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Research Paper

Digital twins for dynamic life cycle assessment in the built environment

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ABSTRACT

Dynamic life cycle assessment (LCA) integrated with digital twin technologies is emerging as a transformative approach to evaluating and managing environmental performance in the built environment. This study presents the Building Life-cycle Digital Twin (BLDT) framework—a novel methodology that combines real-time data from Internet of Things (IoT) devices, machine learning algorithms, and semantic interoperability to deliver dynamic, predictive, and high-resolution LCA for construction and infrastructure systems.

The framework, developed within the Computational Urban Sustainability Platform (CUSP), addresses the limitations of traditional static LCA by enabling continuous, data-driven sustainability assessments. Incorporating predictive modelling, BLDT empowers stakeholders with timely insights into energy use, emissions, and health and safety performance, supporting proactive environmental decision-making.

Validated through a case study at the Port of Grimsby, the BLDT framework facilitated a 25% reduction in energy consumption while enhancing operational efficiency. These results demonstrate the model's potential to support decarbonisation strategies, regulatory compliance, and long-term planning in the construction sector. By operationalising dynamic LCA through digital twins, this research contributes to the advancement of real-time sustainability analytics and resilient urban development.

1. Introduction

Digital twins are increasingly employed within the built environment to facilitate real-time monitoring, performance optimisation, and environmental assessment across the life cycle of buildings and infrastructure. Their integration into Life Cycle Assessment (LCA) represents a significant advancement, offering the capacity to assess environmental impacts dynamically rather than retrospectively. Traditional LCA methodologies, while robust for static evaluations, often lack the responsiveness to temporal and spatial variability, system dynamics, and evolving environmental conditions (Zheng et al., 2017). This inherent rigidity limits their applicability in data-rich, rapidly changing contexts such as smart construction. Accordingly, there is a growing imperative for dynamic LCA approaches capable of incorporating real-time data and localised factors, thereby yielding more accurate, actionable, and context-specific insights (Fnais et al., 2022; Ghoroghi et al., 2024).

Dynamic digital twins – virtual counterparts of physical systems that continuously synchronise with real-world operations – offer a promising avenue for overcoming these limitations (Madni et al., 2019). Unlike conventional digital representations, dynamic twins are characterised by continuous data integration, predictive modelling, and feedback capabilities. In construction and the broader built environment, they enable LCA that reflect real operational conditions rather than hypothetical scenarios. Demonstrated successes in industries such as aerospace and manufacturing – where digital twins improve maintenance planning, cost control, and operational efficiency – underscore their potential in construction applications (Xie et al., 2019; Deng et al., 2021). Within building systems, digital twins can optimise construction processes, monitor operational performance, and support end-of-life planning, aligning closely with sustainable development goals (Akinshipe et al., 2022; Borjigin et al., 2022).

The convergence of emerging technologies – digital twins, the Internet of Things (IoT), and blockchain – is reshaping environmental assessment in the built environment. Digital twins have shown potential to enhance energy efficiency and reduce carbon emissions via real-time performance optimisation (Kumar et al., 2019). IoT devices support this by continuously capturing detailed environmental data, such as energy use and emissions (Chen et al., 2022), thereby improving the granularity and relevance of LCA metrics. Blockchain technology adds transparency and trust, offering a decentralised, secure platform for data sharing among stakeholders in complex civil projects (Höjer and Wangel, 2015). Together, these technologies enable precise tracking of embodied and operational carbon, allowing for responsive and targeted emission reduction strategies throughout a building's life cycle (Mukherjee et al., 2022).

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This technological synergy enables a transition from static, centralised LCA models to dynamic, context-sensitive frameworks. Dynamic LCA incorporates real-time data and predictive analytics, adapting assessments to variations in climate, resource availability, and occupancy patterns (Sokolova and Fernández-Caballero, 2010; Amin and Mourshed, 2024). It also encourages stakeholder engagement, drawing insights from local actors to enrich impact evaluations with regional and cultural context. This participatory model strengthens transparency, accountability, and relevance, while aligning environmental decisions with real-world variability. Ultimately, dynamic LCA enhances not only the technical accuracy of assessments but also their utility for sustainable policy development and resilient infrastructure planning (Kibert, 2016).

Despite growing academic and industry interest in digital twins and life cycle modelling, existing literature largely addresses these domains in isolation. Many studies focus on the theoretical capabilities of digital twins or the methodological evolution of LCA, but few provide an integrated, operational framework that harnesses real-time data for environmental impact assessment in construction. Current applications often remain static, manually updated, or limited to isolated project phases, lacking temporal adaptability and systemic integration. This research addresses that gap by proposing a novel framework – the Digital Twin Bearing Life Cycle Model (BLDT) – that integrates digital twin technologies, continuous IoT data streams, and machine learning (ML) algorithms into a cohesive, dynamic LCA system. The innovation lies in the framework's ability to enable real-time, predictive, and context-aware environmental assessments across all stages of the built environment's life cycle. By moving beyond static models and using real-time data, automated analysis, and local context, the BLDT framework offers a practical and innovative step towards making environmental assessments more useful and responsive in real-world construction projects.

Through the demonstrating of the proposed BLDT framework, this research aims at: (i) examining the extent to which digital twin technologies enhance the precision and temporal responsiveness of LCA; (ii) investigating the challenges and opportunities involved in integrating digital technologies with traditional LCA frameworks; and (iii) assessing how such integration contributes to sustainable development within the built and urban environment. These objectives are guided through three research questions:

1. How can digital twin technologies improve the accuracy and efficiency of LCA in the built environment?
2. What are key challenges and opportunities associated with integrating digital technologies into traditional LCA methodologies?
3. How can the proposed integration framework contribute to the sustainability in the built and urban environment?

By addressing these questions, the research provides a comprehensive understanding of the potential of digital twin technologies to revolutionise LCA practices in the built environment, thus contributing to the larger goal of sustainable urban development. The remainder of this paper is structured as follows: Section 2 presents a review of relevant literature concerning digital twins and dynamic LCA. Section 3 introduces the proposed BLDT framework, outlining its structural components and data integration mechanisms. Section 4 details a case study application of the framework. Section 5 discusses the empirical findings and contrasts them with conventional LCA practices. Finally, Sections 6 and 7 outline future research directions and present the concluding remarks.

2. Related work

2.1. Advances in digital twin technology in LCA

Recent advances in digital twin technology have enabled greater understanding and advanced analysis of built and construction assets, offering unprecedented opportunities to improve LCA. Integrating these technologies into LCA processes represents a significant shift towards more dynamic, accurate, and comprehensive environmental impact evaluations.

A systematic review by Deng et al. (2021) highlights the evolution of intelligent building representations, from building information modelling (BIM) to advanced digital twins, underscoring their potential to revolutionise building management through real-time data analytics and simulation capabilities. This transition facilitates a deeper understanding of the environmental footprint of a building throughout its lifecycle and enables proactive decision-making to mitigate adverse impacts. Research by Kineber et al. (2023) on modelling the relationship between digital twin implementation and embodied carbon construction presents a compelling case for the synergistic use of digital twin technology and LCA. The study demonstrates how IoT-enabled digital twins can provide a granular, real-time view of a building's performance, thereby enhancing the accuracy of embodied carbon assessments. This approach not only refines the precision of the LCA results but also paves the way for targeted strategies to reduce carbon emissions in the construction sector.

