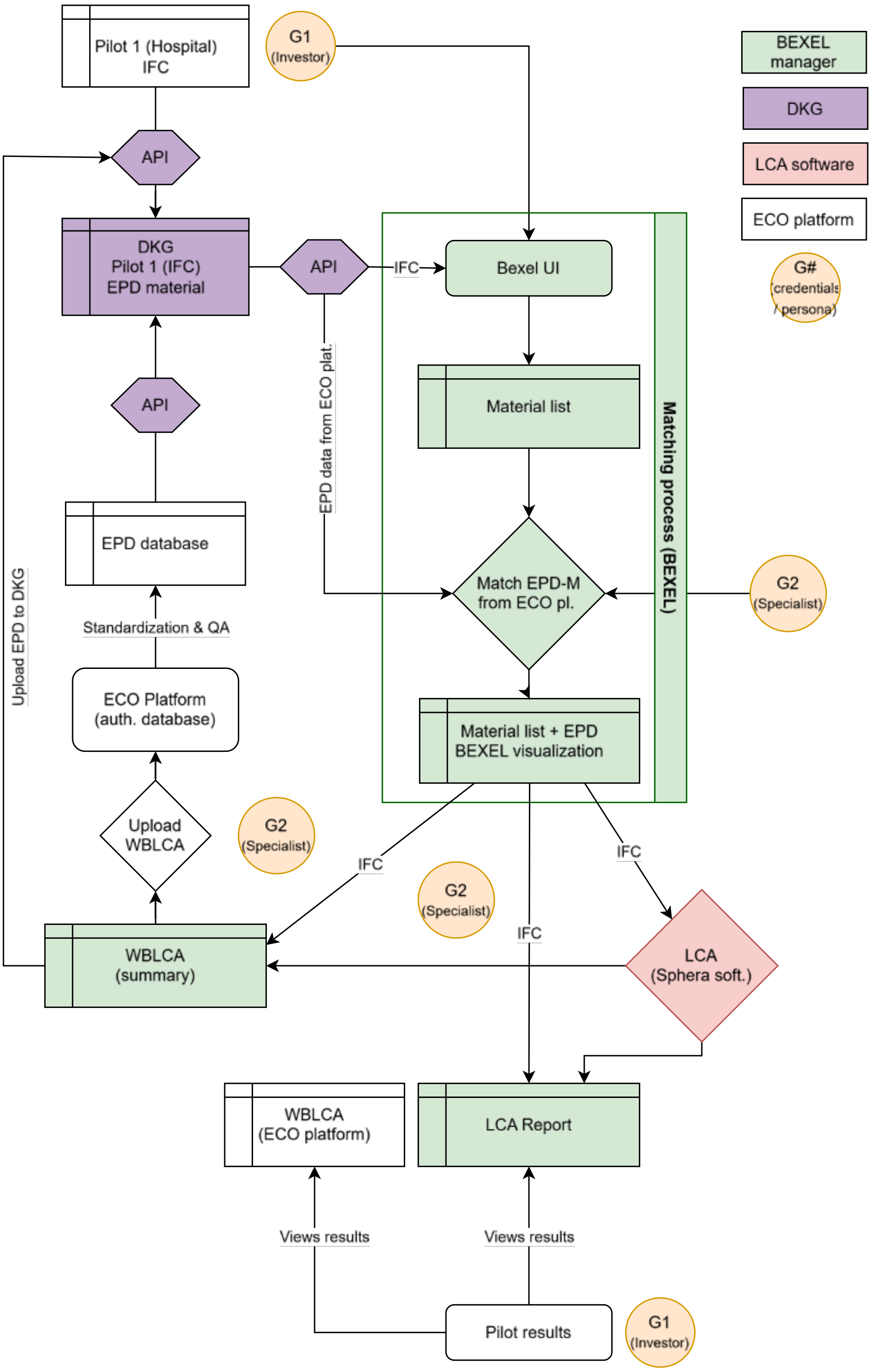

Figure 3. Flowchart of a proposed process, with colours corresponding to various software domains

As illustrated in Figure 3, the schema for our solution gets quite complicated, even with colour coded elements, showing what software handles what. But note that the data of our use-case is already added in the flowchart, so we can explain the flowchart on the story in this specific case, thereby enhancing conceptual clarity.

