DELIVERABLE 1.1

Integral components of smart buildings whole life digitized assessment

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1. Introduction

1.1. Overview of the SmartWins Project

The **SmartWins** project aims to advance the research and development of **smart, energy-efficient, and carbon-neutral buildings** through the integration of **Digital Twin technologies, Life Cycle Assessment (LCA), and Building Information Modelling (BIM)**. The project recognizes the growing need for **sustainable urban development and data-driven decision-making** in the construction and building management sectors. The **built environment** is responsible for a significant proportion of global energy consumption and carbon emissions, making it imperative to implement **holistic, whole-life cycle impact assessments** for smart buildings.

Deliverable **D1.1 – Integral Components of Smart Buildings Whole Life Digitized Assessment** provides a **structured analysis of sustainability assessment frameworks**, data integration techniques, and advanced methodologies required to evaluate the **entire life cycle of buildings**. By leveraging **real-time monitoring technologies, material impact assessments, and digital automation**, the deliverable contributes to the **broader goal of decarbonizing the building sector** while ensuring compliance with evolving **energy policies and regulatory frameworks**.

1.2. The Need for a Multi-Disciplinary Approach in Smart Building Assessments

The assessment of **smart buildings** requires an **interdisciplinary** approach, combining **environmental, technological, and economic evaluations**. By integrating:

- **Sustainability evaluation tools**, such as LCA, to assess the **environmental footprint of materials and energy use**.
- **Digital monitoring technologies**, such as **IoT sensors, RFID systems, and automated data analytics**, to optimize **building performance in real-time**.
- **Advanced simulation models**, including **BIM-based automation and Digital Twin technology**, to predict **long-term energy efficiency and material sustainability**.

This **interconnected approach** ensures that **smart buildings** are not only **energy-efficient but also resilient, adaptable, and designed with long-term sustainability in mind**. Within the European Union, several policy frameworks reinforce the importance of **sustainable building strategies**, including:

- The **Energy Performance of Buildings Directive (EPBD)**, which mandates the transition to **Zero Emission Buildings (ZEBs) by 2030**.

- The **Energy Efficiency Directive (EED)**, which enforces **building renovation strategies and digital energy management solutions**.
- The **Renewable Energy Directive (RED)**, which promotes the integration of **renewable energy sources and whole-life energy assessments**.

These **directives mandate the use of LCA-driven sustainability assessments and digital monitoring tools** to **optimize energy performance and resource allocation**. By embedding **LCA, BIM, and Digital Twin methodologies into the smart building framework**, the **SmartWins project** aligns with these **regulatory requirements** while paving the way for **innovative sustainability solutions**.

1.3. Scope and Objectives of Deliverable D1.1

This deliverable focuses on the **whole-life cycle impact assessment of smart buildings**, with an emphasis on four key research areas:

1. **Life Cycle Assessment (LCA) methodologies**, emphasizing **benchmarking sustainability performance across different European building geometries**.
2. **Integration of Digital Twins with IoT and RFID**, enabling **real-time monitoring, automation, and predictive maintenance**.
3. **Enhancing LCA applications through BIM-based automation**, ensuring **seamless data-driven environmental assessments**.
4. **Exploring how smart buildings impact user performance and well-being**, with a focus on **educational environments, indoor air quality, and occupant comfort**.

Each of these **research pillars** contributes to the **broader goal of creating data-driven, sustainable building ecosystems** that are **optimized for efficiency, environmental impact, and user experience**.

1.3.1 Integrating LCA for Whole-Life Building Sustainability

LCA methodologies play a crucial role in **quantifying the environmental impact of buildings** across their entire **life cycle**, from **material extraction and production to operational energy use and eventual deconstruction or reuse**. This deliverable explores:

- **The relationship between building geometry, climatic factors, and sustainability performance**.
- **How digital assessment tools improve material selection and embodied carbon tracking**.
- **Circular economy strategies for reducing waste and improving material lifecycle performance**.

1.3.2 Digital Twins and RFID for Smart Monitoring and Decision-Making

The integration of **Digital Twin technologies** with **RFID and IoT sensors** allows for **real-time, data-driven decision-making in smart buildings**. The deliverable discusses:

- **How Digital Twins create a virtual counterpart of a physical building**, enabling continuous monitoring and predictive modeling.
- **The role of RFID in tracking materials, energy consumption, and system performance** to optimize **building operations**.
- **The benefits of real-time data analytics and AI-driven simulations in reducing carbon emissions and improving occupant well-being**.

These technologies play a fundamental role in **building automation, fault detection, and sustainability performance optimization**.

1.3.3 Enhancing LCA with BIM-Based Automation

BIM integration enhances **LCA assessments** by enabling **automated material tracking, embodied carbon calculations, and energy performance analysis**. This deliverable explores:

- **BIM as a digital tool for improving sustainability assessments through enhanced visualization and simulation capabilities**.
- **The role of LCA-BIM plug-ins in automating environmental impact calculations**.
- **BIM-based deconstruction planning tools for optimizing material reuse and circular construction strategies**.

1.3.4 User-Centric Smart Building Design and Well-Being

The **impact of smart buildings on user comfort and productivity** is a key consideration in sustainability assessments. This deliverable evaluates:

- **The influence of smart building technologies on indoor air quality, lighting conditions, and thermal comfort**.
- **How IoT-enabled environmental monitoring enhances occupant well-being and building performance**.
- **The integration of adaptive HVAC systems and smart automation to reduce energy waste while maintaining user comfort**.

1.4. Relevance to Smart Building Research

Smart buildings rely on a combination of **digitalization, automation, and sustainability frameworks** to **optimize energy efficiency, reduce resource consumption, and enhance indoor environmental quality**. This deliverable provides a **comprehensive**

synthesis of methodologies, case studies, and technological advancements, offering a **holistic perspective on how digital assessment tools drive sustainable building practices**.

The integration of **RFID-based monitoring, BIM-enhanced LCA, and real-time data analytics** marks a **transformative shift in sustainability assessments**, enabling **smarter, data-driven decision-making in the built environment**.

1.4.1 Structure of the Deliverable

To provide a structured and in-depth analysis, the deliverable is organized into the following sections:

- **Section 2 (Background):** Reviews the **state-of-the-art methodologies** in **LCA, Digital Twin technology, and BIM applications** for smart building assessments.
- **Section 3 (Methodology & Achievements):** Explores the **key data integration techniques, case studies, and experimental findings** used in sustainability assessments.
- **Section 4 (Gained Knowledge by KTU):** Highlights the **scientific and technical advancements** achieved in smart building research.
- **Section 5 (Individual Section, if applicable):** Discusses **additional findings or emerging methodologies** beyond the core research scope.
- **Section 6 (Conclusions):** Summarizes the **key takeaways, policy implications, and recommendations for future research directions**.

2. Background

2.1. State of the Art Review on Smart Building Assessments and Whole-Life Cycle Impact Studies

2.1.1 Introduction to Smart Building Assessments

Smart buildings incorporate **advanced digital technologies, energy efficiency strategies, and sustainable construction practices** to enhance both **operational performance and environmental sustainability**. The growing need for **low-carbon, high-efficiency, and intelligent buildings** has led to increased adoption of methodologies such as **Life Cycle Assessment (LCA), Building Information Modelling (BIM), and Digital Twin technology**. These approaches enable a **comprehensive analysis of sustainability performance across the entire building life cycle**, encompassing **design, construction, operation, maintenance, renovation, and end-of-life considerations**.

The assessment of **whole-life cycle impacts** in smart buildings requires the integration of **environmental, social, and economic factors** to **optimize resource efficiency, minimize emissions, and enhance resilience**. This approach aligns with **global climate policies, European energy directives, and Industry 4.0 advancements**, promoting **data-driven decision-making in the built environment**.

This section reviews **key methodologies, digital innovations, regulatory frameworks, and emerging trends** in smart building assessments, emphasizing the role of **LCA, BIM, and Digital Twins** in **evaluating and improving sustainability performance**.

2.1.2 Methodologies for Smart Building Sustainability Assessments

Life Cycle Assessment (LCA) for whole building sustainability analysis

LCA is a standardized methodology for **quantifying the environmental impacts of buildings** across their full life cycle. It provides a **data-driven approach to assessing energy use, carbon footprint, material efficiency, and waste generation**, enabling **sustainability comparisons across different building typologies and construction strategies**.

LCA is structured into **four primary life cycle stages**:

- **Production Phase (A1–A3):** Includes **raw material extraction, processing, and manufacturing** of building components.
- **Construction Phase (A4–A5):** Covers **transportation, assembly, and on-site construction activities**.
- **Operational Phase (B1–B7):** Encompasses **energy consumption, maintenance, retrofitting, and renovation** during the building's lifetime.

- **End-of-Life Phase (C1–C4):** Includes **demolition, deconstruction, material recovery, recycling, and final disposal**.

The evolution of **Dynamic LCA (DLCA)**[1] **and real-time monitoring techniques** has allowed for **continuous evaluation of energy and resource consumption** throughout a building's life cycle. The use of **digital tools such as BIM-integrated LCA models** improves **efficiency and accuracy**, facilitating **automated material tracking, embodied carbon analysis, and compliance with sustainability benchmarks**.

Building Information Modelling (BIM) for Life Cycle Assessment

BIM has revolutionized **sustainability assessment in smart buildings** by **integrating 3D modeling, environmental simulations, and automated data collection** into the LCA process. The convergence of **BIM and LCA** enhances **real-time material selection, energy performance optimization, and carbon footprint reduction** [2].

Key applications of **BIM in LCA-based building assessments** include:

- **Automated material impact analysis** through LCA-BIM plug-ins.
- **Simulation of embodied carbon and energy efficiency performance**.
- **Building envelope optimization** for improved thermal performance and reduced energy demand.
- **Post-occupancy monitoring** to track **real-world sustainability performance**.

Research demonstrates that **BIM-enhanced LCA can reduce material waste by 30-50% and improve energy efficiency by up to 20%**, compared to **conventional sustainability assessment methods** [3]. The integration of **BIM with Digital Twin technology** further strengthens **data-driven building assessments and real-time performance optimization**.

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[1] Sohn, J., Kalbar, P., Goldstein, B., & Birkved, M. (2020). Defining temporally dynamic life cycle assessment: a review. *Integrated environmental assessment and management*, *16*(3), 314-323.

[2] Panteli, C., Kylili, A., & Fokaides, P. A. (2020). Building information modelling applications in smart buildings: From design to commissioning and beyond A critical review. *Journal of Cleaner Production*, *265*, 121766.

[3] Anand, C. K., & Amor, B. (2017). Recent developments, future challenges and new research directions in LCA of buildings: A critical review. Renewable and sustainable energy reviews, 67, 408-416.