A critical overview by Di Matteo et al. (2024) on the challenges and potentialities of BIM and digital twins in building energy and sustainability further elucidates the transformative impact of these technologies. The paper argues that digital twins, as multidimensional digital representations of physical assets, can significantly accelerate the benefits of BIM by offering a more nuanced and comprehensive analysis of energy usage and sustainability metrics. This synergy between BIM and digital twins is posited as a reliable approach to achieving energy savings and environmental strategies, highlighting the need for enhanced interoperability between these technologies to realise their potential in the construction industry.

These recent studies underscore the growing role of digital twins in refining LCA methodologies within the construction sector. These technologies offer a pathway to more sustainable and environmentally responsible building practices by harnessing real-time data and advanced simulation capabilities. However, the full potential of integrating digital twins with LCA tools remains under-explored, particularly in dynamic and predictive environmental impact assessments. The reviewed literature underscores the need for dynamic LCA models, aligning with our research objective to integrate digital twins for real-time environmental assessments.

Recent studies (Shanbhag and Dixit, 2025; Padhiary et al., 2024) have integrated IoT to gather usage data for energy simulations, but these approaches often update life-cycle inventories only at discrete intervals rather than in real time. These examples underscore the necessity of real-time sensor data for dynamic LCA (DLCA) – a focus our BLDT framework addresses by integrating IoT and digital twin simulations. Despite these advancements, the literature lacks a holistic DLCA framework incorporating real-time data streams from IoT and digital twins. The following sections address this gap by proposing a novel BLDT framework that continuously updates LCA assessments in near-real time.

2.2. State-of-the-art LCA solutions

Recent years have seen a growing interest in LCA applications in critical areas of decarbonising the built environment at all lifecycle stages (Fnais et al., 2022). Researchers have developed LCA-based frameworks to facilitate the workflow for assessing building materials and various design options (Budig et al., 2021; Shrestha, 2021; Helal et al., 2020; Zeng et al., 2020). Given the computational complexity of performing LCA during the design stage and the multifaceted decision process involving environmental, economic, and social factors, researchers have integrated LCA with computational and analytical techniques such as optimisation (Kiss and Szalay, 2020), ML (Płoszaj-Mazurek et al., 2020), and data envelope analysis (Tavana et al., 2021).

During the use phase, LCA has been widely used to evaluate the retrofit and renovation strategies of existing building stock to improve thermal performance and reduce energy consumption (Galimshina et al., 2020; Pittau et al., 2019; Gulotta et al., 2021). Several studies have applied LCA to evaluate the environmental performance of alternative construction systems, such as prefabrication and modular construction, due to the intensity of energy and significant carbon emissions associated with building construction (Balasbaneh and Ramli, 2020; Kamali et al., 2019). Another key area of current LCA research concerns the embodied impacts of buildings, which can be reduced by improving material efficiency and using alternative construction materials (Hertwich et al., 2019; Kylili and Fokaides, 2019).

Performing LCA for buildings is challenging due to numerous uncertain sources, such as service life, replacement rate, choice uncertainty, and emissions data. Researchers have used various approaches to address uncertainty, including probabilistic, statistical, and simulation-based methods (Goulouti et al., 2020; Morales et al., 2020; Ylmén et al., 2020). Various solutions have been developed to integrate LCA tools with building domain models, such as BIM, to facilitate LCA practice in the building sector. These solutions include using BIM to collect building material information (Soust-Verdaguer et al., 2017), embedding LCA data into the BIM model, or using plug-in tools to perform LCA calculations within BIM (Wastiels and Decuypere, 2019).

2.3. Machine learning advances in LCA

ML methods are increasingly applied in LCA to improve prediction accuracy, optimise processes, and manage large datasets. ML techniques can handle the complexity and uncertainty associated with LCA, providing more precise and reliable environmental impact assessments. Studies Ghoroghi et al. (2022) show that ML is commonly applied at the inventory level for prediction, finding missing data, and optimising during model simulation. ML methods can significantly enhance the precision of LCA results by identifying patterns and trends that may not be apparent through traditional analytical methods. This capability is particularly valuable in handling the vast amounts of data generated by IoT sensors and digital twin technologies. Developing ML techniques, including predictive model control and optimisation algorithms, can help policymakers deliver actionable information, thus developing various control strategies and corrective measures to reduce the gap between predicted and actual environmental impacts (Ghoroghi et al., 2022). These techniques can streamline the LCA process by automating data collection and processing, reducing the time and cost constraints traditionally associated with LCA studies.

Digital Twin technology can describe the multidimensional attributes of physical objects and reflect their entire life cycle by interacting with virtual models of these objects (Liu et al., 2023a). As a complete information model, a digital twin integrates the information of a project from different stages of the lifecycle into a model to facilitate better asset management and communication through data visualisations with participants (Kaewunruen et al., 2020). The use of digital twins for performance is critical and, for capital-intensive equipment such as jet engines, has proven to be successful in cost savings and improved reliability (Li et al., 2022). The benefits of Digital Twins for the construction and maintenance of trains include higher cost efficiency and an optimal schedule, helping to reduce unexpected consumption and waste (Guo et al., 2022). Digital twins can increase efficiency in building construction, management, and deconstruction (Chen et al., 2022) while improving the maintenance scheme and estimate the remaining useful life of electric machines (Liu et al., 2023b). Digital twins can evaluate performance throughout the life cycle of light rail systems in a digital twin environment, which is time-saving, flexible, and highly accurate. Therefore, digital twin technology can support LCA by providing real-time data and insights throughout the life cycle of a system.

In an LCA process, there is a large number of input parameters to be considered. Therefore, the factorial strategy is needed to reduce and mitigate the environmental impact of a complex artefact. In our evaluation, a built asset is used, that needs to be divided into discrete and manageable scenarios, such as optimising the energy mix of an energy system. When addressing these scenarios in isolation using ML, a reduction in environmental impacts through LCA can be applied more broadly (Ghoroghi et al., 2022).

Computational LCA explores a product or process environmental impact throughout its life cycle (Bare, 2011). FLASC (Fast Lifecycle Assessment for Synthetic Chemists) is a tool to assess the simplified life cycles of compounds and provides reduced lifecycle data for materials through processing. LCA is an internationally standardised method for assessing environmental burdens and resources consumed throughout the life cycle of products or processes (Balasbaneh and Ramli, 2020). The LCA method has been developed to assess the possible environmental impacts of technical processes and systems and is widely applied in research and industry (Balasbaneh and Ramli, 2020). LCA can be used to identify, classify, and evaluate the triple bottom line sustainability criteria (TBL) for mid-rise residential buildings based on a broad range of environmental and socioeconomic criteria (Hossaini et al., 2014).

2.4. SRI solutions

In the evolving landscape of sustainable urban development, Smart Readiness Indicators (SRI) solutions play a pivotal role in integrating advanced technologies such as IoT and Digital Twins to drive efficiency and sustainability in buildings. This section explores two key initiatives, DigiPLACE and CDBB, that exemplify these technologies' innovative approaches and applications in achieving sustainability goals.

DigiPLACE (Digital Platform for Construction) is a European initiative that aims to create a common digital framework for the construction industry and facilitate the adoption of digital technologies throughout Europe. DigiPLACE addresses several challenges in the construction industry, such as fragmented processes, inefficient resource use, and environmental impacts enabling seamless data sharing and collaboration between stakeholders, promoting transparency and reducing project delays and costs. This platform integrates various digital technologies, including BIM, IoT, and digital twins, to improve project management and LCA processes (Zook and Graham, 2007; Akroyd et al., 2020). The integration of LCA within DigiPLACE allows real-time monitoring and assessment of environmental impacts throughout the construction project's lifecycle. IoT sensors collect energy consumption, emissions, and resource use data, fed into digital twin models. These models simulate different scenarios and provide insight into the most sustainable practices, enabling stakeholders to make informed decisions that minimise environmental impacts and promote sustainability (Zook and Graham, 2007).

