

DiggiTwin: End-to-end use of digital twins to realize a climate-neutral building stock

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Abstract: The construction sector is one of the most resource-intensive sectors and responsible for a considerable share of energy consumption and greenhouse gas emissions. In order to achieve the sector targets of the German government's climate protection plan, the planning, construction, operation, maintenance and dismantling of buildings must be completely rethought and reassessed. This paper proposes an end-to-end digital method which captures the entire life cycle of a building. An interdisciplinary work that combines expertise from the fields of computer science, electrical, civil and energy engineering and tests the method on existing buildings at Aachen University of Applied Science with a main focus on optimising the building's energy consumption. The digital twin is created using methods from the field of Building Information Modelling and linked with sensor technology, data analysis and artificial intelligence in order to identify anomalies in energy consumption. With the availability of geometric, functional and real-time data from the sensors, one can identify key performance indicators relevant to the respective use cases and simulate "what if" scenarios by making predictions to achieve optimum results in terms of sustainability.

Keywords: Simulation, Digital Twin, Monitoring & Optimisation, IoT, Anomaly Detection



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1 Introduction

In the European Union (EU), energy production and use are responsible for 80% of all greenhouse gas (GHG) emissions. Buildings account for about 40% of EU's final energy and 36% of CO₂ emissions, consequently associated with a significant untapped energy saving potential [1]. Building Information Modelling (BIM) is one of the most recognized and rapidly increasing technologies to minimise building energy use in recent years [2]. However, there have been many challenges in utilising BIM during asset operations, which have hindered asset owners from deriving value from their initial investments. The Architecture, Engineering and Construction (AEC) industry is struggling with the transition of BIM-based deliverables from the design and construction phases to the operations and use phase. This may be due to the divergent nature between these phases in terms of the aims,

objectives and scope of operations [3]. It is therefore crucial that the models not only cover the planning phase, but also the entire life cycle of a building in order to identify potential energy savings and ensure sustainable building operation. A key feature of BIM is the 3D model commonly referred to as the BIM model which is realised with object-oriented software. However, the BIM model is limited in providing dynamic real-time data of the physical environment. Yet, construction projects and assets are both implemented within a dynamic physical environment generating a vast amount of non-geometric data. The emerging concept of the digital twin (DT) offers an opportunity to address the limitations of BIM [4]. The integration of the physical and digital worlds by adding dynamic real-time data to a static BIM model is now known as DT. Due to the lack of standardisation and misconceptions about the definitions of DTs, developing a standardised DT framework for information management processes regarding construction assets is essential [5]. With regard to the climate targets of the Federal Republic of Germany, this paper focuses on sustainable building optimisation using DTs. The basis for holistic building monitoring and optimisation is digitalisation and automation in the sense of a smart building. This paper examines the most popular and promising BIM to life cycle assessment (LCA) tools according to the German assessment system "Bewertungssystem Nachhaltiges Bauen" (BNB). Additionally, it explores strategies for detecting operational anomalies using IoT (Internet of Things) sensor technology to enhance energy-efficient building operations. The focus is on precise monitoring and anomaly detection of critical building data to identify and utilize untapped energy-saving potential. As DTs in the built environment are still in nascent stages, a novel end-to-end process chain is proposed, starting from the design and construction phase up to the operational phase for energy efficient renovation of a university building located in the western part of Germany.

2 State of the Art

In this section, the PRISMA method [6] for collecting data is applied to identify, evaluate and synthesize the existing body of knowledge on the topics of digital tools and strategies implemented for sustainable building optimization.

2.1 BIM-To-LCA

In order to achieve a holistically sustainable building design, expertise on environmental assessment has to be offered to stakeholders to reduce the life-cycle related GHG emissions of buildings [7]. Recently, LCA is increasingly applied for assessing the environmental performance of buildings not only in research, but also in practice in the form of a post-design evaluation for sustainability certification purposes. Digital tools based on BIM provide the potential to decrease the additional effort for LCA and speed up the process [8]. Three research questions were posed to facilitate the understanding of previous studies that supported the idea of BIM based LCA tools.

Q1: What are the available open-source and commercial tools for assessing building life-cycle?

Q2: What are the LCA databases for buildings in Germany?

