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LIFECYCLE ENERGY PERFORMANCE IN DIGITAL TWINS: A SEMANTIC APPROACH FOR SUSTAINABLE BUILDING MANAGEMENT

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Abstract

Buildings account for a significant share of global energy consumption and CO_2 emissions, necessitating holistic monitoring for sustainable lifecycle performance. This research explores how Digital Twins (DTs) integrate semantic reasoning to enhance operational and embodied energy assessment. By linking BIM, BMS, and LCA data via ontology-driven knowledge graphs, the study develops a conceptual framework for interoperable, lifecycle-aware energy performance tracking. Addressing challenges in LCA integration, semantic interoperability, and real-time synchronization of Energy Performance Indicators (EnPIs), this work contributes to data-driven decision-making in sustainable building management.

Introduction

While the climate crisis has triggered strong pressure for change in the construction industry, it has not been without consequences. Buildings are responsible for 40% of energy consumption in Europe and as much as 36% total CO2 emissions. Overall, 75% of buildings on European soil are still considered energy inefficient (Piazolo, 2024). Analysing buildings throughout their life cycle requires comprehensive background data on energy supply systems, material supply chains, and manufacturing processes of building components. Additionally, the integration of circular economy practices further complicates data collection, requiring ongoing assessments of the effects on impacts (Kourkoumpas et al., 2018). Emerging technologies such as building information system (BIM), energy management systems (EMS), and digital twins (DT) offer promising potential for increasing the energy efficiency of properties through centralised data collection, analysis, and visualisation (Davila Delgado and Oyedele, 2021). Especially DTs, as virtual replicas of physical assets or systems, enhance real-time monitoring, predictive maintenance, and data-driven decision-making, making them essential for sustainability assessment. By integrating data from multiple sources, they provide a comprehensive view of system performance, enabling optimisation of sustainability strategies (Arsecularatne et al.2024). (Costa and Sicilia, 2023) emphasise that web- based technologies with standardised data representation are crucial for developing efficient processes in building simulation. Semantic web technologies (SWT) enable formal representation of information, linking of concepts and offer the possibility of sharing data using formal semantics. In order to draw conclusions in these systems, quantitative measurements of energy performance using energy performance indicators (EnPIs) are necessary (O'Brien et al., 2017). In addition to operational performance measurement, Energy Performance Indicators (EnPIs) are also used to assess a building's environmental performance throughout its entire lifecycle, including embodied energy, which accounts for the total energy consumption from material production to disposal or recycling (Dixit et al. 2013).

Research challenges

Integrating LCA-principles into BIM-powered DTs

Conducting an LCA requires gathering and connecting data from various fields, a task that is often complex and time-consuming (Boje et al., 2023). Such fragmentation of data makes it difficult to achieve a seamless workflow for LCA within BIM-frameworks. Moreover, ensuring that sustainability considerations are easily integrated into these workflows without demanding specialized knowledge from designers and engineers remains a significant challenge, highlighting the need for more intuitive and accessible tools (Llatas et al. 2020).

Semantic Interoperability for Energy Performance Assessments

(Pritoni et al., 2021) identify the fragmentation of metadata schemas and the limited adoption of ontologies as key barriers to semantic interoperability in building energy applications, while (Aniakor et al. 2024) emphasize that energy performance assessments are hindered by inconsistent data quality, and the computational complexity of integrating diverse data sources. (Pritoni et al., 2021) (Aniakor et al. 2024) call for the need for standardized data exchange mechanism automated data validation, and scalable DT frameworks that support seamless stakeholder collaboration.

Proposed approach

This research will explore LCA in DTs, focusing on dynamic energy monitoring across different lifecycle stages of buildings. As a foundation for this work, we have already developed an initial prototype that continuously synchronizes KPIs between real-time sensor data and KGs (cp. Fig.1). As a part of ongoing research, a comprehensive literature analysis will explore how DTs leverage semantic reasoning to optimize both operational and embodied energy. This study will examine ontology- driven knowledge graphs linking BIM, BMS, and LCA data to enhance sustainability assessment. Key aspects include semantic interoperability, rule-based inference, and automated KPI calculations. The findings will contribute to a conceptual framework that supports lifecycle-aware decision-making, improving energy performance and sustainability in DT-driven buildings.

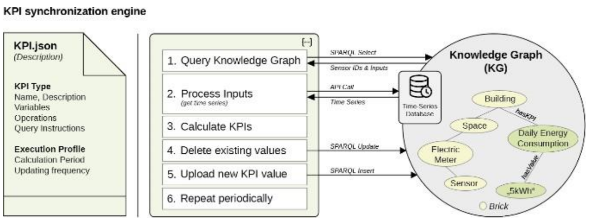

Figure 1: KPI synchronisation Engine

Expected results

Building on the existing prototype, this research will bridge gaps in lifecycle energy performance assessment by introducing semantic integration approach for DTs. It will clarify how BIM, BMS, and LCA can be effectively linked using knowledge graphs, improving energy performance tracking over a building's lifecycle. The results of this research will directly contribute to the horizon-funded project ENERGENIUS by providing a conceptual framework to support data-driven sustainability decisions and enhance interoperability among building systems.

Conclusion

This study will establish a new perspective on lifecycle-aware energy monitoring in DTs, emphasizing the importance of semantic reasoning in the energy and building sector.

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