In the UK, the Center for Digital Built Britain (CDBB), on the other hand, focuses on developing and implementing digital twins, IoT, and BIM to enhance the design, construction, and operation of buildings and infrastructure (Akroyd et al., 2020). This framework promotes the use of digital twins to improve the management and maintenance of infrastructure assets, optimise resource use, and reduce environmental impacts (Akroyd et al., 2020). The CDBB enables dynamic and real-time environmental impact assessments by integrating LCA with digital twins. IoT sensors deployed on infrastructure assets provide continuous data streams on their performance, energy use, and environmental impacts. This data is integrated into digital twin models, allowing the simulation and optimisation of various scenarios. The real-time insights these models provide help stakeholders identify and implement sustainable practices, improving infrastructure management's overall efficiency and sustainability (Akroyd et al., 2020).

The above examples demonstrate that Digital Twins represent a cutting-edge approach to creating virtual replicas of physical assets that are continuously updated with real-time data. These technologies have significant applications in various sectors, including construction, urban planning, and environmental management (Xia et al., 2022). Digital twins provide a comprehensive view of the entire lifecycle of assets, from design and construction to operation and decommissioning. Digital twins offer real-time monitoring and analysis of assets' performance and environmental impacts by integrating IoT data streams. This continuous feedback loop identifies inefficiencies and areas for improvement, facilitating proactive management and optimisation (Xia et al., 2022).

In the context of LCA, digital twins offer a dynamic and precise tool for environmental impact assessments. IoT sensors collect data on various parameters such as energy consumption, emissions, and material use. This data is fed into digital twin models that simulate the environmental impacts of different scenarios and provide information on the most sustainable practices (Xia et al., 2022). These technologies support efficient resource management, reduce carbon footprints, and improve the quality of life of residents (Badawi et al., 2021). DigiPLACE and CDBB developments utilise digital twins technologies with SRI solutions to highlight the transformative potential of digital technologies in achieving sustainability goals. Using IoT, digital twins, and advanced data analytics, these initiatives provide dynamic, real-time environmental impact assessments that drive efficient and sustainable practices in urban development. This comprehensive approach improves the precision and relevance of LCA and supports the development of resilient and sustainable urban environments (Kumar et al., 2019). IoT technologies can collect data related to pollution, gas emissions, energy consumption, and various other parameters, enhancing the precision and relevance of LCA (Chen et al., 2022). For example, IoT sensors can monitor real-time data on energy usage, emissions, and other parameters, providing valuable insights for dynamic LCA models (Lu et al., 2021).

Digital twins enabled with IoT can provide a granular, real-time view of the performance of a building, improve the precision of embodied carbon assessments, and facilitate targeted strategies to reduce carbon emissions in the construction sector (Mukherjee et al., 2022). Continuous data streams from IoT sensors ensure that digital twin models are up to date, reflecting the actual conditions of the physical entities they represent. Integrating IoT networks into the LCA process can also improve connectivity, energy efficiency, and quality of services (Khan and Fernandez, 2019). Therefore, the IoT can be used to improve the efficiency of analysis and services and can be used in various fields to support LCA.

2.5. LCA emerging attempts

LCA approaches play a crucial role in urban sustainability and adaptation to climate change. The literature emphasises the need to adapt to climate change, which involves adjustments in various sectors such as agriculture, forest management, and natural resource management (Akinnagbe and Irohibe, 2015; Das, 2021; Chah et al., 2018; Mulyasari et al., 2023; Mushi and Edward, 2021; Das, 2021). The literature highlights the importance of understanding the perceptions and adaptation responses of different communities, such as rural farmers and small-scale fisheries communities, to climate change (Ofuoku, 2011; Mulyasari et al., 2023; Swai et al., 2012). This understanding is essential for developing practical LCA approaches tailored to specific urban contexts.

The literature also emphasises the importance of integrating traditional ecological knowledge into adaptation strategies to climate change (Hosen et al., 2019). Traditional knowledge associated with biodiversity can enrich the development of sustainable adaptation and mitigation strategies for climate change, particularly in urban settings. Furthermore, the literature emphasises the role of gender in adaptation practices, indicating that women are likely to be more affected by climate change and that gender-specific adaptation strategies must be considered (Swai et al., 2012), highlighting the importance of incorporating gender perspectives into dynamic LCA approaches for urban sustainability and adaptation to climate change. The literature reports also a need for policy formulation and institutional capacity building to support adaptation to climate change (Hanson et al., 2022; Okoro et al., 2022; Oramah and Olsen, 2021). Effective policies and funding mechanisms are essential to promote dynamic LCA approaches and ensure their integration into sustainable urban development plans. The literature also highlights the role of awareness and education in promoting sustainable soil nutrient management and agricultural adaptation in the face of climate change (Thiombiano et al., 2018), underscoring the importance of educational initiatives and awareness campaigns as part of dynamic LCA approaches in urban areas.

Furthermore, the literature emphasises the need for adaptive management and resilience in the face of climate change (Peterson et al., 1997). Adaptive policies and practices are crucial to address the dynamic and evolving nature of the impacts of climate change on urban environments. Several studies identify the potential of microfinance and livelihood support to help vulnerable populations adapt to climate change (Hammill et al., 2009), highlighting the importance of considering socioeconomic factors and livelihood support within LCA for urban sustainability and adaptation to climate change.

LCA approaches are gaining attention in the context of urban sustainability and adaptation to climate change (da Luz Rosário de Sousa et al., 2012). Dynamic approaches to urban stormwater management can be evaluated using LCA to compare the environmental efficiency of different strategies (da Luz Rosário de Sousa et al., 2012). LCA can be used to assess the environmental profile of a system and the distribution of burdens and impacts at various stages of the life cycle (Keoleian et al., 2003). LCA can also be used as an analytical tool to prevent pollution, life cycle design, and optimisation modelling (Keoleian et al., 2003). LCA has been used to analyse the environmental impacts of wastewater treatment technologies (WWT) in developing countries (Garrido et al., 2019). LCA can be used to compare the environmental benefits and burdens of phosphorus recovery in centralised and decentralised municipal wastewater systems (Moser et al., 2015). Therefore, LCA can be used to evaluate the environmental impact approaches to urban stormwater management, wastewater treatment, and phosphorus recovery. LCA can also be used as an analytical tool for pollution prevention, life cycle design, and optimisation modelling.

Digital twin technology, on the other hand, can be used to improve LCA by providing a virtual instance of a physical system that is continually updated with the latter's performance, maintenance, and health status data throughout the life cycle of the physical system (Kaewunruen et al., 2020; Madni et al., 2019). A digital twin integrates information from different stages of the life cycle of a project into a model to facilitate better asset management and communication through data visualisations with participants (Kaewunruen et al., 2020). The ability to connect in real-time to sensors deployed online in an environment has led to the emergence of the digital twin of the built environment, which aims to synchronise the real world with a virtual platform (Deng et al., 2021). Digital twin technology can extend the simulation to later life cycle phases as a core product/system functionality, which can help optimise system performance (Tao et al., 2018). Therefore, digital twin technology can enhance LCA by providing real-time data and insights throughout the life cycle of a system.