Q3: Which certification schemes support BIM-based submission of LCA results?

Web of Science, Scopus and Scholar were used as databases for this review and Boolean operators were used in the 'Title, Abstract and Keywords' fields to search articles using the keywords "BIM software", "LCA tools", "Open-source tools & Databases", "BNB", "Dynamic LCA", "Building lifecycle" & "Systematic literature review". Thus, according to the PRISMA methodology, 360 articles were found to be published within last 5 years. The most prominently used German environmental database is Ökobau.dat, developed in 2012 from Bundesinstitut für Bau-, Stadt- und Raumforschung (BBSR). eLCA, also developed by BBSR, is a reliable open source web-based LCA tool which supports assessment of only office and administration buildings. Generis [9], CAALA, LEGEP and Umberto NXT are some of the commercially available tools which support BIM-based submission of LCA results for BNB and DGNB certification.

2.2 Operational Anomaly detection

The building's consumption data is available as a time series. For the purposes of pattern and anomaly detection, a decision must be made first whether this should be based on the time series or on characteristics derived from them, such as cumulative or average consumption. Furthermore, there are different types of anomalies, which are shown in Figure 1.

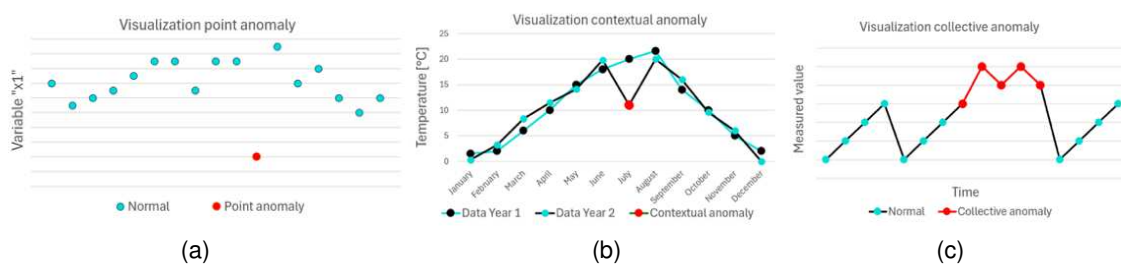


Figure 1 Visualization of a (a) point anomaly (b) contextual anomaly (c) collective anomaly

Point anomalies (Figure 1a) are the easiest anomalies to recognise. They can be caused by an outlier which occur when a data point significantly deviates from the range of values of the other data points. Examples of point anomalies are measurement errors or a sudden drop in energy consumption due to a technical failure. Since point anomalies occur independently of context, they can be detected in univariate data. This is different for contextual anomalies. An anomaly is called contextual if its value differs significantly from the value of other data points in the same context. Figure 1b illustrates this using the example of a temperature curve: the low temperature in the context of the month of July is anomalous. It is important to note that data points can be classified as abnormal in one context but normal in another context. A third type of anomaly is described by the collective anomaly (Figure 1c). Such an anomaly describes a subset of data points within a data set. It is not the individual data points themselves that are anomalous, but their joint occurrence. Examples of collective anomalies are unusual sequences in a time series, as shown in Figure 1c. Further details about anomalies in time series can be found in the work by [10].

3 Methodology

Effective information transfer is crucial for the success of AEC projects, yet it often presents significant challenges due to the multifaceted nature of project requirements and stakeholder involvement. As all project participants have different starting points, it is essential to have a defined digital knowledge transfer to ensure accurate and transparent information transfer. The core of the proposed end-to-end process chain is an Information Transfer Matrix (ITM). According to Mohan et. al. standardised ITM must be created based on specific use cases to optimise the digital twin for specific applications. These should be used in all phases of planning, construction and operation to ensure the bi-directional transfer of relevant data between the actors and the digital twin [11]. As shown in Figure 2, first a BIM model of the building under consideration is created. This is using the scan2BIM methodology where a 3D representation of the building is created using a LIDAR point cloud reconstructed in Revit. The BIM model forms the basis for the digital twin of the building based on the which refurbishment concepts can be created and evaluated.