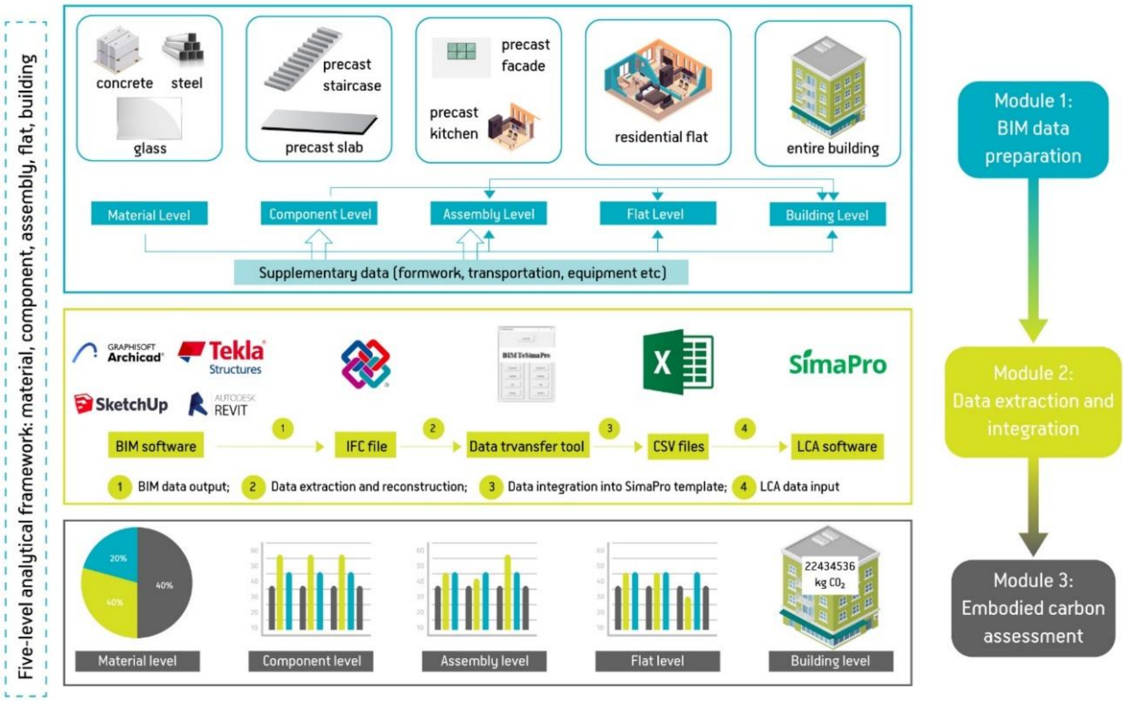

Figure 1. The framework of the developed BIM-integrated LCA solution.

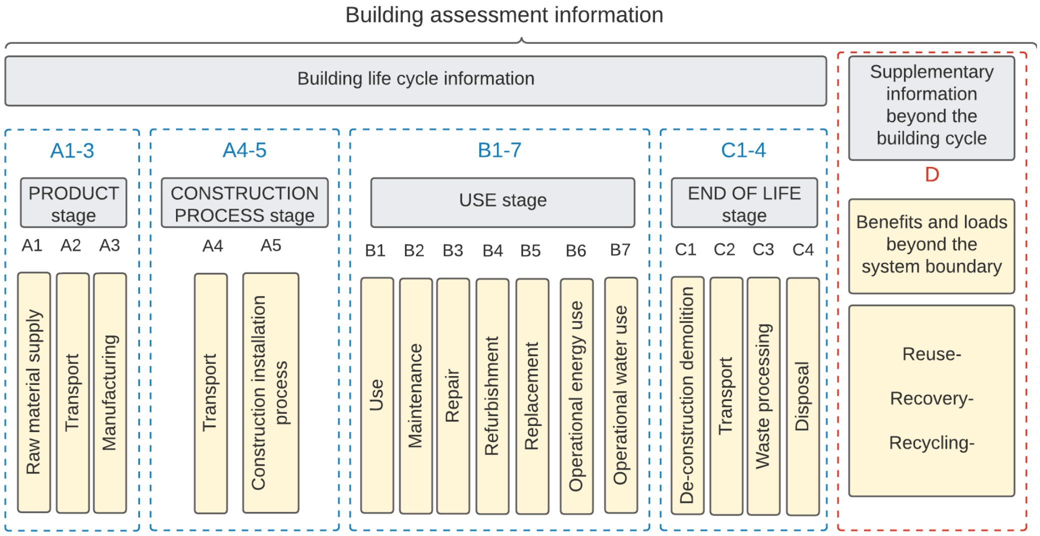

Figure 2. Building's LCA stages according to EN 15978 [4]

[4] CEN (European Committee for Standardization). (2011). EN 15978: Sustainability of construction works – Assessment of environmental performance of buildings – Calculation method. Brussels, Belgium.

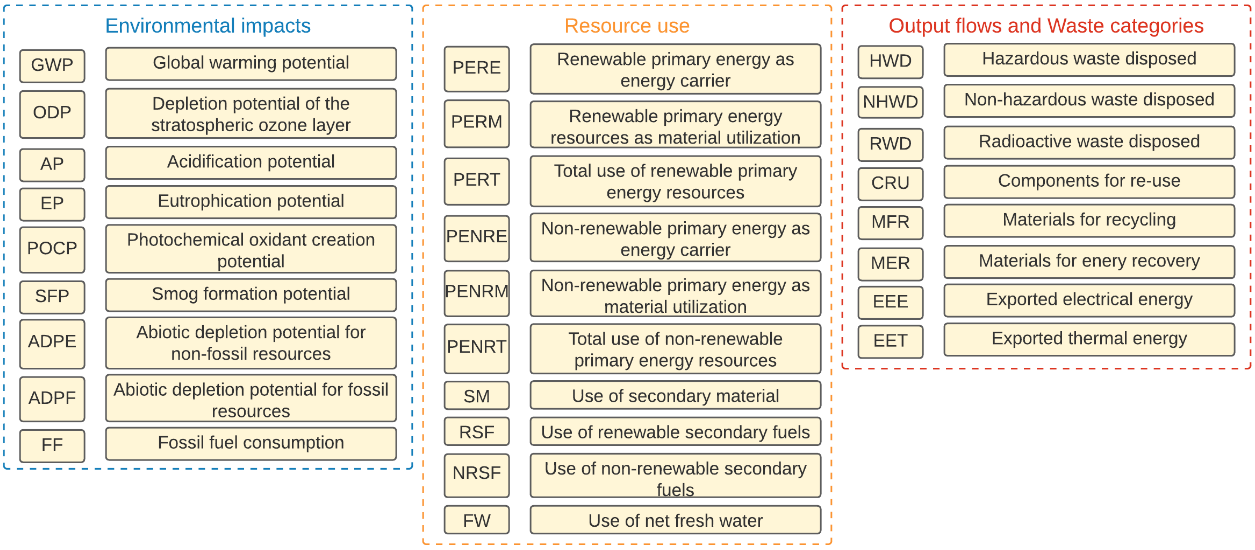

Figure 3. Information categories presented in EPDs

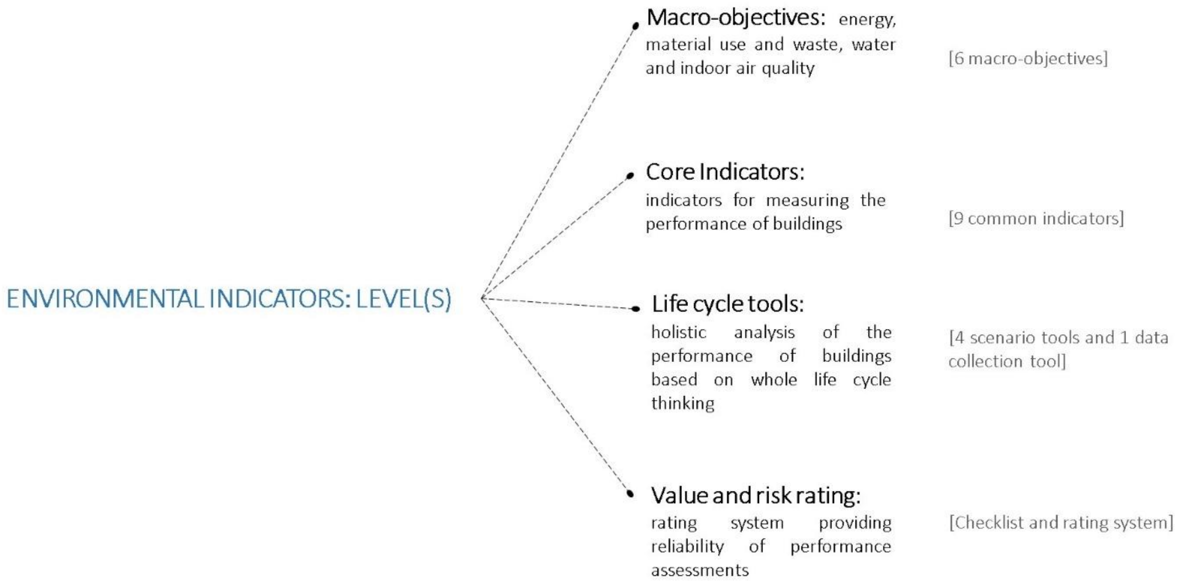

Figure 4. Diagram of Level(s) objectives

Digital Twin Technology for Whole-Life Cycle Impact Assessment

Digital Twin technology represents a significant advancement in **smart building assessments**, creating **real-time digital replicas of physical structures** that continuously update through **IoT sensors, AI-driven analytics, and energy performance simulations**. Digital Twins enhance **predictive maintenance, resource efficiency, and environmental performance monitoring**.[5]

The integration of **Digital Twins in life cycle assessment frameworks** allows for:

[5] Yang, S., Yu, Z., Ma, W., Ma, L., Li, C., Fu, L., ... & Yang, Y. (2023). Coupling the digital twin technology and life cycle assessment: carbon dioxide emissions from polysilicon production. *Sustainable Production and Consumption*, *41*, 156-166.

- **Proactive maintenance strategies**, reducing operational carbon emissions.
- **Optimization of resource allocation**, improving **material efficiency and energy use**.
- **Enhanced occupant comfort and smart automation**, responding to **real-time environmental conditions**.
- **Data-driven decision-making for renovations and adaptive reuse**, extending the **functional life of buildings**.

Studies indicate that **Digital Twin technology can improve building efficiency by 30-40%**, contributing to **significant carbon reductions and operational cost savings** [6]. The **convergence of Digital Twins, BIM, and LCA** ensures a **comprehensive and data-driven approach to sustainability in smart buildings**.

2.1.3 Policy and Regulatory Frameworks for Smart Building Assessments

Smart building assessments are increasingly shaped by **regulatory frameworks at global, national, and EU levels**, ensuring that **sustainability and energy efficiency targets are met**. The **European Union (EU) has implemented directives and standards** to enforce **sustainable construction practices and whole-life cycle accountability**.

Energy Performance of Buildings Directive (EPBD) [7]

The EPBD establishes **mandatory sustainability criteria** for **new and existing buildings**, including:

- **Zero Emission Building (ZEB) requirements** for new constructions by 2030.
- **Mandatory integration of LCA methodologies** for carbon footprint reduction.
- **Implementation of Digital Twins, BIM, and smart monitoring systems** for optimized energy performance.

Energy Efficiency Directive (EED)[8]

The EED enforces measures to **reduce energy demand in buildings**, requiring:

- **Retrofitting strategies for existing structures** to improve energy efficiency.
- **Smart energy management systems** and **real-time performance monitoring**.

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[6] Chen, C., Zhao, Z., Xiao, J., & Tiong, R. (2021). A conceptual framework for estimating building embodied carbon based on digital twin technology and life cycle assessment. *Sustainability*, *13*(24), 13875.
[7] European Parliament & Council of the European Union. (2024). *Directive (EU) 2024/1275 of the European Parliament and of the Council of 24 April 2024 on the energy performance of buildings (recast)*. Official Journal of the European Union, L 156, 75-91. https://eur-lex.europa.eu/eli/dir/2024/1275/oj/eng
[8] European Parliament & Council of the European Union. (2023). Directive (EU) 2023/1791 of the European Parliament and of the Council of 13 September 2023 on energy efficiency (recast). *Official Journal of the European Union*, L 231, 1-74. https://eur-lex.europa.eu/eli/dir/2023/1791/oj

- **Integration of LCA in building renovation programs** to evaluate **embodied energy**.

Renewable Energy Directive (RED)[9]

The RED promotes the **adoption of on-site renewable energy solutions** to achieve **climate neutrality goals**, including:

- **Life cycle energy analysis** to quantify the impact of renewable integration.
- **Decarbonization strategies through energy efficiency improvements**.
- **Smart grid integration for enhanced energy management**.