In conclusion, the literature provides valuable information on the role of dynamic LCA approaches in urban sustainability and adaptation to climate change. The review emphasises the need for tailored adaptation strategies, gender-sensitive approaches, policy support, traditional knowledge integration, and adaptive management to address the multifaceted challenges of climate change in urban environments. Although significant progress has been made in integrating digital twins, IoT, and ML with LCA, several gaps remain. Existing studies often focus on specific aspects, such as energy consumption or carbon emissions,

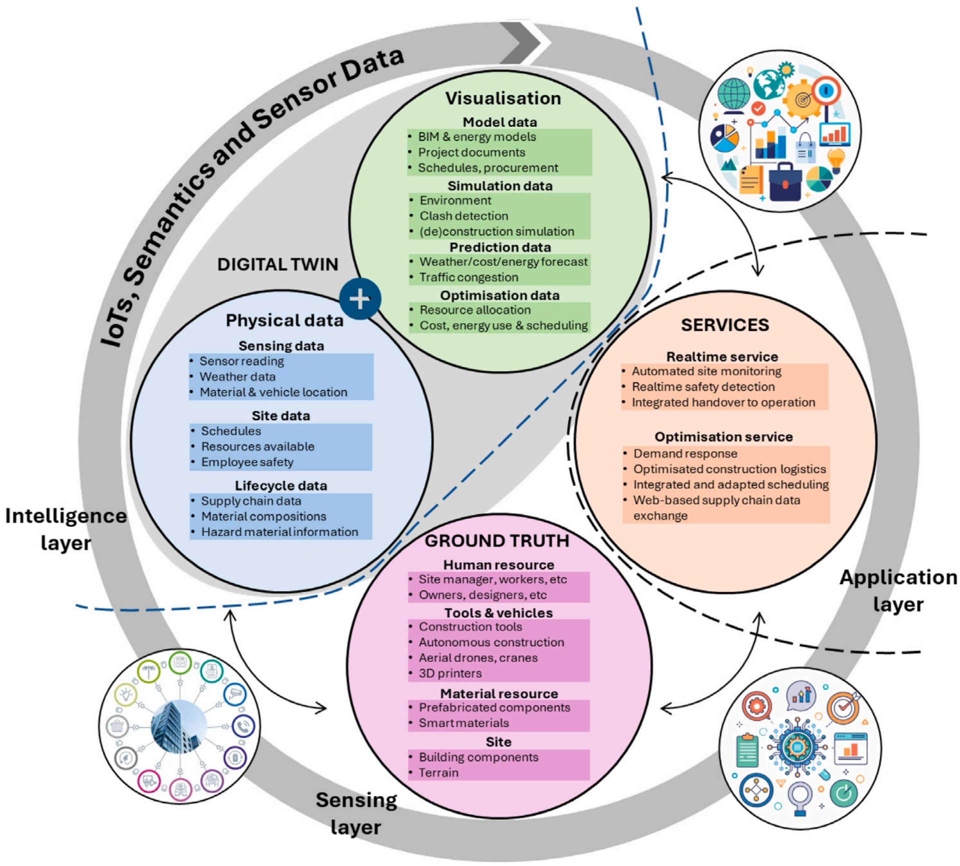

Fig. 1. A schematic of the architecture of digital twin-bearing life cycle model (BLDT) within the Computational Urban Sustainability Platform (CUSP).

without a comprehensive approach integrating multiple environmental and social factors. Additionally, the dynamic capabilities of digital twins are under-utilised in LCA methodologies, which traditionally rely on static models. While BLDT offers significant advantages, its reliance on real-time data raises concerns about privacy and security. Future work should explore robust encryption methods and compliance with data protection regulations.

3. A digital twin framework for LCA

This section introduces the Building Life-cycle Digital Twin (BLDT), a methodological framework developed to integrate digital twin technology with dynamic LCA processes. The BLDT framework enables near real-time environmental impact assessment within the built environment by combining continuous data streams, predictive analytics, and sustainability metrics. It operates as a core component of the Computational Urban Sustainability Platform (CUSP), a modular digital twin platform developed to support urban and industrial sustainability planning through data-driven simulation, optimisation, and decision-making tools.

CUSP is a cloud-integrated digital twin platform designed to support data-driven sustainability planning in urban and industrial environments. It enables dynamic interaction between physical assets and their virtual representations, using sensor data, machine learning, and semantic interoperability layers to monitor and evaluate building performance across multiple sustainability dimensions. The platform supports multi-domain assessments – spanning energy efficiency, emissions reduction, social well-being, and environmental compliance – through modular, scalable services.

The BLDT is embedded within CUSP as a specialised engine that conducts real-time LCA. While traditional LCA models offer static assessments that are updated periodically, BLDT within CUSP enables dynamic evaluations by integrating real-time sensor data and predictive analytics. This makes it particularly suitable for applications where sustainability metrics must be continuously monitored, such as ports, airports, and smart cities.

Fig. 1 presents the architecture of the BLDT framework within CUSP. The system captures data from physical assets using a network of sensors distributed across the Port of Grimsby. This data is then processed by a semantic middleware layer, which harmonises heterogeneous inputs into a unified structure based on ontologies (e.g., Brick schema). The processed data is passed through machine learning modules for predictive modelling and into LCA modules for real-time environmental assessment. The insights are finally delivered through the CUSP User Interface, which allows stakeholders to interact with visualisations, scenario simulations, and sustainability KPIs. The dynamic and modular nature of this architecture differentiates BLDT from conventional LCA approaches, offering a more flexible, adaptive, and real-time alternative that enhances operational and strategic decision-making in complex, data-rich environments.

3.1. Workflow and components

Fig. 2 illustrates the end-to-end workflow of the BLDT framework, showing how raw sensor data from the physical environment is processed through a semantic middleware layer, analysed via machine learning models, and evaluated in real-time using dynamic LCA tools. These components collectively enable continuous monitoring, scenario modelling, and adaptive decision support.

3.1.1. Semantic middleware component

The semantic middleware layer serves as the data translation and integration engine of the BLDT framework. It receives raw data from

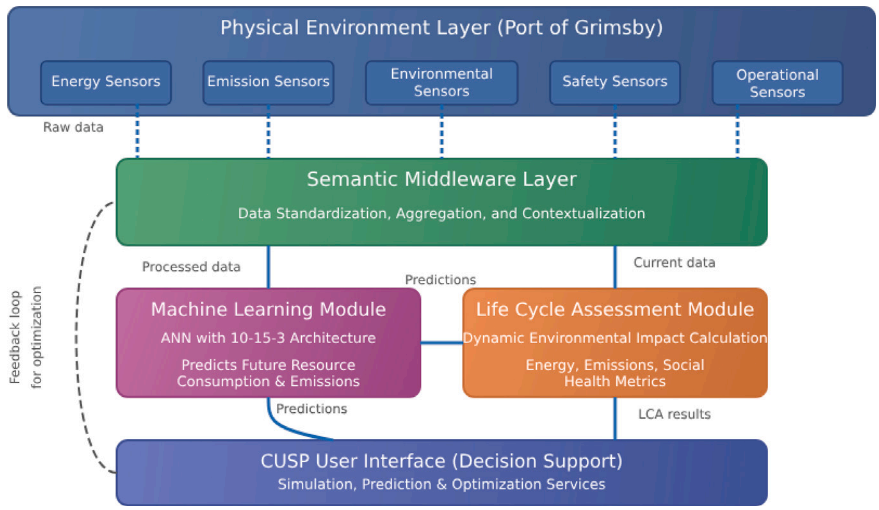

Fig. 2. Workflow diagram illustrating the data flow between components of the BLDT framework.

diverse sensors – measuring temperature, humidity, power usage, emissions, and occupancy – and converts them into a standardised semantic format compliant with ISO 13374-1. To enable interoperability, the system instantiates the Brick ontology, which models spatial and device relationships in a structured knowledge graph.

```
:Zone_Temp_Sensor_01 a brick:Temperature_Sensor ;
brick:isPointOf :Laboratory_Zone .
```

This process ensures that heterogeneous data sources are harmonised before being used for prediction or LCA characterisation. The middleware also timestamps, cleans, and organises incoming data streams, thus laying the foundation for accurate, high-resolution environmental modelling.