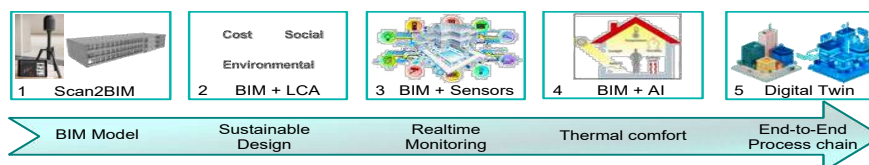


Figure 2: Digital Twin for energy efficient renovation

Kylili et al. [12], reviewed previous studies that employed the key performance indicators (KPIs) approach in sustainable building renovation and identified eight generic KPI categories related to economic, environmental, social, technological, time, quality, disputes and project administration aspects. In the next step suitable sensors are specifically chosen to gather real time data relevant for the selected KPIs. All data recorded using the selected sensors, are initially stored centrally on an external data storage / cloud storage system. The stored data is continuously analysed to identify consumption patterns and anomalies ensuring the building can be used energy-efficiently during operation and identify optimisation potential. This is based on pattern and anomaly recognition methods from the field of machine learning. For reliable functioning of these algorithms, a lot of training data is necessary [13]. After collecting enough data, pre-trained models are tested and evaluated.

3.1 Design and Construction phase

3.1.1 BIM-To-LCA

The general workflow of BIM based LCA is summarised in Figure 3. The building element templates specific to the project are first created on the basis of Environmental Product Declarations (EPDs) and generic datasets (Ökobau.dat) and assigned to the respective cost groups according to DIN 276 in the eLCA software, generating the IDs for each of the element templates. Both cost groups and the eLCA element-ID, are now stored as attributes for the corresponding elements of the BIM model. With the extension of the element properties, the BIM model can then either be exported directly in the vendor-neutral IFC file format or a component list can be created and exported as CSV. When

using the IFC interface, the IFC file is transferred to the eLCA program automatically and evaluated. When using the CSV interface, however, the component list is manually linked with the corresponding attributes generated in the first step and then imported into eLCA for evaluation.

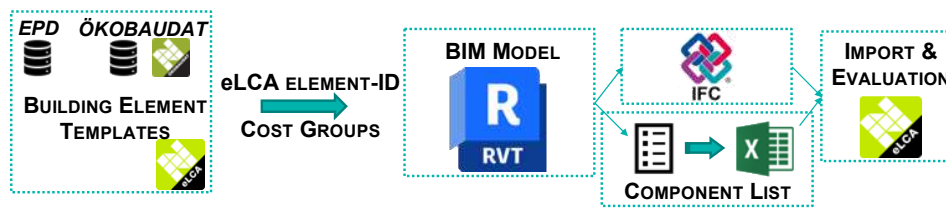


Figure 3: Process for calculation of embodied impacts based on BIM

3.2 Operations and Use phase

3.2.1 Communication protocols for monitoring

The centralized storage is crucial, as it allows for efficient data management and accessibility for subsequent processing stages. State-of-the-art communication protocols like LoraWAN [14], Enocean [15] and Thread [16] can transmit data from sensors wirelessly over long distances and in an energy-efficient manner. These protocols ensure reliable and long-range communication and ensure that sensors that rely on batteries are guaranteed a long service life, making them ideal for various IoT applications. The data collected by the IoT sensors is integrated into an open-source IoT automation framework, Home-Assistant [17]. This platform is responsible for gathering, processing, and storing the data in a centralised database.

3.2.2 BIM-To-SIM

Some of the KPIs relevant to the respective use case in the current project are: 1) Life Cycle Costs (EUR/m²), 2) Indoor Air Quality (CO₂ concentration ppm), 3) Thermal comfort (temperature range in °C), 4) Climate change (CO₂ eq. emissions), 5) Energy consumption (kWh/m²a) and 6) Onsite energy ratio (%) [18]. As a higher goal, for the selected building, initial KPIs that are planned to be measured and evaluated are energy loss in the building and thermal comfort [20] defined in the European norm EN ISO 7730 [21]. The decision on which sensors and actuators to use depends on the requirements a room must fulfill (e.g. an auditorium has different requirements than a boiler room). The input comprises of diverse datasets from different rooms, providing a comprehensive overview of the building's environment. When the anomaly detection system identifies an anomaly, detailed output specifying the start and end times of the detected anomaly, the specific room where the anomaly occurred, and an estimation of the suspected problem's nature is made available to the user. Figure 4 shows the data acquisition and processing of data captured from the sensors. The sensors continuously gather a wide range of data, capturing multivariate time series information. The collected data is then transmitted through intermediary devices known as gateways and securely stored in an external database designed to handle large volumes of complex sensor data.