3. Use case demonstration

A streamlined process, as outlined in the previous section, is being applied to conduct a test LCA on a pilot building within the BUILDCHAIN project, serving as a proof of concept. At the time of writing, the work is ongoing and currently in the testing phase. The prototype tool, implemented within BEXEL manager, is operational and integrated with a pilot-specific DKG network. A BIM model of a hospital building prepared by one of our partners is being used as input.

The scenario underpinning this use case involves the investor persona (G1 in figure 3) selecting the most environmentally preferable hospital design. To aid in this, a comparative assessment of environmental footprints is undertaken. Using an API, the investor uploads a BIM model as IFC file featuring different construction designs (e.g. concrete, wood) to DKG. An LCA Specialist (G2 in fig.3) is then informed and receives a BIM model in BEXEL software and matches building elements/materials with relevant EPD data from ECO platform. This represents a key advantage, as this step is typically a major bottleneck in the analysis process. By using DKG technology, the LCA Specialist can streamline the analytical process by consolidating all the necessary data into a single "enriched" IFC file ("materials list + EPD" in fig.3). This approach also assures the LCA Specialist of the validity of material information, obtained through a recognized authority. With data enriched IFC, the LCA Specialist can generate a whole building LCA (WBLCA) directly within BEXEL manager or, if necessary, use specialized software to address data gaps. This added step would most likely be used if EPD data for some materials is not available or deemed insufficient by the specialist (e.g. EPD made with a different scenario or lacking some modules). In either case, the final comprehensive WBLCA report is uploaded to BEXEL software by the specialist, ready to be viewed by the investor ("pilot results" in fig.3). A summary of the report—referred to here as the "EPD building"—can also be uploaded to the DKG network using the same API employed at the initial stage. Additionally, it may be submitted to the relevant authority database, such as the ECO Platform, or an alternative repository as appropriate.

In the end, the investor (G1 at bottom of fig.3) can then view LCA report in BEXEL and can receive a WBLCA summary of the proposed designs from (and verified by) an authority. This can then be shared with stakeholders in the construction process for purpose of transparency, broader accessibility and validation. This provides the investor with a robust basis for selecting the hospital design with the lowest environmental impact.

4. Future work and conclusion

We believe this process meets all the requirements outlined in Section 2, making it a valuable and innovative approach to performing LCA. Certain challenges remain, such as familiarizing stakeholders with the relatively new DKG technology—a task complicated by the current lack of user-friendly interfaces. Another issue is that even the most comprehensive databases may lack EPDs for certain materials, and EPDs themselves may not remain the gold standard in the future. Both valid concerns can be addressed by pointing out to the flexibility of our solution. EPD databases are expected to grow with increased usage, and if they eventually prove inadequate, alternative frameworks will likely emerge. And this form, whatever it turns out to be, can most likely be included in the process by adjusting or rewriting the prepare API of decentralized knowledge graphs. It seems implausible that the new framework would be so different as to prohibit this.

While there are different possible ways to tackle the problem of digitally ossified LCA process, the proposed approach provides both readily presentable upgrade as well as scalability and flexibility to simplify adding other potential capabilities, chief of which is the involvement of AI. The matching process described in this paper is essentially a classification problem, which could benefit significantly from machine learning algorithms. These algorithms could potentially be added to the DKG network and thus integrated in the process. This constitutes a key direction for future research on this solution.

From a business perspective, future work could explore using DKGs as a foundation for a marketplace framework to facilitate the exchange of LCA expertise. While this can be done in different ways, a basic function of providing additional payment authority and monetizing access for expert work would almost certainly be a part of such marketplace.

As this paper has outlined, integrating DKG technology into the LCA process opens several promising opportunities. The process can be streamlined and sped up, it can leverage digitalization progress in this area and help with verification and validation, and it can do this with existing models and databases. And finally, it is flexible enough to include future developments and processes (AI) that are right now coming into their own.

Acknowledgment

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