3.1.2. LCA modules

The dynamic LCA component processes both real-time sensor data and machine learning forecasts to evaluate the life-cycle impacts of port operations. It is structured into three key assessment domains:

- **Energy:** Focuses on monitoring energy use, load profiles, and operational efficiency. Smart metering and predictive analytics help detect anomalies, recommend optimisation strategies (e.g., load shifting), and evaluate the feasibility of renewables such as solar or wind power.
- **Social:** Integrates health and well-being indicators to assess the socio-environmental consequences of operational activities. Reductions in airborne pollutants (e.g., CO_2, $PM_{2.5}$) are evaluated for their effects on workforce health and nearby communities.
- **Environmental:** Quantifies emissions of CO_2, NO_x, and SO_x from vessel traffic, cargo handling, and building systems. Forecasted values are mapped to life-cycle inventory (LCI) flows and assessed using the ReCiPe 2016 (hierarchist) method within the Brightway2 framework, according to Algorithm 1. The system performs 15 min interval mapping for high temporal resolution.

Algorithm 1: Mapping ANN outputs to LCI flows

foreach $t \in$ *timestamps* **do**
  $\mathbf{f}(t) \leftarrow \mathbf{k} \cdot \hat{\mathbf{y}}(t)$;
  impact$(t) \leftarrow$LCIA$(\mathbf{f}(t))$;
end

3.1.3. Machine learning component: Data training and prediction

The BLDT framework employs a lightweight artificial neural network (ANN) to generate short-term predictions for energy consumption, carbon emissions, and safety-related conditions. This model enables proactive decision-making by forecasting environmental and operational parameters based on real-time data inputs.

- **Model design:** The ANN features 10 input neurons, a single hidden layer with 15 neurons, and 3 output neurons (energy, CO_2, and safety index). ReLU and linear activation functions are used for hidden and output layers, respectively, as detailed in Table 1.
- **Training and validation:** The model was trained using 35,401 records (15-min intervals) from the Port of Grimsby collected throughout 2023. Input features include power demand, temperature, humidity, wind speed, and tidal conditions across three time lags (t, t–30min, t–60min). Data were z-score normalised, with missing values under 2 min forward-filled. Larger gaps were discarded.
- **Performance metrics:** Cross-validation (blocked 5-fold) yielded MAE = 5.8 kWh, RMSE = 8.3 kWh, and R^2 = 0.92 for energy prediction. A baseline linear model achieved lower accuracy (MAE = 7.3 kWh, $R^2 = 0.81$), validating the ANN's effectiveness.
- **Interpretability:** SHAP analysis identified outdoor temperature and tidal state as the most influential variables, jointly explaining 61% of model variance.
- **Hyperparameter optimisation:** Bayesian tuning (100 trials) determined optimal values: learning rate = 10^{-3}, batch size = 256, random seed = 42.
- **Data accessibility:** All training scripts and model weights are archived within Cardiff University's secure research data repository and available to qualified researchers under NDA.

3.2. Sensor setup and quality assurance

Twelve IoT sensor nodes were deployed across the Port of Grimsby, including:

- Environmental monitors: Bosch BME680 for T–RH–VOC and Plantower PMS7003 for $PM_{2.5}$.
- Power meters: Smart meters for building-wide and zonal energy use.
- Occupancy and CO_2 sensors: Installed at critical indoor and control zones.

Table 1
Architecture and parameters of the Artificial Neural Network (ANN). These choices balance rapid training and inference (critical for real-time LCA updates) with sufficient model accuracy on dynamic port data.

Parameter	Value
Input Layer Neurons	10
Hidden Layer Neurons	15
Output Layer Neurons	3
Activation Function (Hidden Layer)	ReLU
Activation Function (Output Layer)	Linear
Optimiser	Adam
Learning Rate	0.001
Batch Size	32
Epochs	100
Loss Function	Mean Squared Error (MSE)
Training Data Split	70% Training, 15% Validation, 15% Testing

Table 2
Sensor deployment and interface configuration.

Parameter measured	Sensor type	Port zone	Connection type
Temperature	iPoint	Quay 3 control room	I/O to AS
Temperature	iPoint	Sub-station B	Gateway
Humidity	iPoint	Quay 3 control room	I/O to AS
Humidity	SHO100	Sub-station B	Gateway
CO_2	iPoint	Quay 3 control room	I/O to AS
CO_2	iPoint	Sub-station B	Gateway
Occupancy	Smart Meter	Quay 3 control room	I/O to AS
Occupancy	Smart Meter	Sub-station B	Gateway
Energy consumption	Smart Meter	Whole building	I/O to AS
Thermal consumption	Smart Meter	Whole building	I/O to AS

Each sensor node aggregates readings every 60 s and transmits data in JSON-LD format via LoRaWAN to a central MQTT broker. TimescaleDB is used for long-term storage. A nightly QA/QC routine performs the following:

- Filters out-of-range values based on manufacturer specifications.
- Applies a three-sigma spike filter.
- Flags clock drift and performs timestamp correction.
- Runs calibration conformity checks (two-point factory recalibration every six months, following Spinelle et al. (2015)).

The uncertainty of ±2% sensor drift and ANN residuals was propagated using a first-order Taylor expansion, yielding a combined uncertainty of ±7% (95% CI) on annual global warming potential (GWP) values(see Table 2).

4. Case study: dynamic BLDT application

This section presents a case study demonstrating the implementation and validation of the BLDT framework at the Port of Grimsby. The case study follows a structured approach, beginning with an energy and carbon audit to establish baseline conditions, followed by LCA integration of various scenarios, and concluding with an analysis of the results and benefits achieved. A detailed audit established the carbon and energy profile at Grimsby Port as a baseline for analysis. Subsequently, the CUSP digital twin simulated different energy management and carbon reduction scenarios. This phase aimed to identify optimal strategies that balance operational efficiency with environmental sustainability. The selection of IoT sensors was based on their ability to capture real-time energy, emissions, and safety data. At the same time, ML algorithms were chosen for their predictive accuracy and scalability. As such, our approach to dynamic LCA supports the Port of Grimsby's decarbonisation goals and sets a promising benchmark for other ports. By integrating energy, social, and environmental considerations, we ensure that the strategies developed are holistic and sustainable. This facilitated the development of a resilient maritime industry and provided a vision of a future in which sustainability is at the core of port operations.

- **Simulation services** within the CUSP platform leverage IoT sensor data and semantic middleware to create accurate digital replicas of physical systems. For the Port of Grimsby, this involves simulating the port's operational processes, infrastructure usage, and energy consumption patterns. Simulation capabilities allow stakeholders to explore different scenarios, such as varying levels of cargo throughput, energy usage under various weather conditions, and the impact of infrastructure upgrades on operational efficiency.
- **Prediction Services** of CUSP use ML algorithms and historical data to forecast future trends and potential issues. At the Port of Grimsby, prediction models can estimate future energy demands, anticipate maintenance needs, and forecast the impact of increased shipping activities on local traffic and environmental conditions. By predicting these variables, port authorities can proactively manage resources, schedule maintenance, and implement mitigation strategies to minimise adverse impacts.
- **Optimisation services** focus on enhancing operational efficiency and sustainability. For the Port of Grimsby, these services involve optimising energy usage, improving logistics, and reducing carbon emissions. Optimisation algorithms consider multiple factors, such as energy prices, cargo handling times, and emission limits, to provide actionable recommendations. These services ensure the port operates efficiently while adhering to environmental regulations and safety standards.