Together, these directives drive the **digitalization of sustainability assessments**, ensuring **smart buildings align with carbon neutrality objectives and regulatory compliance**.

2.1.4 Emerging Trends in Smart Building Assessments

Ongoing advancements in **smart building assessment methodologies** are focused on:

Artificial Intelligence and Machine Learning for LCA

- AI-driven **material selection algorithms** optimize **carbon reduction strategies**.
- Machine learning models predict **energy consumption trends and adaptive efficiency solutions**.

Circular Economy and Smart Material Reuse

- Development of **circular LCA models** to improve **material recovery and reuse**.
- BIM-integrated **deconstruction planning tools** for sustainability tracking.

Blockchain for Sustainability Tracking

- **Secure and transparent recording of material sourcing and emissions data**.
- **Decentralized certification systems** to enforce **sustainability compliance**.

Human-Centric Smart Building Design

- **Adaptive HVAC and IAQ monitoring systems** to improve occupant well-being.
- **Real-time feedback loops based on user behavior modeling** for energy efficiency.

[9] European Parliament & Council of the European Union. (2023). *Directive (EU) 2023/1791 of 13 September 2023 on the promotion of the use of energy from renewable sources (recast)*. Official Journal of the European Union, L 231, 1-128.

2.2. The Role of LCA in Smart Buildings

2.2.1 Overview of Life Cycle Assessment in Smart Buildings

Life Cycle Assessment (LCA) is a critical tool for evaluating the environmental performance of buildings throughout their entire lifespan, from material extraction and manufacturing to construction, operation, maintenance, and eventual demolition or reuse. The integration of LCA into smart building assessments ensures that sustainability performance is quantified using a systematic and data-driven approach [10].

The application of LCA allows for the analysis of material choices, energy consumption patterns, carbon footprint, and waste generation, offering insights into the long-term environmental impact of different design decisions. With the growing emphasis on climate-conscious construction and stringent energy regulations, incorporating LCA methodologies into smart building design has become essential for achieving carbon neutrality and compliance with regulatory frameworks.

Buildings in different climatic regions exhibit significant variations in energy performance and sustainability. To optimize the environmental performance of smart buildings, assessments must consider region-specific factors such as thermal performance, insulation efficiency, and material selection. The use of standardized LCA approaches enables architects, engineers, and policymakers to implement tailored sustainability strategies based on local climate conditions [11].

2.2.2 Influence of Building Geometry and Climatic Conditions on Sustainability Performance

The sustainability performance of buildings is heavily influenced by their geometry and climatic context. Different building typologies—ranging from single-family homes to multifamily residential buildings—demonstrate varying levels of embodied and operational carbon emissions [12].

Buildings designed for cooler climates tend to incorporate high-performance insulation, compact forms, and energy-efficient heating systems, leading to lower life cycle emissions. In contrast, buildings in warmer climates often require additional cooling systems, which, if not optimized, can increase overall energy consumption. [13]

[10] Fnais, A., Rezgui, Y., Petri, I., Beach, T., Yeung, J., Ghoroghi, A., & Kubicki, S. (2022). The application of life cycle assessment in buildings: challenges, and directions for future research. *The International Journal of Life Cycle Assessment*, *27*(5), 627-654.
[11] Walter, S., Chavez-Okhuysen, D., Achour, M., Dia, A., Avril, L., & Makhoul, N. (2023, October). Life Cycle Assessment of a Smart Building: Energy Optimization Integration. In *The Proceedings of the International Conference on Smart City Applications* (pp. 481-496). Cham: Springer Nature Switzerland.
[12] Akbarnezhad, A., & Xiao, J. (2017). Estimation and minimization of embodied carbon of buildings: A review. *Buildings*, *7*(1), 5.
[13] Mahmoud, H., & Ragab, A. (2020). Urban geometry optimization to mitigate climate change: Towards energy-efficient buildings. *Sustainability*, *13*(1), 27.

These variations in performance highlight the need for climate-adapted building design, ensuring that construction methods align with environmental conditions to minimize carbon footprints.

Building geometry plays a crucial role in determining the sustainability impact of a structure [14]. Compact, well-insulated designs with minimal thermal bridging tend to exhibit superior energy efficiency. Larger, more complex structures, while offering benefits such as increased natural ventilation potential, may also result in higher embodied energy and construction material demand.

The relationship between thermal performance and sustainability is evident in cost-optimal energy efficiency strategies, where well-insulated envelopes and passive design techniques reduce heating and cooling loads, lowering operational energy consumption. However, achieving sustainability goals requires balancing operational performance with material efficiency, ensuring that buildings meet energy efficiency standards while minimizing embodied carbon.

2.2.3 Material Selection and Embodied Carbon Considerations

The choice of materials significantly impacts the life cycle environmental footprint of a building. Conventional materials such as concrete and steel contribute substantially to embodied carbon emissions due to energy-intensive manufacturing processes. By contrast, bio-based and low-carbon alternatives such as timber, hempcrete, and recycled materials offer opportunities to enhance sustainability performance[15].

LCA-based decision-making facilitates the selection of environmentally responsible materials by quantifying their long-term impact. The use of environmental product declarations (EPDs) enables designers to assess material-specific carbon footprints, leading to more informed choices in construction projects[16].

For smart buildings, material selection is further enhanced through digital modeling and simulation, allowing for scenario-based evaluations of sustainability performance. This enables the integration of materials with high thermal efficiency, durability, and recyclability, ensuring long-term environmental benefits.

To promote circular economy practices, life cycle thinking must extend beyond initial material selection. Designing for deconstruction and reuse ensures that materials can be repurposed at the end of a building’s life cycle, reducing landfill waste and minimizing resource depletion. Integrating LCA-driven circular economy strategies

[14] Lotteau, M., Loubet, P., & Sonnemann, G. (2017). An analysis to understand how the shape of a concrete residential building influences its embodied energy and embodied carbon. *Energy and Buildings*, *154*, 1-11.
[15] Grazieschi, G., Asdrubali, F., & Thomas, G. (2021). Embodied energy and carbon of building insulating materials: A critical review. *Cleaner Environmental Systems*, *2*, 100032.
[16] Passer, A., Lasvaux, S., Allacker, K., De Lathauwer, D., Spirinckx, C., Wittstock, B., ... & Wallbaum, H. (2015). Environmental product declarations entering the building sector: critical reflections based on 5 to 10 years experience in different European countries. *The International Journal of Life Cycle Assessment*, *20*, 1199-1212.

into smart buildings strengthens sustainability performance while aligning with emerging regulatory requirements for embodied carbon reduction.

2.2.4 Enhancing LCA with Digital Integration

The integration of LCA with digital design tools and building information modeling (BIM) represents a major advancement in sustainability assessments. Digital workflows enable automated data collection and material inventorying, streamlining the evaluation of environmental impacts across different construction and operation scenarios.

BIM-based LCA assessments offer several key advantages [17]:

- **Automated Material Impact Analysis**: Digital models facilitate rapid assessments of embodied carbon, eliminating the need for extensive manual calculations.
- **Dynamic Performance Simulations**: Smart buildings can be designed with real-time sustainability optimization, allowing designers to adjust specifications based on predictive LCA models.
- **Improved Data Interoperability**: Linking BIM with LCA databases ensures seamless integration with regulatory sustainability benchmarks.

Digital integration also enhances post-occupancy monitoring, providing a continuous feedback loop for sustainability performance. IoT sensors and smart meters enable real-time tracking of energy consumption, allowing for adjustments to improve efficiency. These technologies contribute to whole-life sustainability by optimizing both embodied and operational carbon management [18].

Another critical aspect of digital integration is its role in supporting prefabrication and modular construction techniques. By simulating various design scenarios before construction begins, digital tools can minimize material waste, improve logistical efficiency, and optimize resource use. The use of digital twins—virtual representations of buildings that evolve alongside their physical counterparts—further enhances sustainability by enabling data-driven maintenance strategies and long-term performance optimization [19].

2.2.5 Whole-Life Carbon Optimization Strategies

Smart building design must account for both operational and embodied carbon to achieve true sustainability. Whole-life carbon optimization involves:

[17] Hollberg, A., Genova, G., & Habert, G. (2020). Evaluation of BIM-based LCA results for building design. *Automation in construction*, *109*, 102972.
[18] Santos, R., Costa, A. A., Silvestre, J. D., Vandenbergh, T., & Pyl, L. (2020). BIM-based life cycle assessment and life cycle costing of an office building in Western Europe. *Building and Environment*, *169*, 106568.
[19] Eneyew, D. D., Capretz, M. A., & Bitsuamlak, G. T. (2022). Toward smart-building digital twins: BIM and IoT data integration. *IEEE access*, *10*, 130487-130506.

- **Reducing Embodied Carbon**: Selecting low-impact materials, optimizing structural efficiency, and incorporating carbon sequestration techniques.
- **Enhancing Operational Performance**: Integrating passive design principles, high-performance building envelopes, and renewable energy systems.
- **Promoting Adaptive Reuse**: Designing buildings with flexibility for future retrofits, expansions, and repurposing.

Adopting whole-life carbon strategies requires a shift from conventional assessment methods toward more dynamic, data-driven approaches. Integrating real-time energy modeling with LCA methodologies allows for continuous monitoring and refinement of sustainability performance.

Regulatory frameworks increasingly emphasize whole-life carbon accounting as part of building certification and compliance measures. This approach ensures that smart buildings are designed not only for immediate energy efficiency but also for long-term environmental resilience.

2.3. Digital Twin and RFID Integration

2.3.1 Introduction to Digital Twin Technology in Smart Buildings

Digital Twin technology has emerged as a powerful tool for optimizing smart building performance by creating **virtual representations of physical assets**. These digital replicas continuously update in real-time through **sensor data, Internet of Things (IoT) devices, and advanced simulation algorithms**. By integrating **real-world operational data** with predictive analytics, Digital Twins enable **enhanced decision-making, proactive maintenance, and resource efficiency** in the built environment [20].

One of the key enablers of Digital Twin technology is **RFID (Radio Frequency Identification)**, which facilitates real-time tracking of materials, components, and building elements. RFID technology allows for **seamless integration between physical and digital environments**, ensuring that data is continuously updated to reflect the actual conditions of the built asset [21].

2.3.2 The Role of RFID in Smart Buildings

RFID technology is widely recognized for its ability to **enhance automation, streamline asset tracking, and improve operational efficiency** in smart buildings[22]. The key applications of RFID in construction and building management include:

[20] Voipio, V., Elfvengren, K., Korpela, J., & Vilko, J. (2023). Driving competitiveness with RFID-enabled digital twin: case study from a global manufacturing firm's supply chain. *Measuring Business Excellence*, *27*(1), 40-53.
[21] Demčák, J., Židek, K., & Krenický, T. (2024). Digital twin for monitoring the experimental assembly process using RFID technology. *Processes*, *12*(7), 1512.
[22] Jia, M., Komeily, A., Wang, Y., & Srinivasan, R. S. (2019). Adopting Internet of Things for the development of smart buildings: A review of enabling technologies and applications. *Automation in construction*, *101*, 111-126.

- **Material and Component Tracking**: RFID tags embedded in **construction materials and prefabricated components** allow for real-time tracking of their movement, reducing waste and optimizing supply chain logistics.
- **Facility Management and Maintenance**: RFID-enabled sensors provide continuous updates on **building system conditions**, allowing predictive maintenance strategies to be implemented efficiently.
- **Security and Access Control**: Smart buildings utilize **RFID-based access control systems** to manage entry permissions and track personnel movement within facilities.

RFID's ability to **collect and transmit data wirelessly** makes it a valuable asset for **real-time monitoring of building systems**, particularly when combined with **Digital Twin environments**[23].