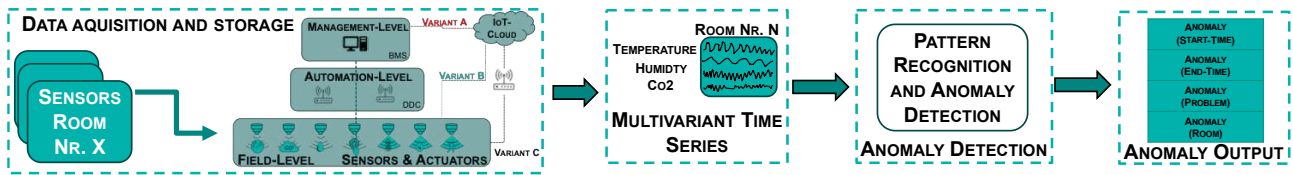


Figure 4: Process diagram for data acquisition and processing.

Energy modeling tools like IDA ICE can be used to predict energy consumption and evaluate optimal parameters in the energy renovation process. However, often discrepancies can be observed between the actual usage and predicted performance due to the uncertainties in the data input, namely assumptions of the U-values, system efficiencies factors that were not possible to determine on the job site, randomness and variability of the weather data and occupancy input [22]. In this method the real time data gathered using the different sensors take into account these discrepancies and help model an accurate DT. The DT consequently aids in developing reliable building energy models (BEMs) to simulate different scenarios (by varying occupancy, system failure, weather etc.) in turn predicting energy consumption and help evaluate suitable renovation strategies.

4 Experiment & Results

The selected building for testing of the methodology is the FH Aachen campus building located in Bayernallee, Aachen. A commercial LIDAR scanner – Leica BLK360 Generation 1 is used to capture the building as point cloud and commercial software Revit is used to create the BIM model. The BIM model consisting of 5 wings was developed with the help of point cloud data which was prepared with approximately 1200 individual scans. The LCA analysis in this paper will be limited to the third wing (Department of Civil Engineering). The building, which dates back to 1962 has a net floor area (“Nettogrundfläche” NGF) of 3262 m². The environmental impacts of the building's life cycle are normalised to one year and one m² NGF. While the gas requirement for the building is 190.3 kWh/m²a, 7.3 kWh/m²a is the electricity requirement. From Table 1 it can be seen that the operation stage (B6 – energy use) has been highlighted as the main contributor to the Global Warming Potential (GWP).

Table 1: GWP values [kg CO₂-eqv.] according to life cycle module

Total (INCL. A1 - A3, B6, C3, C4)	A1-A3	B6	C3	C4	Maintenance and repair (INCL. A1-3, C3, C4)
44.37	0	41.63	0.1	0.41	2.236

Six different rooms are fitted with sensors to gather real time information about the building operation namely, Auditorium, Office room, Computer Lab, Architecture Studio, Boiler Room and Toilet. They are selected in order to reduce the DT as individual control rooms to create simple BEM which when extrapolated would represent the entire building.

5 Conclusion

This paper presents a methodology for end-to-end use of digital twins to realise a climate-neutral building stock. The suggested methodology is tested for developing a renovation strategy for a university building which consists of 6 different types of rooms depending on their usage. The sensors employed in this research along with the necessary anomaly detection strategies will be published subsequently discussing the potentials of using DT for optimising building operational energy. Although there are different BIM based LCA tools available for achieving a holistically sustainable building design, the only open-source tool is eLCA that is available for submitting results for certification in accordance with the German assessment system (BNB). Even eLCA does not fully support vendor neutral IFC format which again promotes the use of commercial tools. The presented methodology can further be expanded to include other types of buildings which promotes the standardised framework for applying DTs for building monitoring by asset and facility managers.

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