The implementation of BLDT at the Port of Grimsby resulted in a 25% reduction in energy consumption and a 15% decrease in carbon emissions over six months, demonstrating its practical efficacy.

4.1. Lifecycle assessment aspects

Fig. 3 illustrates the CUSP's user interface (UI) in action using data and models from the Port of Grimsby. This interface integrates various functionalities to facilitate simulation, prediction, and optimisation services, offering users a comprehensive view of the port's operational parameters. UI elements are designed to support detailed analysis and decision-making, particularly in the context of lifecycle assessments that include technical, social, and environmental aspects;

4.1.1. Technical assessment (energy efficiency)

The CUSP platform integrates real-time energy monitoring, predictive analytics, and optimisation tools for a dynamic LCA focusing on energy, social and environmental analysis at the Port of Grimsby. The energy assessment of the CUSP platform at the Port of Grimsby begins with deploying IoT sensors to capture real-time data on energy consumption across various port operations. This data is processed by semantic middleware, providing a detailed overview of energy performance. The semantic middleware then processes this data, contextualising it within the port's broader operational framework. Simulation services test various energy-saving measures and predict their impact on overall energy consumption. Fig. 4 displays historical and real-time data trends fed into predictive models, which forecast future conditions based on current and past data. Optimisation algorithms then identify the most effective strategies for reducing energy usage, such as shifting to renewable energy sources, upgrading to energy-efficient equipment, and scheduling cargo handling activities during off-peak hours to reduce energy costs.

4.1.2. Social assessment (health and safety)

Incorporating social factors into the dynamic LCA involves a detailed assessment of health and safety conditions at the Port of Grimsby. IoT sensors monitor environmental conditions, such as indoor air temperature and noise levels, to assess health and safety and track worker activities. The semantic middleware processes this data to identify potential health and safety risks. Simulation models evaluate different

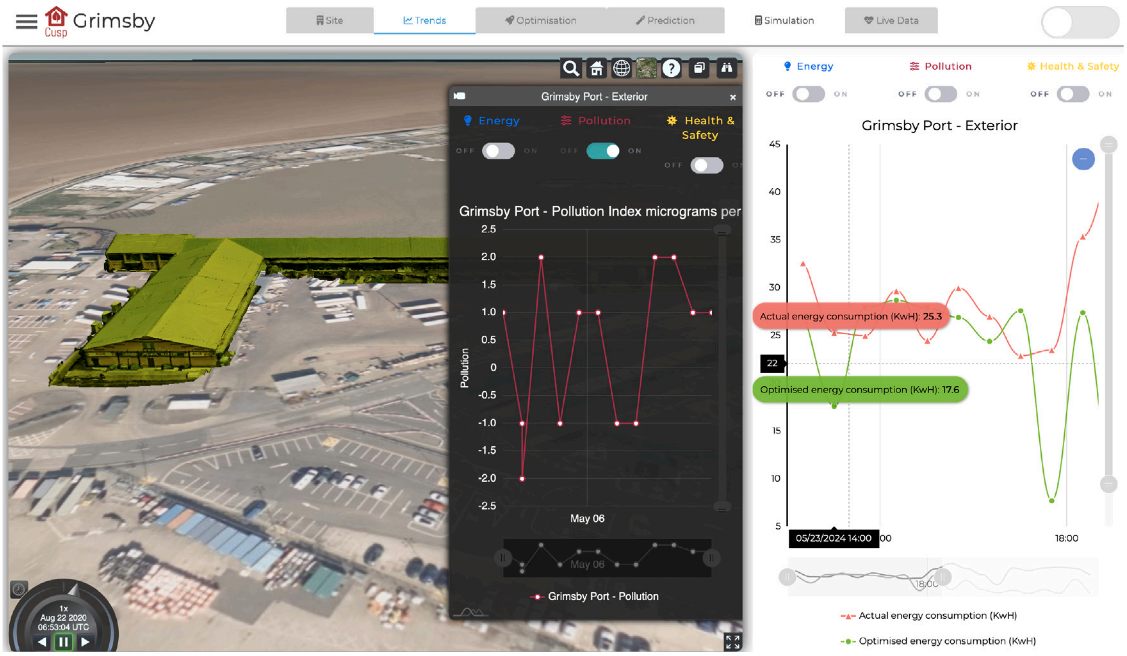

Fig. 3. The Port of Grimsby Digital Twin through the Computational Urban Sustainability Platform (CUSP).

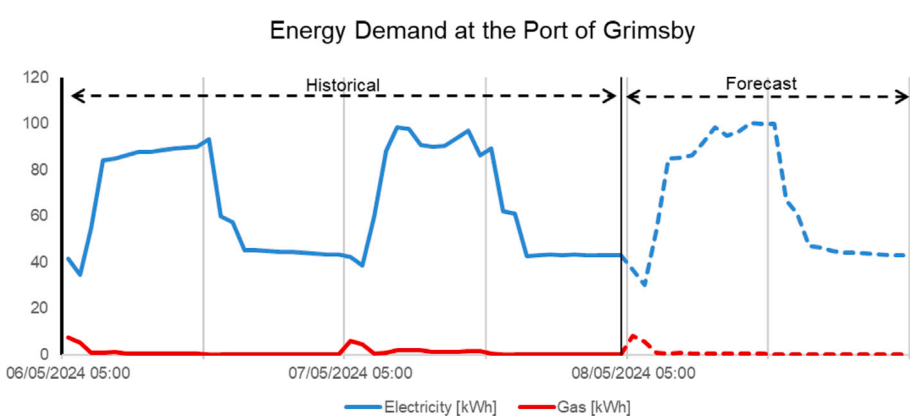

Fig. 4. The Port of Grimsby Digital Twin, future energy needs based on historical and current energy loads.

safety scenarios, such as emergency evacuations or hazardous material spills. Prediction algorithms forecast the next 24-hour profiles of indoor air temperatures based on historical data and outdoor conditions, as shown in Fig. 5.

Optimisation services recommend strategies to enhance worker safety and well-being, such as improving ventilation systems, implementing noise reduction measures, and providing comprehensive safety training programmes. For example, the platform can identify high-risk areas where additional safety protocols are needed or suggest modifications to work schedules to minimise exposure to harmful conditions.

4.1.3. *Environmental assessment (carbon emissions)*

The assessment of environmental factors, particularly carbon emissions, is critical for the dynamic LCA at the Port of Grimsby.

Carbon emissions are assessed by analysing the data streams of IoT sensors, which track emissions from various sources, including ships, trucks, and port machinery. The semantic middleware interprets these data to provide a comprehensive view of the port's carbon footprint. Simulation models explore the impact of emission reduction strategies, such as adopting low-emission fuels, electrifying port vehicles, and optimising logistics to reduce idle times. Prediction models forecast future emissions based on projected port activities and regulatory changes, as displayed in Fig. 6. Optimisation services identify the most effective measures to minimise emissions while maintaining operational efficiency. For example, the platform can recommend transitioning to electric vehicles for on-site transportation, implementing a more efficient scheduling system for cargo handling to reduce idle times, and retrofitting older machinery with cleaner technologies.