2.3.3 Integration of RFID with Digital Twins

Digital Twins **synchronize the physical and digital worlds**, and RFID provides a crucial link by ensuring that **real-time data from physical assets is accurately reflected in the virtual model** [24]. The integration of RFID and Digital Twin technology supports:

- **Dynamic Updating of Building Models**: RFID-tagged components allow Digital Twins to **continuously update with real-world changes**, ensuring accurate and up-to-date asset models.
- **Predictive Analytics for Building Maintenance**: RFID-enabled sensors detect **early signs of system failures**, feeding data into Digital Twin platforms for **predictive maintenance scheduling**.
- **Enhanced Energy Performance Monitoring**: By tracking real-time energy use and occupant behaviors, RFID and Digital Twins **help optimize energy consumption** and identify areas for efficiency improvements.

In smart construction, RFID tags can be embedded within **structural elements, HVAC components, and electrical systems**, allowing for **automated condition monitoring** throughout a building's life cycle. This level of automation minimizes the need for **manual inspections**, reducing costs and enhancing efficiency.

[23] Spachos, P., Papapanagiotou, I., & Plataniotis, K. N. (2018). Microlocation for smart buildings in the era of the internet of things: A survey of technologies, techniques, and approaches. *IEEE Signal Processing Magazine*, *35*(5), 140-152.
[24] Demčák, J., Židek, K., & Krenický, T. (2024). Digital twin for monitoring the experimental assembly process using RFID technology. *Processes*, *12*(7), 1512.

2.3.4 Challenges and Opportunities in RFID-Digital Twin Integration

While the benefits of integrating RFID with Digital Twins are significant, there are challenges that must be addressed for widespread adoption[25]:

- **Data Security and Privacy**: Since RFID transmits sensitive operational data, **cybersecurity measures** must be in place to **prevent unauthorized access**.
- **Interoperability Issues**: The lack of **standardized protocols** for integrating RFID systems with Digital Twin platforms can lead to **compatibility challenges** across different vendors.
- **Implementation Costs**: Deploying RFID-based monitoring systems requires **initial investments in infrastructure**, though these costs are often offset by long-term operational savings.

Despite these challenges, **advancements in IoT, AI, and cloud computing** continue to improve the feasibility of RFID-Digital Twin integration. Emerging **standardized data-sharing frameworks** are also facilitating seamless interoperability, enabling buildings to benefit from **real-time digital simulations and enhanced operational efficiency**.

[25] Komma, P., Vogelbruch, M., & Jung, M. (2024, August). Digital Twins in Industrial Automation: A Closer Look On RFID Read/Write Components for Virtual Commissioning. In *2024 IEEE 22nd International Conference on Industrial Informatics (INDIN)* (pp. 1-8). IEEE.

3. Methodology and Achievements

3.1. Implementation of Smart Building LCA Approaches

The content presented in the *Methodology and Achievements* section is informed by and builds upon findings and methodologies developed in prior academic works. Specifically, the principles, analytical frameworks, and case insights are derived from the following peer-reviewed studies:

- Klumbyte, E., Georgali, P. Z., Spudys, P., Giama, E., Morkunaite, L., Pupeikis, D., ... & Fokaides, P. (2023). *Enhancing whole building life cycle assessment through building information modelling: principles and best practices*. *Energy and Buildings*, 296, 113401.
- Osadcha, I., Jurelionis, A., & Fokaides, P. (2024). *Patterns and trends in the use of RFID within the construction industry and Digital Twin architecture: a Latent Semantic Analysis*. *International Journal of Sustainable Energy*, 43(1), 2421281.
- Spudys, P., Osadcha, I., Morkunaite, L., Manhanga, F. C., Georgali, P. Z., Klumbyte, E., ... & Fokaides, P. (2024). *A comparative life cycle assessment of building sustainability across typical European building geometries*. *Energy*, 302, 131693.
- Vestfal, P., & Seduikyte, L. (2024). *Systematic review of factors influencing students' performance in educational buildings: focus on LCA, IoT, and BIM*. *Buildings*, 14(7), 2007.

3.1.1 Introduction to Whole-Life Cycle Assessment in Smart Buildings

Life Cycle Assessment (**LCA**) is a key methodology in the evaluation of smart buildings, enabling the **quantification of environmental impacts** across the entire building lifespan. By assessing **resource consumption, carbon emissions, material efficiency, and energy performance**, LCA provides a **data-driven approach** to improving sustainability in the built environment. The integration of **digital tools** such as **Building Information Modelling (BIM), Digital Twins, and IoT-driven analytics** enhances the precision and applicability of LCA, ensuring that smart buildings achieve **greater efficiency, resilience, and regulatory compliance**.

Traditional building assessments often focus **primarily on operational energy use**, but a **whole-life cycle approach (WLCA)** extends this perspective to include **embodied carbon, material sustainability, construction impacts, and end-of-life disposal**. This **holistic methodology** ensures that environmental performance is **measured comprehensively**, providing insights into how **design decisions, material selection, and building management strategies** influence long-term sustainability.

3.1.1.1. Integrating Whole-Life Cycle Assessment in Smart Buildings

The effectiveness of WLCA in smart buildings relies on **precise data integration, real-time monitoring, and accurate predictive models**. The key challenges in implementing WLCA include:

- **Ensuring interoperability between different digital platforms**, such as **BIM, LCA software, and IoT-based monitoring systems**.
- **Developing standardized material databases** to accurately assess **embodied carbon and life cycle energy demand**.
- **Linking sustainability performance to real-time building operation**, allowing for **dynamic optimization of energy use and resource efficiency**.

By addressing these challenges, WLCA enables smart buildings to be **evaluated across multiple life cycle stages**, ensuring that **sustainability benchmarks** are met for:

- **Material selection and supply chain efficiency** during the design and construction phases.
- **Operational energy consumption and maintenance strategies** for in-use performance optimization.
- **End-of-life deconstruction and material recovery**, supporting **circular economy principles** in the built environment.

Key Areas of Smart Building LCA Implementation

The **application of LCA in smart buildings** extends across multiple domains, where digital tools and simulation technologies play a crucial role. This section highlights three core areas of implementation:

Benchmarking Building Geometries and Thermal Performance

Building geometry significantly affects **thermal performance, energy consumption, and material efficiency**. By analyzing different building typologies and climatic adaptations, LCA methodologies can:

- **Identify optimal geometries that minimize heat loss in cold climates and reduce cooling loads in warm climates**.
- **Evaluate the impact of building form on passive design strategies**, such as **daylighting, ventilation, and thermal mass optimization**.
- **Optimize surface-to-volume ratios** to improve **insulation efficiency and material use**.

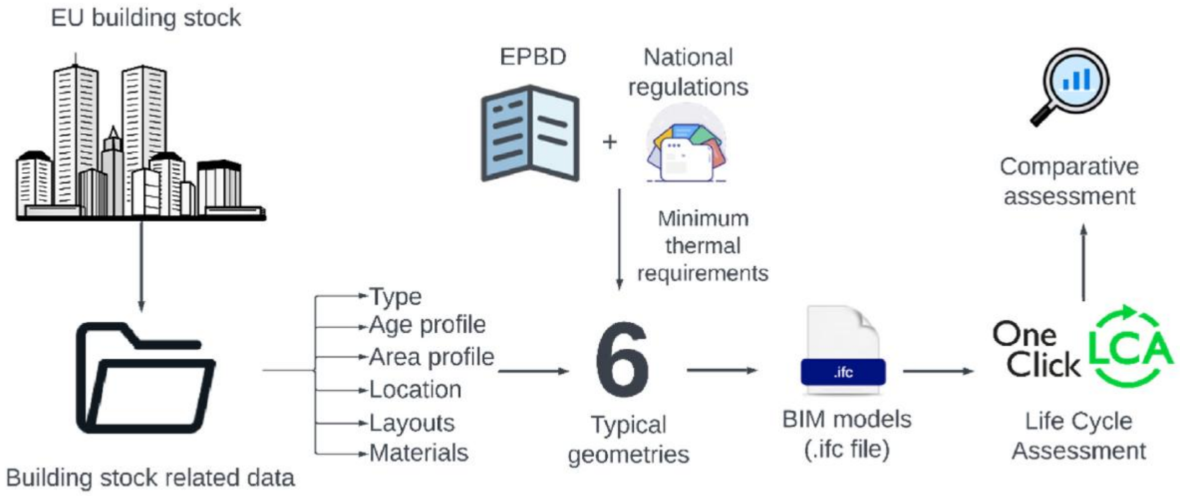

Figure 5. Comparative whole building life cycle assessment workflow

Thermal performance assessments further refine **whole-life cycle impact analysis**, ensuring that:

- **Building envelopes are designed for minimal energy loss**, incorporating **high-performance insulation, glazing, and adaptive façade technologies**.
- **Heating, ventilation, and air conditioning (HVAC) systems** are **sized appropriately**, reducing **unnecessary energy demand**.
- **Building orientation and shading techniques** are **optimized to harness passive solar gains**, minimizing operational energy needs.

By integrating **real-time thermal performance data** into **digital assessment models**, LCA calculations become more **precise and adaptable**, allowing **climate-specific recommendations** for sustainability improvements.

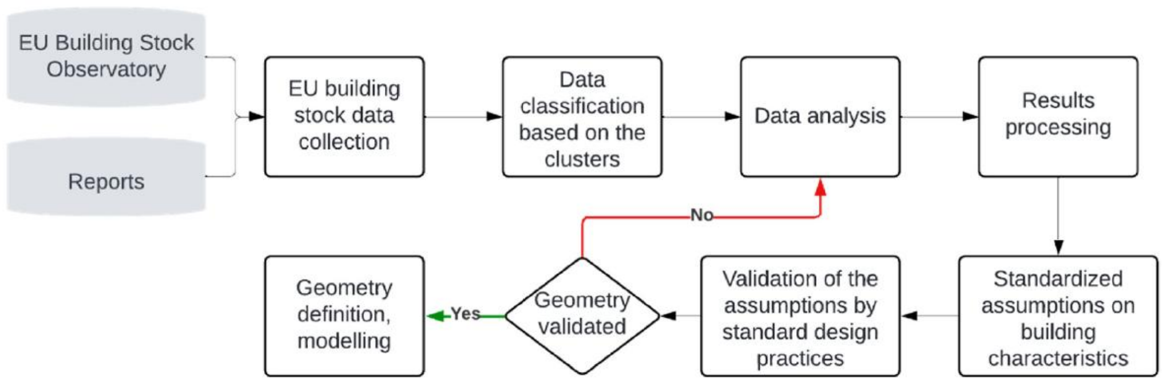

Figure 6. Comparative whole building life cycle assessment workflow

3.1.1.2. BIM-Driven LCA Methodologies for Automated Sustainability Analysis

The integration of **BIM with LCA software** enhances **automated environmental assessments**, improving **data accuracy, consistency, and efficiency**. BIM-driven LCA methodologies:

- **Reduce manual input errors**, enabling **automated extraction of material quantities and embodied carbon calculations**.
- **Support real-time scenario modeling**, allowing designers to **compare multiple sustainability options** before construction begins.
- **Enhance compliance with environmental regulations**, linking LCA benchmarks to **EU directives such as EPBD, EED, and RED**.

BIM-based LCA frameworks also **facilitate cross-disciplinary collaboration**, ensuring that:

- **Architects, engineers, and sustainability experts** have access to **real-time performance insights**.
- **Project teams can track sustainability indicators** throughout **the design, construction, and operational phases**.
- **End-of-life deconstruction planning** is integrated into early-stage design processes, **optimizing material reuse and recycling strategies**.

As **BIM-based automation continues to evolve**, smart buildings will **increasingly leverage digital workflows** to streamline **sustainability assessments and optimize resource efficiency**.