4.2. *Integrative dynamic lifecycle assessment*

The dynamic LCA approach at the Port of Grimsby integrates energy, social, and environmental factors to provide a holistic assessment. The process begins with comprehensive data collection through IoT sensors, which monitor energy usage, health and safety conditions, and carbon emissions. The semantic middleware processes this data, creating a detailed and context-aware profile of the port's operations.

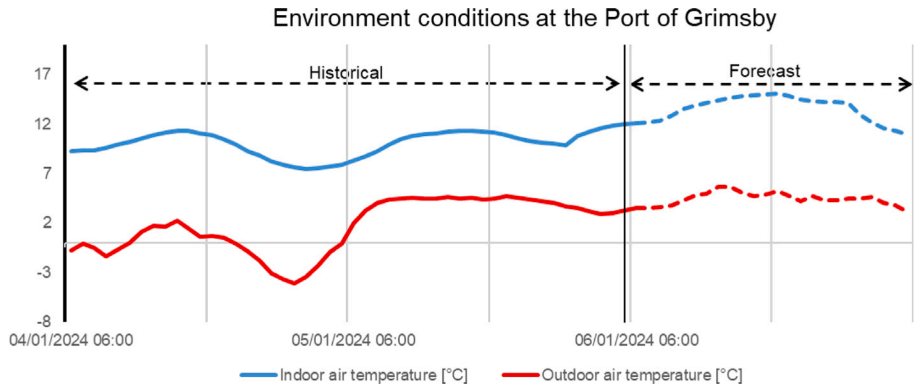

Fig. 5. Predicting future indoor and outdoor air temperature at the Port of Grimsby based on historical and real-time data.

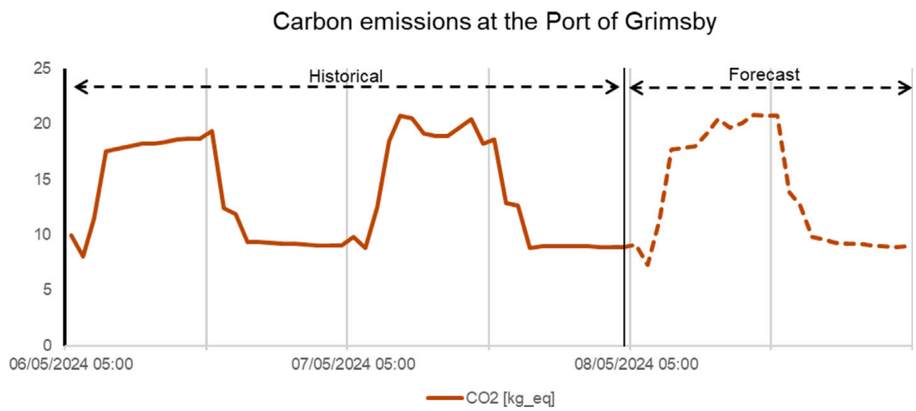

Fig. 6. Predicting future carbon emissions of the Port of Grimsby based on historical and real-time data.

The simulation services then test various scenarios to evaluate the impact of different strategies on energy consumption, worker safety, and emissions. Prediction models forecast future trends, allowing for proactive management and planning. Optimisation services provide actionable recommendations to enhance overall sustainability.

By integrating these assessments, the CUSP platform enables port authorities to make informed decisions that balance operational efficiency, worker safety, and environmental sustainability. For example, the platform can recommend combining energy savings measures, safety protocols, and emission reduction strategies that collectively improve the port's sustainability profile. This comprehensive approach ensures that all relevant factors are considered, leading to a more effective and sustainable port operations management.

The application of the CUSP platform at the Port of Grimsby demonstrates the potential of digital twin technology for performing dynamic lifecycle assessments. By integrating energy, social, and environmental factors, the platform provides a holistic and comprehensive approach to sustainability. Simulation, prediction, and optimisation services enable port authorities to make informed decisions that improve operational efficiency, worker safety, and environmental sustainability. This case study highlights the importance of a dynamic and context-sensitive LCA, showcasing the value of the CUSP platform in achieving sustainable urban management.

5. Discussion

This section critically evaluates the findings of our research, comparing the BLDT framework with traditional LCA approaches and discussing the implications for environmental impact assessment in the built environment. We examine both the advantages and challenges of implementing dynamic LCA through digital twin technologies. Although dynamic LCA offers numerous benefits, it also presents challenges, including the potential for inconsistencies in methodological approaches and the difficulty in aggregating localised data for broader analyses. Ensuring the comparability of LCA results across different regions requires the development of harmonised frameworks and guidelines that maintain a balance between standardisation and flexibility (Guinée et al., 2011).

In this paper, we have explored the transformative potential of integrating LCA with Digital Twins in the built environment, focusing on an LCA in a port industrial site. Our primary objective was to develop and validate a framework that enhances the precision and applicability of environmental impact assessments by leveraging these advanced technologies. By addressing the research questions, we aimed to bridge the gap between traditional static LCA methodologies and the dynamic, real-time, data-driven capabilities of digital twins and IoT.

Our research demonstrates that digital twins can significantly enhance the accuracy and efficiency of LCA by providing real-time data and continuous updates on environmental conditions. The dynamic LCA model we developed integrates these technologies to create a 'living' model that reflects real-world conditions more accurately than traditional static models. For example, in our case study of the Port of Grimsby, IoT sensors continuously monitored energy consumption, emissions, and safety conditions, providing granular data that enriched the digital twin and allowed precise real-time environmental impact assessments. This continuous data flow ensures that the LCA model remains current, improving the reliability and relevance of the assessments.

Integrating digital twins into traditional LCA methodologies presents challenges and opportunities. One significant challenge is the complexity of managing and analysing the vast amounts of data generated

Table 3
Comparison between BLDT and Traditional LCA approaches.

Aspect	BLDT	Traditional LCA
Data Update Frequency	Continuous (real-time)	Periodic (often annual)
Predictive Capability	ML-based forecasting	Limited or none
Granularity of Results	Captures short-term variations	Averages over time periods
User Intervention	Ongoing optimisation	Post-assessment only
Case Study Outcome	25% energy reduction in 6 months	No interim improvements

by IoT sensors. This requires robust data processing and management systems and advanced analytical techniques, such as ML to extract meaningful insights. Ensuring interoperability between different systems and standards is critical to seamless integration. However, the opportunities are substantial. Digital Twin integration facilitates more detailed and contextually relevant environmental assessments, as local conditions and real-time data can be incorporated into the LCA. This leads to more accurate and actionable information, allowing stakeholders to make informed decisions that align with sustainability goals. Our research highlighted the potential for predictive analytics, enabled by ML algorithms, to anticipate future environmental impacts and optimise strategies proactively, further improving the efficacy of LCA.

The BLDT framework offers several significant advantages over traditional LCA approaches, as summarised in Table 3. Traditional LCA typically relies on static data collected at specific points in time, resulting in assessments that may not reflect current conditions. In contrast, BLDT continuously integrates real-time data from IoT sensors, enabling near-instantaneous updates to environmental impact calculations. This dynamic approach provides more accurate and timely insights, allowing for more responsive decision-making.

Integrating LCA with digital twin technologies significantly contributes to urban sustainable development by providing a comprehensive tool for environmental management. In the Port of Grimsby case study, the dynamic LCA framework allowed detailed assessments of energy consumption, emissions, and health and safety conditions. This holistic approach ensured that sustainability considerations were integrated into all aspects of port operations, from energy management to waste reduction and safety protocols. The predictive capabilities of the framework enable city planners and policymakers to anticipate and mitigate future environmental impacts, thus fostering long-term sustainability. By identifying sustainability hotspots and providing actionable recommendations, the framework supports the development of resilient urban infrastructure that minimises environmental footprints and promotes social well-being.