The Role of Dynamic Simulations in Evaluating Material Efficiency, Energy Performance, and End-of-Life Sustainability Strategies

Dynamic simulation tools allow for **real-time analysis of material sustainability, energy efficiency, and end-of-life impacts**. These tools are used to:

- **Model real-world energy consumption patterns**, adjusting LCA results to reflect **actual building performance** rather than static assumptions.
- **Predict how materials will degrade over time**, influencing **maintenance schedules, refurbishment strategies, and material replacement decisions**.
- **Assess circular economy potential**, analyzing **reuse scenarios for construction waste and deconstruction strategies for material recovery**.

Smart buildings benefit from dynamic simulations by:

- **Reducing uncertainty in sustainability assessments**, improving the **accuracy of life cycle predictions**.
- **Optimizing real-time performance adjustments**, ensuring that **energy management systems dynamically respond to occupant behavior and environmental conditions**.
- **Enhancing building adaptability**, allowing for **data-driven modifications to material use, energy consumption, and operational strategies**.

By **standardizing LCA methodologies within smart building frameworks**, sustainability targets can be **quantified more precisely**, ensuring that smart buildings achieve **optimal performance under diverse conditions**.

3.1.2 Whole-Life Cycle Assessment Methodologies in Smart Buildings

Life Cycle Assessment (**LCA**) methodologies serve as a **comprehensive framework for evaluating the environmental impact of buildings**, ensuring that sustainability considerations extend **beyond operational energy use** to encompass **material sourcing, construction processes, and end-of-life disposal**. Whole-Life Cycle Assessment (**WLCA**) methodologies are structured to **analyze the full range of environmental impacts** throughout a building's lifespan, enabling informed decision-making to **reduce carbon emissions, improve energy efficiency, and optimize material utilization**.

WLCA provides a **structured approach** to assessing a building's sustainability performance by breaking down its **life cycle into distinct stages**, ensuring that each phase is analyzed for **energy use, resource consumption, and environmental footprint**. The standard framework for WLCA is outlined in **ISO 14040 and ISO 14044**, which define the four primary life cycle stages:

3.1.1.3. Life Cycle Stages in Smart Building Assessments

Production Phase (A1–A3): Raw Material Extraction, Processing, and Component Manufacturing

The production phase accounts for the **initial environmental impact of materials**, focusing on:

- **Extraction of raw materials**, such as concrete, steel, timber, and insulation materials.
- **Energy-intensive manufacturing processes**, including material refining, chemical treatments, and fabrication.
- **Embodied carbon emissions associated with material production**, contributing to the **overall life cycle carbon footprint of a building**.

Smart buildings **mitigate environmental impacts** at this stage by:

- **Selecting low-carbon or bio-based materials** to minimize embodied emissions.
- **Implementing circular economy principles**, using **recycled or upcycled materials**.
- **Reducing energy use in manufacturing** by adopting **efficient industrial production techniques**.

Construction Phase (A4–A5): Transportation, On-Site Assembly, and Building Construction Activities

The construction phase **contributes significantly to overall environmental impact** due to:

- **Transportation emissions from material delivery** to construction sites.
- **Energy use in machinery and construction processes**, affecting sustainability performance.
- **Waste generation from inefficient material use**, requiring disposal or recycling.

WLCA methodologies in smart buildings help **optimize this phase by**:

- **Using BIM-integrated LCA models** to reduce **on-site material waste and improve logistical efficiency**.
- **Implementing prefabrication techniques**, reducing **construction time, resource consumption, and emissions**.
- **Leveraging digital tools for supply chain management**, ensuring efficient material transport and reducing fuel consumption.

Operational Phase (B1–B7): Energy Consumption, Maintenance, Retrofitting, and Material Replacement

The operational phase represents the **longest and most energy-intensive period** of a building's life cycle, covering:

- **Direct energy use for heating, cooling, lighting, and ventilation**.
- **Ongoing maintenance, repairs, and retrofitting**, influencing energy efficiency over time.
- **Occupant behavior and environmental control systems**, affecting overall sustainability performance.

Smart buildings **enhance sustainability in this phase through**:

- **Integration of IoT-based energy monitoring**, enabling **real-time tracking and optimization of energy use**.
- **Automated climate control systems**, adjusting heating, ventilation, and air conditioning (**HVAC**) based on occupancy patterns.
- **Predictive maintenance models**, reducing energy-intensive system failures and prolonging equipment lifespan.

WLCA ensures that **operational sustainability assessments** account for both **direct energy consumption and long-term material durability**, optimizing building performance while **reducing environmental impact over time**.

End-of-Life Phase (C1–C4): Demolition, Deconstruction, Material Recovery, and Final Disposal

At the end of its life cycle, a building undergoes **deconstruction, demolition, and material disposal**, determining its **final environmental footprint**. This phase includes:

- **Demolition and removal of structural components**, generating waste materials.
- **Recycling or repurposing of materials**, influencing **circular economy integration**.
- **Landfill disposal for non-recyclable materials**, contributing to environmental degradation.

WLCA methodologies improve **end-of-life sustainability through**:

- **Deconstruction planning using BIM models**, maximizing material reuse potential.
- **LCA-driven waste management strategies**, optimizing **material recovery and recycling rates**.
- **Circular economy principles**, ensuring **adaptive reuse of structural components**.

Smart buildings with **planned end-of-life strategies** significantly **reduce landfill waste and embodied carbon impacts**, ensuring **a more sustainable and resource-efficient transition to reuse or redevelopment**.

3.1.1.4. Key WLCA Integration Strategies in Smart Buildings

WLCA methodologies in smart buildings go beyond **basic life cycle impact assessments**, integrating advanced **data-driven sustainability evaluation techniques** to ensure a **comprehensive and adaptive approach**. The following **strategies enhance WLCA applications in smart buildings**:

Energy Performance Benchmarks for Smart Buildings

Ensuring compliance with **energy performance benchmarks** is crucial for smart buildings, particularly in meeting:

- **EPBD requirements for Zero Emission Buildings (ZEBs)**.
- **Energy efficiency standards set by global sustainability frameworks**.
- **Carbon neutrality goals through optimized material and energy use**.

LCA methodologies **integrate energy performance indicators** such as:

- **Life cycle energy demand analysis**, evaluating the long-term energy performance of a building.
- **Whole-life carbon accounting**, tracking embodied and operational emissions.
- **Renewable energy integration assessments**, ensuring on-site solar, wind, or geothermal energy sources contribute to sustainability goals.

3.1.1.5. Material Sustainability Indicators in WLCA

Material sustainability assessment is a core element of WLCA, focusing on:

- **Embodied carbon tracking**, measuring the carbon footprint of material production and use.
- **Recyclability and circular economy potential**, assessing material reuse viability.
- **Durability and longevity assessments**, ensuring that materials require minimal replacements over time.

Smart buildings leverage **digital material databases** to **automate material sustainability tracking**, ensuring that **WLCA methodologies align with real-time performance data**.

Digital Simulations for Real-Time Performance Tracking

The integration of **dynamic digital simulations** allows for **real-time LCA monitoring and performance forecasting**, enabling:

- **Predictive energy modeling**, optimizing heating, cooling, and ventilation strategies.
- **Scenario-based waste reduction planning**, ensuring construction and demolition waste is minimized.
- **Adaptive building control systems**, responding to occupancy and environmental conditions.

Real-time simulations **enhance WLCA accuracy** by providing **updated sustainability performance metrics** that align with **changing building operations**.

3.1.1.6. Interdisciplinary Approach in WLCA for Smart Buildings

WLCA in smart buildings **combines multiple disciplines** to achieve **optimal sustainability outcomes**, integrating:

- **Energy modeling techniques**, ensuring minimal carbon emissions.
- **Environmental analysis tools**, tracking embodied carbon and material efficiency.
- **Circular economy principles**, optimizing waste reduction and material reuse.

By linking **digital simulations, material tracking, and real-time operational data**, WLCA methodologies support **smart building frameworks that are adaptable, resource-efficient, and future-ready**.

3.1.3 Benchmarking Building Geometries and Thermal Performance

Smart buildings are designed to **maximize energy efficiency and sustainability** by optimizing **building geometry, material selection, and climatic adaptations**. A building's **form, orientation, and thermal performance** significantly impact **heating and cooling demands, daylight utilization, and natural ventilation potential**. Benchmarking building geometries and thermal performance is essential for **developing Whole-Life Cycle Assessment (WLCA) strategies** that align with **regional climate variations and material efficiency goals**.

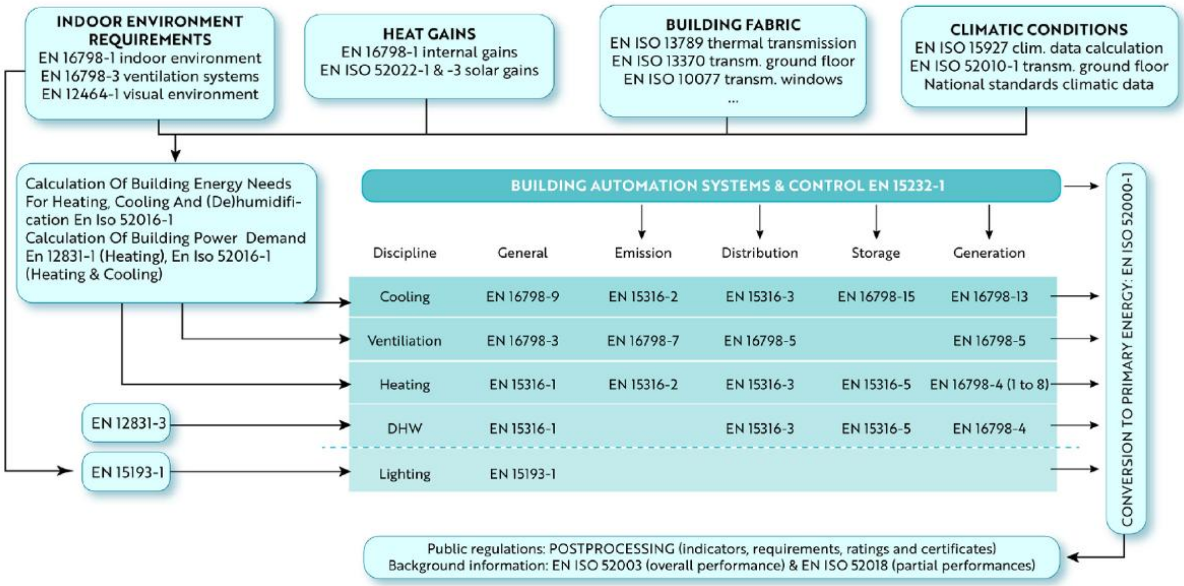

Figure 7. Standard for overall EPB assessment by calculations.

By **evaluating different building typologies**, WLCA methodologies can identify **design strategies that minimize environmental impact while maximizing operational efficiency**. Integrating **advanced digital simulation tools** into these assessments enables designers and engineers to **predict energy consumption patterns**, optimize **material use**, and ensure compliance with **sustainability regulations**.

3.1.1.7. Impact of Building Geometry on Life Cycle Performance

Building geometry influences **heat transfer, solar exposure, ventilation efficiency, and embodied energy**, all of which determine a structure's **long-term environmental footprint**. The relationship between geometric design and sustainability can be analyzed through:

Compact Forms and Thermal Efficiency in Cold Climates

Buildings in colder climates benefit from **compact, high-mass designs**, which:

- **Minimize external surface area**, reducing **heat loss through walls, roofs, and glazing**.
- **Enhance thermal mass storage**, allowing buildings to **retain heat during the day and release it at night**.
- **Improve insulation efficiency**, reducing **heating energy demand and operational carbon emissions**.

Compact forms, such as **cubic or spherical designs**, result in **lower heating loads**, making them **ideal for energy-efficient structures in high-latitude regions**.

Extended Surface Areas and Passive Cooling in Warm Climates

Buildings in warm climates often incorporate **elongated forms with enhanced surface exposure** to:

- **Facilitate natural ventilation**, reducing reliance on mechanical cooling.
- **Enhance passive cooling mechanisms**, such as **shading devices and ventilated facades**.
- **Increase thermal dissipation**, allowing buildings to maintain **lower indoor temperatures** with minimal energy input.

These design principles align with **WLCA goals**, ensuring that buildings require **less operational energy** while maintaining **thermal comfort**.

3.1.1.8. Optimized Window-to-Wall Ratios for Daylighting and Energy Efficiency

The **placement and proportion of windows** affect both **thermal performance and lighting efficiency**. Optimized window-to-wall ratios allow for:

- **Balanced daylight penetration**, reducing the need for artificial lighting.
- **Minimized thermal losses**, preventing excess heat gain in summer and heat loss in winter.
- **Enhanced occupant comfort**, improving **indoor air quality (IAQ) and visual well-being**.

Benchmarking **window-to-wall ratios** through **LCA simulations** ensures that designs **maximize natural lighting benefits** while **minimizing unwanted heat transfer**.

By analyzing **geometric parameters**, smart buildings can adopt **region-specific design strategies** that reduce **energy consumption, improve sustainability performance, and enhance indoor comfort**.

3.1.1.9. Thermal Performance Assessment for Smart Buildings

Thermal performance is a **critical factor in whole-life cycle impact assessment**, determining how buildings interact with **external climate conditions and internal energy loads**. Smart buildings employ **LCA-based thermal modeling** to evaluate:

Material Thermal Properties and Heat Retention

The **thermal mass of materials** affects:

- **Heat absorption and release cycles**, regulating **indoor temperatures** without excessive energy use.

- **Insulation performance**, reducing **the impact of external temperature fluctuations**.
- **Operational energy savings**, by maintaining **stable indoor climates** with minimal HVAC reliance.

LCA-driven material selection ensures that **high-performance insulative materials** contribute to **long-term energy efficiency**.

3.1.1.10. Insulation Strategies for Heating and Cooling Optimization

Insulation strategies play a crucial role in:

- **Reducing heat transfer**, maintaining indoor temperatures with minimal energy input.
- **Enhancing wall, roof, and floor insulation**, lowering heating and cooling loads.
- **Optimizing U-values**, ensuring that building envelopes meet **energy efficiency standards**.

Smart buildings integrate **LCA-backed insulation assessments** to determine **optimal thermal resistance levels**, reducing **operational carbon footprints**.

3.1.1.11. Passive Design Elements and Climate Adaptation

Passive design elements contribute to **whole-life cycle sustainability** by reducing reliance on **mechanical systems**. Key features include:

- **Solar shading and ventilated facades**, controlling **direct solar radiation**.
- **Natural ventilation strategies**, improving **air circulation and reducing cooling demand**.
- **Heat recovery systems**, capturing and reusing **waste heat for improved efficiency**.

WLCA models assess **passive design efficiency**, ensuring that buildings **respond dynamically to seasonal and climatic variations**.

Evaluating Thermal Performance Through WLCA Methodologies

Benchmarking thermal performance enables smart buildings to:

- **Implement scenario-based energy modeling**, ensuring compliance with **regulatory frameworks such as EPBD**.
- **Enable data-driven decision-making**, optimizing **building envelope designs for climate resilience**.
- **Reduce embodied and operational carbon**, aligning with **Net Zero Energy Building (NZEB) goals**.

By integrating **LCA simulations with real-time performance tracking**, smart buildings can **continuously refine their thermal efficiency**, ensuring **sustainable energy use and minimal environmental impact**.

Benchmarking **building geometries and thermal performance** provides valuable insights into how **material selection, climatic adaptations, and operational strategies** contribute to **whole-life sustainability improvements**.

3.1.4 Enhancing LCA Through BIM Integration

Building Information Modelling (BIM) has transformed the way Life Cycle Assessment (LCA) is applied in smart buildings, providing an advanced digital framework for sustainability evaluations. Traditional LCA methods often rely on static datasets, manual material inventories, and disconnected calculations, making the process both time-consuming and prone to errors. By integrating LCA with BIM, smart buildings benefit from **automated data extraction, real-time material tracking, and comprehensive sustainability simulations** that significantly improve efficiency, accuracy, and decision-making. The **digitalization of LCA workflows through BIM platforms** allows architects, engineers, and sustainability specialists to assess environmental impacts dynamically across all stages of a building's life cycle.

One of the primary advantages of BIM-enhanced LCA is its ability to **automate environmental impact assessments**, reducing manual data entry errors and ensuring that sustainability calculations are continuously updated as design decisions evolve. In traditional LCA processes, material quantities and embodied carbon calculations often require extensive manual input, leading to inefficiencies and inconsistencies. BIM software automates these tasks by linking building models to **Life Cycle Inventory (LCI) databases** and **Environmental Product Declarations (EPDs)**, ensuring that material sustainability assessments are both precise and transparent. This **seamless integration of LCA into digital design workflows** enhances the ability to optimize material choices in real time, allowing project teams to select **low-impact, energy-efficient building materials** that align with sustainability goals.

Another significant benefit of BIM-driven LCA is its capacity to facilitate **real-time material selection tracking**, ensuring that environmental sustainability criteria are incorporated directly into the design and construction process. By embedding **LCA parameters within BIM models**, project teams can evaluate **alternative material options, analyze their embodied carbon footprints, and compare sustainability trade-offs** before finalizing a design. This **dynamic approach to material selection** enables smarter decision-making, particularly in early design phases when the potential for sustainability optimization is highest. Instead of applying LCA retrospectively, BIM allows environmental performance to be continuously assessed and refined, ensuring that sustainable design principles are embedded throughout the entire development process.

BIM-enhanced LCA also supports **scenario-based sustainability simulations**, allowing for predictive modeling of building performance under different environmental conditions. Advanced thermal analysis tools integrated within BIM platforms enable designers to **simulate energy consumption patterns, test passive design strategies, and evaluate the long-term impact of material selections on operational carbon emissions**. By running multiple sustainability scenarios, project teams can identify the most effective strategies for reducing **energy demand, minimizing carbon footprints, and optimizing resource efficiency**. This level of predictive analysis is particularly valuable for **smart buildings**, where energy performance is heavily influenced by **climate conditions, occupancy patterns, and adaptive control systems**.

The **automation of whole-building energy simulations** is another critical advantage of integrating BIM with LCA. Unlike traditional LCA models, which often rely on **static assumptions about building energy use**, BIM-enabled assessments provide **multi-scenario performance modeling** that takes into account **real-time occupancy data, dynamic thermal loads, and seasonal variations in energy demand**. This ensures that **heating, cooling, ventilation, and lighting systems** are optimized not only for regulatory compliance but also for **long-term operational efficiency**. By combining **thermal performance simulations with LCA data**, BIM platforms allow smart buildings to be designed with **enhanced passive strategies, advanced insulation solutions, and energy-efficient system configurations** that significantly reduce both embodied and operational carbon emissions.

Lifecycle carbon accounting is further improved through BIM-driven LCA methodologies, providing **accurate sustainability tracking across all phases of a building's existence**. Tools such as **OneClickLCA, SimaPro, and OpenLCA** enable project teams to automatically generate **carbon footprint reports**, quantifying emissions from **material sourcing, construction activities, operational energy consumption, and end-of-life disposal**. BIM-integrated LCA models ensure that **real-time carbon accounting is synchronized with actual building performance**, allowing sustainability metrics to be continuously updated as design modifications, material substitutions, or operational adjustments are made. This **dynamic feedback loop** is essential for achieving **net-zero carbon goals** and ensuring that smart buildings contribute to broader **climate action objectives**.

By linking LCA calculations directly to **design and operational data**, BIM-driven sustainability assessments enable project stakeholders to move beyond **compliance-based evaluations** and adopt a more **proactive, performance-driven approach** to environmental impact reduction. This integration helps project teams identify **opportunities for circular economy strategies**, such as **material reuse, adaptive building design, and efficient deconstruction planning**, ensuring that sustainability efforts extend beyond operational energy efficiency to **include material lifecycle optimization**. The **real-time adaptability of BIM-integrated LCA also supports carbon**

offset strategies, allowing smart buildings to achieve **verified carbon neutrality goals** through precise emissions tracking and mitigation planning.

The digitalization of LCA within BIM frameworks ultimately leads to **greater efficiency, reduced material waste, and improved sustainability outcomes**. The ability to **automate material tracking, predict energy performance, and dynamically assess whole-life carbon impacts** positions BIM-driven LCA as a crucial methodology for **next-generation smart buildings**. As regulatory frameworks continue to evolve and sustainability standards become more stringent, the adoption of BIM-enhanced LCA will play an increasingly central role in ensuring that smart buildings are **designed, constructed, and operated in alignment with global sustainability commitments**.

3.1.5 Advancing Smart Building Assessments with Data-Driven LCA Strategies

Smart building sustainability assessments increasingly rely on **data-driven Life Cycle Assessment (LCA) strategies** to provide **quantifiable, replicable, and transparent environmental impact measurements**. Traditional LCA methodologies, while effective in evaluating **embodied carbon, resource consumption, and operational energy use**, often suffer from **static data inputs, delayed sustainability assessments, and limited adaptability** to real-world conditions. The integration of **advanced digital technologies**, such as **Building Information Modelling (BIM) and Digital Twin platforms**, enhances the ability to conduct **dynamic, real-time sustainability evaluations**, ensuring that **smart buildings are optimized for both material efficiency and energy performance**.

One of the key advantages of **data-driven LCA strategies** in smart buildings is the ability to **improve material efficiency**, significantly reducing both **embodied carbon emissions and construction waste**. By embedding **LCA parameters directly into BIM models**, designers can **automate material tracking**, ensuring that only **low-carbon, resource-efficient materials** are selected throughout the design and construction process. This approach minimizes the risk of **material overuse, reduces procurement inefficiencies, and facilitates the selection of circular economy-compliant materials**, supporting **waste reduction strategies** at both the construction and end-of-life stages. The ability to **track material sustainability indicators in real time** ensures that smart buildings **adhere to environmental benchmarks**, such as those set by the **EU Taxonomy for Sustainable Activities** and the **Energy Performance of Buildings Directive (EPBD)**.

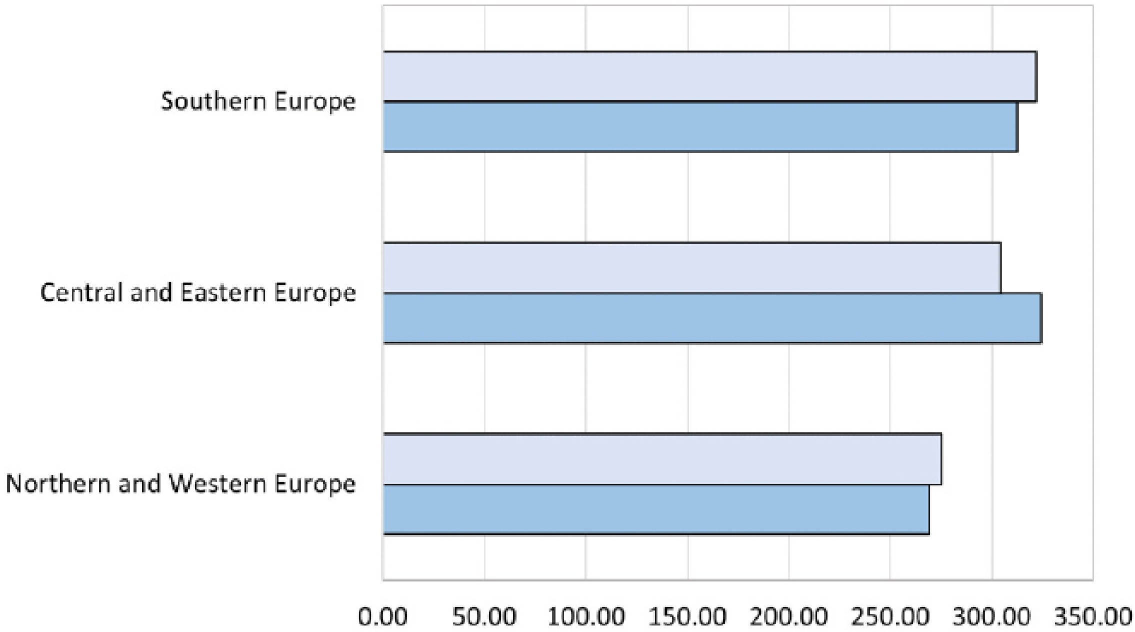

Figure 8. Comparison of typical buildings GWP for different clusters and building types.