Beyond the port case study presented in this paper, the BLDT framework has potential applications in other types of buildings. In domestic buildings, a similar approach could continuously monitor energy consumption, indoor air quality, and occupant comfort, enabling real-time adjustments to building management systems. In urban transportation networks, dynamic LCA could assess the environmental impact of traffic patterns, informing decisions on traffic management and infrastructure development. Manufacturing facilities could implement BLDT to monitor production processes and identify opportunities for reducing resource consumption and emissions.

Our research successfully addressed the main objectives and research questions by developing and validating a novel framework that integrates LCA with digital twin technologies by addressing the following aspects:

Energy efficiency assessment The monitored real-time energy usage and digital twins simulated various energy-saving measures, such as adopting renewable energy sources and energy-efficient equipment. This led to actionable insights that helped reduce the port's energy consumption and carbon footprint.

Health and safety assessment The framework's ability to monitor and simulate health and safety conditions ensured potential risks were proactively identified and mitigated. For example, air quality and noise levels were continuously monitored, and simulation models evaluated the impact of different safety scenarios, enhancing worker safety and community well-being.

Environmental assessment By providing real-time data on emissions and enabling the simulation of various emission reduction strategies, the framework supported the development of effective measures to minimise the port's environmental impact. For instance, transitioning to low-emission fuels and electrifying port vehicles were identified as viable strategies to reduce carbon emissions.

6. Future work

The integration of LCA with Digital Twin technologies can make a substantial contribution to sustainable urban development, potentially shaping the future of our cities.

Developing more sophisticated ML algorithms and data analytics tools is essential to handle the complexity and volume of data generated by IoT sensors. This advancement could significantly improve the accuracy and speed of environmental impact assessments, leading to more informed decision-making and more effective sustainability strategies. Techniques such as deep learning, reinforcement learning, and ensemble methods could be explored to enhance the precision and predictive capabilities of the dynamic LCA model. Furthermore, integrating anomaly detection algorithms will help identify outliers and unexpected patterns in real-time, ensuring continuous improvement and reliability of environmental impact assessments.

Expanding the framework application to diverse sectors and urban environments will help generalise its benefits and validate its effectiveness across various contexts. Future research could investigate the implementation of the dynamic LCA model in residential, commercial, and industrial settings. Each environment presents unique characteristics and challenges that can offer valuable insights and refine the framework. For example, applying the model in residential areas could focus on energy efficiency and waste management, while industrial settings might prioritise emissions reduction and resource optimisation. This diversification will showcase the versatility and robustness of the framework, making it a universally applicable tool for sustainable development.

Establishing standardised protocols and frameworks for interoperability between different sensor systems, digital twins, and LCA tools is not just important but crucial for broader adoption and integration. The diversity of IoT systems, digital twins, and the varying data formats and structures can make standardisation complex. Future work should develop and promote industry-wide standards that facilitate the integration of diverse technologies. Collaboration with international standards bodies and industry stakeholders will be vital in creating guidelines that ensure compatibility, data integrity, and security between different platforms and systems. This concerted effort will lead to a more cohesive ecosystem in which various technologies can work together harmoniously, enhancing LCA practices overall efficiency and effectiveness.

Collaboration with policymakers is a critical next step to integrate the dynamic LCA framework into regulatory and planning processes. Future work should focus on developing guidelines and policy toolkits that support the implementation of advanced technologies in environmental impact assessments. By working closely with regulatory bodies, we can ensure that the BLDT framework becomes an integral part of sustainability governance, supporting evidence-based policy development and implementation.

Enhancing stakeholder engagement through participatory approaches will ensure that local knowledge and preferences are incorporated into the LCA process. This inclusion will improve the relevance and acceptance of the assessments and support community-driven sustainability initiatives. In the proposed participatory LCA framework, stakeholders, including local communities, industry representatives, and policymakers, will provide data and actively contribute to the assessment process.

Integrating the dynamic LCA framework with emerging technologies such as blockchain, artificial intelligence (AI), and edge computing can be a gateway to a new era of sustainable urban development. Blockchain can ensure the transparency and security of data, while AI can provide advanced analytical insights and automation capabilities. Edge computing can facilitate real-time data processing and decision-making at the source, reducing latency and improving responsiveness of LCA workflows. Addressing these areas for future work can significantly improve the integration of LCA with digital twin and IoT technologies, providing a powerful tool to achieve sustainable urban analytics. This comprehensive approach will ensure that environmental impact assessments are accurate, relevant, and actionable, supporting the global effort to build more resilient and sustainable cities.

7. Conclusion

This study has presented the Building Life-cycle Digital Twin (BLDT) framework, an integrated, real-time approach to environmental impact assessment that advances traditional Life Cycle Assessment (LCA) methodologies. Developed within the Computational Urban Sustainability Platform (CUSP), the framework combines digital twin technologies, Internet of Things (IoT) sensor data, semantic interoperability, and machine learning algorithms to enable dynamic and predictive environmental modelling. By addressing the inherent limitations of static LCA, the BLDT offers a robust, adaptable solution for sustainability evaluation in the built environment.

The novelty of this framework lies in its ability to transform LCA from a one-off, retrospective analysis into a continuous, data-driven process. The BLDT enables real-time updates based on actual operational data, delivering a high-resolution view of energy use, emissions, and health-related impacts. This real-time capacity allows stakeholders to identify sustainability hotspots, forecast future impacts, and adjust operational strategies accordingly. In doing so, the framework supports a new paradigm of proactive, evidence-based environmental decision-making.

In response to the research questions, this study has shown:

- RQ1: The research demonstrates that digital twin technologies substantially improve the accuracy and responsiveness of LCA. Real-time data streams and continuous model updates ensure that assessments remain aligned with evolving operational conditions, yielding more reliable and actionable insights.
- RQ2: While integrating digital twins, IoT, and ML poses challenges
  – such as data heterogeneity and system interoperability – these are addressable through semantic middleware and structured data pipelines. The benefits, including higher granularity and contextual specificity in LCA outputs, far outweigh the integration complexities.
- RQ3: The framework enhances sustainability in the built and urban environment by equipping stakeholders with a powerful decision-support tool. It facilitates scenario analysis, energy optimisation, emissions mitigation, and social impact evaluations—each contributing to holistic urban environmental management.

The Port of Grimsby case study validated the framework's real-world applicability. By deploying IoT-enabled monitoring and predictive analytics, the BLDT facilitated a 25% reduction in energy consumption over the study period. It also identified operational inefficiencies and improved worker safety by integrating environmental and social metrics. These results demonstrate that BLDT can meaningfully inform sustainability strategies, regulatory compliance, and investment decisions in urban infrastructure.

This research underscores the potential for dynamic LCA frameworks to reshape how environmental assessments are conducted in practice. As urban environments become increasingly sensorised and data-rich, tools like BLDT will be essential for operationalising sustainability in real-time. The framework aligns with policy shifts towards adaptive, context-sensitive regulation and provides a robust platform for ongoing innovation in environmental performance management.

CRediT authorship contribution statement

Ioan Petri: Writing – original draft, Methodology, Funding acquisition, Conceptualization. **Amin Amin:** Validation, Software, Data curation. **Ali Ghoroghi:** Validation, Formal analysis, Data curation. **Andrei Hodorog:** Visualization, Software, Data curation. **Yacine Rezgui:** Writing – review & editing, Supervision, Investigation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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