Beyond material efficiency, **data-driven LCA strategies also optimize operational energy performance**, ensuring compliance with **EU climate goals and global decarbonization targets**. Traditional energy modelling often relies on **predictive estimations** that may not fully account for **real-world variations in occupancy, climate conditions, and system efficiencies**. The integration of **Digital Twin technology** with LCA solves this limitation by allowing for **continuous monitoring and adjustment of energy consumption patterns** in response to **real-time performance data**. By linking IoT sensors with Digital Twin platforms, buildings can **dynamically adjust HVAC systems, lighting configurations, and passive design elements** to reduce **operational energy demand while maintaining indoor environmental quality**. This ability to **automatically calibrate energy performance based on real-time conditions** enhances **long-term sustainability outcomes**, preventing energy inefficiencies that arise due to static LCA assumptions.

A critical component of data-driven LCA in smart buildings is the facilitation of **whole-life carbon accounting**, ensuring that sustainability indicators are continuously tracked **across each phase of a building's life cycle**. Unlike traditional LCA approaches, which often focus on **one-time sustainability evaluations**, data-driven methodologies enable **longitudinal tracking of carbon emissions, material performance, and operational energy consumption** over time. This continuous assessment allows for **adaptive sustainability improvements**, where buildings can be **retrofitted, re-optimized, or redesigned** based on **real-world performance data** rather than theoretical estimates. The integration of **AI-driven analytics and machine learning algorithms** into LCA platforms further enhances the **predictive capabilities of whole-life carbon**

assessments, allowing smart buildings to anticipate **potential sustainability gaps and proactively implement corrective measures**.

The convergence of **BIM, Digital Twins, and real-time analytics** ensures that **data-driven LCA strategies are more precise, adaptable, and aligned with real-world building performance metrics**. By integrating **predictive modeling, automated material selection, and operational energy optimization**, smart buildings can **achieve higher sustainability performance with greater accuracy**. This technological advancement enables project stakeholders to **transition from compliance-based sustainability evaluations to proactive, performance-driven decision-making**, ensuring that **buildings are continuously optimized for carbon neutrality and resource efficiency**. As smart building technologies continue to evolve, **data-driven LCA strategies will play a central role in shaping the next generation of sustainable, intelligent, and climate-resilient built environments**.

3.2. Digital Twin and Data Integration for Monitoring Smart Buildings

The integration of Digital Twin technology with data-driven monitoring systems has transformed the way smart buildings are designed, operated, and maintained. By creating **real-time digital replicas** of physical structures, Digital Twins enable continuous **data collection, performance analysis, and predictive decision-making**, ensuring that buildings operate at peak efficiency while minimizing environmental impact. The ability to integrate Digital Twins with advanced **IoT-based sensor networks, Radio Frequency Identification (RFID) tracking, and Building Information Modelling (BIM)** has further enhanced their potential, allowing for **seamless synchronization between physical and virtual assets**. This digital convergence optimizes **energy management, material tracking, predictive maintenance, and occupant comfort**, positioning Digital Twin technology as a key enabler of **sustainable and intelligent building ecosystems**.

The adoption of RFID technology within Digital Twin frameworks has significantly improved **asset tracking and material management** in smart buildings. RFID sensors provide **real-time visibility into material flows, equipment conditions, and construction progress**, ensuring that building components are monitored throughout their entire life cycle. Unlike traditional asset tracking methods, which rely on **manual inspections and periodic audits**, RFID-enabled Digital Twins offer **continuous, automated data updates**, reducing errors and improving overall efficiency. This integration is particularly valuable in **construction site logistics**, where RFID-based Digital Twins can optimize **inventory management, material deployment, and waste reduction strategies**. By maintaining a **fully digitized record of building components**, RFID enhances **traceability, supports circular economy principles, and facilitates adaptive reuse of materials**.

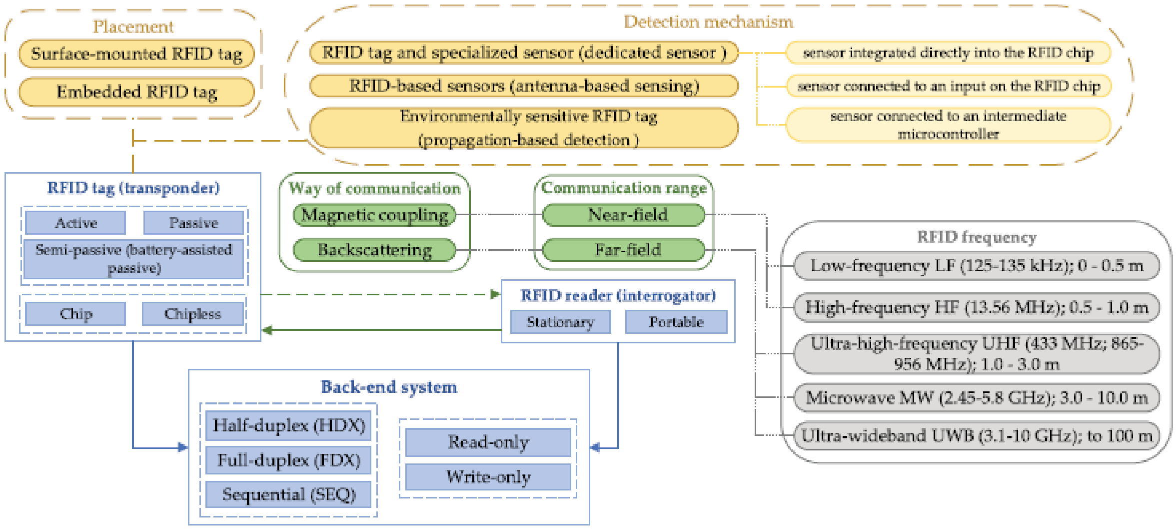

Figure 9 Main components of the RFID system

In addition to RFID, the deployment of IoT-based sensor networks within Digital Twin environments has revolutionized **building performance monitoring and operational efficiency**. IoT sensors collect **real-time environmental data**, tracking parameters such as **temperature, humidity, air quality, occupancy levels, and energy consumption**. This data is continuously fed into Digital Twin models, allowing for **instantaneous analysis and dynamic adjustments to building systems**. For instance, if occupancy sensors detect a change in room usage patterns, the Digital Twin can automatically adjust **HVAC settings, lighting intensity, and ventilation rates**, optimizing energy efficiency without compromising occupant comfort. By leveraging **machine learning algorithms and AI-driven analytics**, Digital Twin models become **self-adaptive**, enabling buildings to respond proactively to environmental changes and usage demands.

Beyond real-time monitoring, Digital Twins play a crucial role in **predictive maintenance and fault detection**, reducing operational costs and enhancing long-term sustainability. Traditional building maintenance often relies on **reactive strategies**, where issues are only addressed after they have caused significant inefficiencies or failures. Digital Twins, however, utilize **historical performance data and AI-powered diagnostics** to anticipate potential system failures before they occur. For example, an IoT-connected Digital Twin monitoring a building's **HVAC system** can detect **irregular energy consumption patterns, airflow inconsistencies, or temperature fluctuations**, signaling an impending malfunction. By identifying **early warning signs of system degradation**, maintenance teams can **intervene preemptively**, preventing costly repairs and minimizing downtime. This predictive approach not only extends the lifespan of building equipment but also contributes to **energy conservation and carbon footprint reduction**.

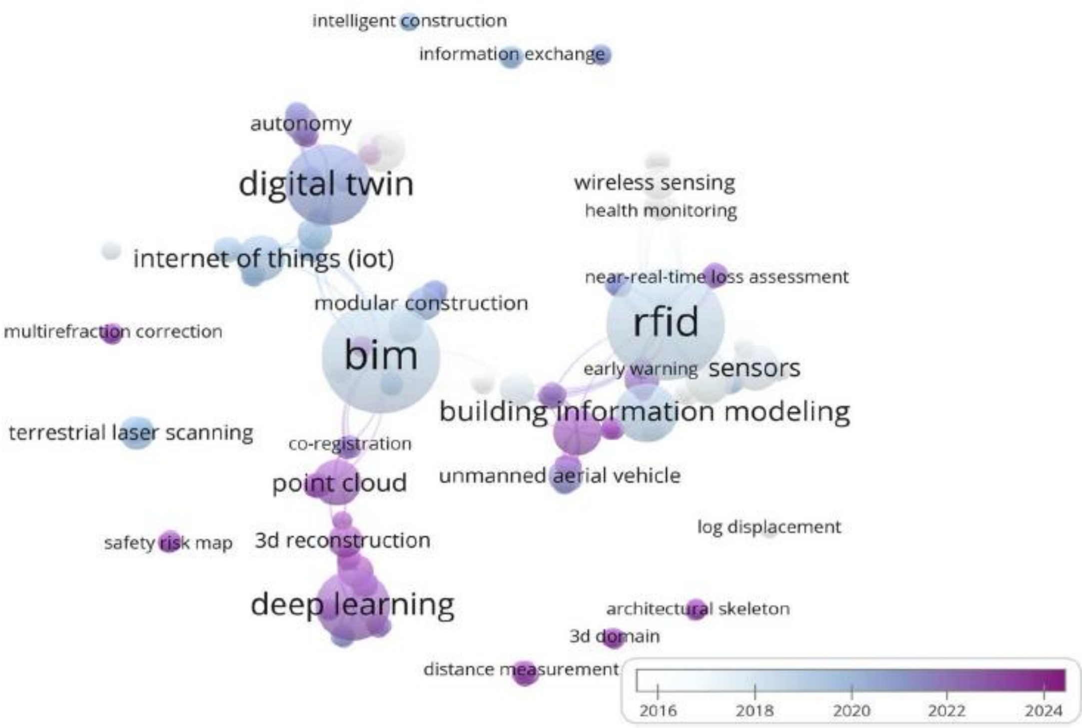

Figure 10 Keyword co-occurrence network

The synergy between Digital Twin technology and BIM has further expanded the possibilities for **smart building optimization, simulation, and decision-making**. While BIM has traditionally been used for **design and construction planning**, its integration with Digital Twins allows for **continuous lifecycle management**, bridging the gap between **static design models and dynamic operational data**. Digital Twins **extend BIM functionality beyond the construction phase**, ensuring that building models remain **up to date, data-enriched, and responsive** to real-world conditions. This seamless transition from **BIM-based design to Digital Twin-driven operation** enables architects, engineers, and facility managers to **analyze real-time building performance, simulate energy-saving scenarios, and refine sustainability strategies**.

One of the most significant advantages of **BIM-Digital Twin integration** is its ability to **optimize energy performance and environmental impact assessments**. Traditional energy modeling often relies on **predefined assumptions and standardized inputs**, which may not fully capture the **complex interactions between building systems, external climate conditions, and occupant behavior**. Digital Twins enhance energy simulations by incorporating **real-time sensor data**, providing a more **accurate and dynamic representation of actual building performance**. This level of precision enables **data-driven decision-making**, allowing stakeholders to **fine-tune heating, cooling, ventilation, and lighting systems** based on real-world usage patterns. In large-scale smart buildings, Digital Twin-enabled energy optimization has led to **significant reductions in energy consumption, operating costs, and greenhouse gas emissions**.

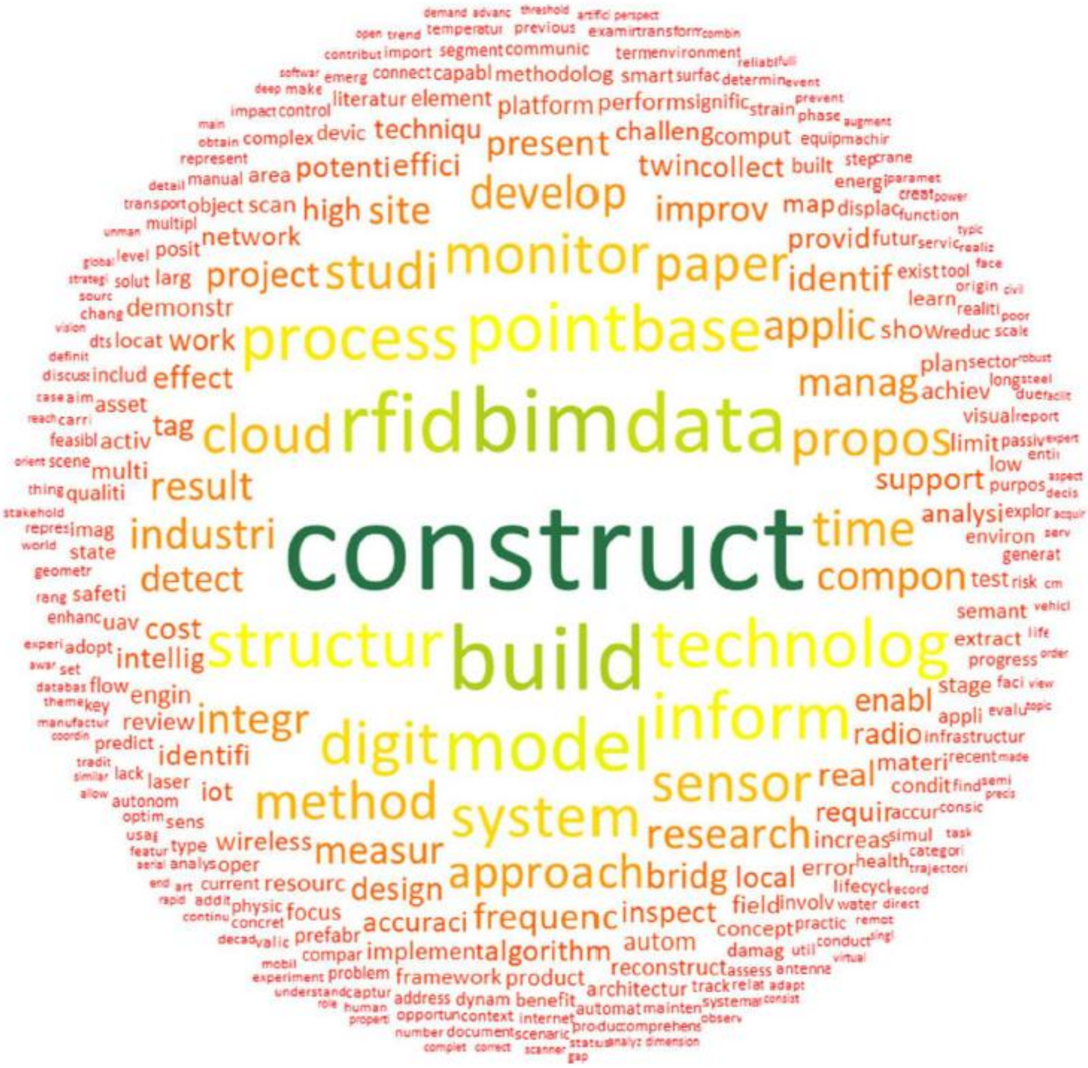

Figure 11 Word cloud of tokens in the dataset

Digital Twins also play a vital role in **emergency response and disaster resilience**, particularly in **fire safety, structural health monitoring, and evacuation planning**. By maintaining **real-time spatial awareness**, Digital Twins provide **detailed visibility into building layouts, emergency exits, and critical infrastructure systems**, enabling first responders to **navigate complex environments with greater accuracy**. In seismic-prone regions, IoT-equipped Digital Twins can monitor **structural integrity**, detecting **micro-damage and stress fractures in building materials** before they escalate into major safety risks. This level of **proactive monitoring** enhances **building resilience, occupant safety, and long-term structural durability**, supporting the transition toward **future-proof smart cities**.

The use of Digital Twins in **large-scale building portfolios and urban infrastructure projects** is becoming increasingly prevalent. Smart city initiatives are now leveraging **Digital Twin ecosystems** to coordinate **building performance data, energy grids, and transportation networks**, creating a more **interconnected and efficient urban environment**. In these large-scale implementations, Digital Twins aggregate **multi-**

source data from different buildings, enabling city planners to **optimize resource allocation, enhance grid stability, and improve overall energy resilience**. By integrating **distributed energy resources, district heating systems, and renewable energy solutions**, Digital Twins facilitate **holistic urban sustainability strategies**, reducing reliance on **fossil fuels and minimizing environmental impact** at a broader scale.

The future of Digital Twin technology in smart buildings is expected to evolve alongside advancements in **AI, IoT connectivity, and blockchain-based data security**. As buildings become increasingly **automated and self-regulating**, Digital Twins will continue to refine their **predictive modeling capabilities**, optimizing **energy efficiency, space utilization, and circular economy adoption**. The incorporation of **blockchain technology** in Digital Twin platforms will further enhance **data integrity, cybersecurity, and decentralized decision-making**, ensuring that **sustainability metrics are accurately tracked and transparently reported**.

The synergy between **Digital Twins, IoT sensors, RFID tracking, and BIM-based simulations** is reshaping the landscape of **smart building monitoring and performance optimization**. The ability to **integrate real-time data, predict maintenance needs, enhance energy efficiency, and improve occupant well-being** positions Digital Twins as a cornerstone of **next-generation sustainable building solutions**. As the built environment moves toward **more intelligent, resilient, and adaptive systems**, the role of **Digital Twin-driven data integration** will continue to expand, driving **efficiency gains, carbon reductions, and smarter resource management** for decades to come.

3.3. Assessing Educational Building Performance and IAQ Integration

The performance of educational buildings is a critical factor in ensuring **energy efficiency, sustainability, and occupant well-being**. Unlike traditional commercial or residential buildings, educational facilities accommodate **large, fluctuating occupancy levels** throughout the day, leading to dynamic variations in **indoor air quality (IAQ), thermal comfort, and energy consumption**. Smart buildings, particularly those in the education sector, require **advanced monitoring systems** to maintain **optimal environmental conditions** while adhering to **stringent energy efficiency standards**. The integration of **IoT-based monitoring strategies** into educational buildings has revolutionized **performance assessment methodologies**, allowing for real-time tracking of **IAQ parameters, ventilation efficiency, lighting conditions, and thermal comfort levels**.

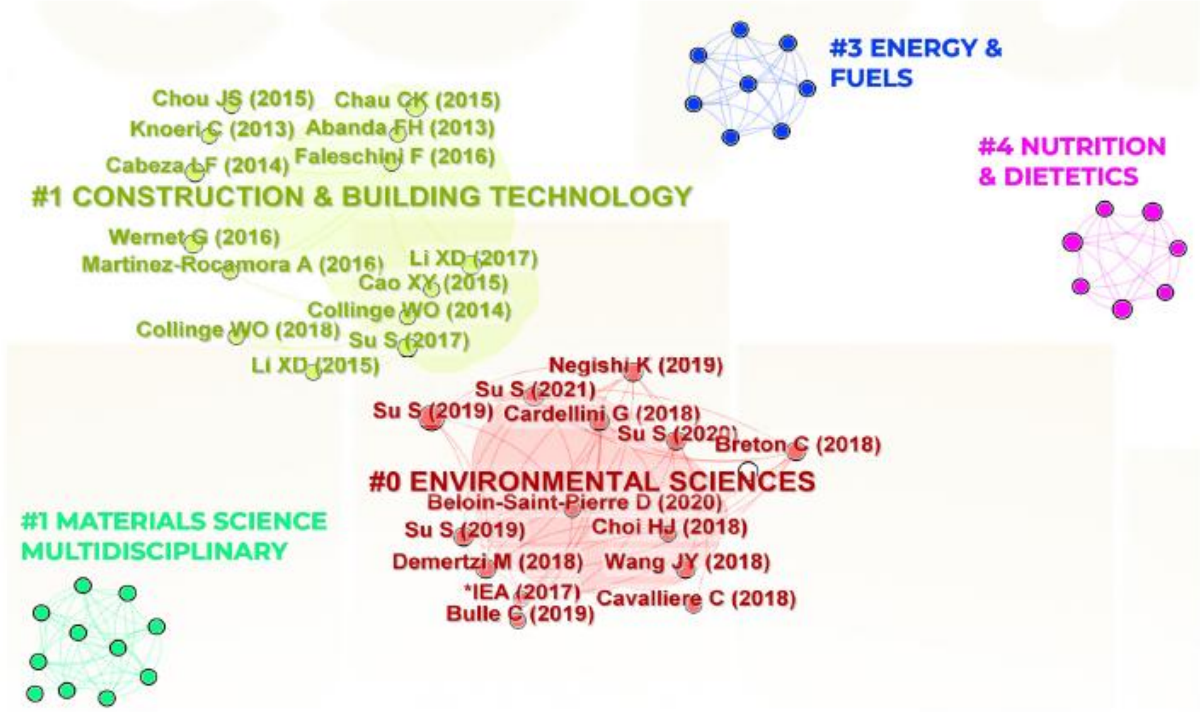

Figure 12. CiteSpace visualisation of the multidimensional fields of LCA and cluster analyses for SLR research.

Indoor air quality in educational buildings has a **direct impact on student productivity, cognitive function, and overall health**. Poor IAQ, caused by **insufficient ventilation, high CO_2 levels, volatile organic compounds (VOCs), and particulate matter**, can lead to **reduced concentration, increased absenteeism, and respiratory issues among students and faculty**. Traditional IAQ assessment methods have relied on **periodic manual measurements** and **fixed ventilation rates**, which fail to capture **real-time fluctuations in indoor air pollutants**. The adoption of **IoT-based environmental monitoring systems** within Digital Twin frameworks has significantly improved IAQ management by **enabling continuous air quality tracking and automated building response mechanisms**.

The implementation of IoT monitoring strategies in educational buildings has transformed **real-time data acquisition, environmental optimization, and predictive IAQ management**. IoT sensors deployed throughout classrooms, lecture halls, and study areas continuously measure **CO_2 levels, humidity, temperature, airborne pollutants, and ventilation efficiency**. These sensors feed **real-time environmental data into Digital Twin models**, providing a **dynamic representation of IAQ conditions** and allowing for **automated system adjustments based on occupancy and pollutant levels**. For instance, if a spike in CO_2 concentration is detected in a crowded classroom, the Digital Twin can trigger **increased ventilation rates, activate air purifiers, or adjust HVAC settings** to restore air quality to optimal levels. This level of **automated, data-driven control enhances occupant comfort while maintaining energy**

efficiency, ensuring that ventilation systems **operate only when necessary**, thereby reducing **unnecessary energy expenditure**.

Beyond IAQ, IoT monitoring plays a crucial role in optimizing **thermal comfort and lighting conditions** within educational spaces. Temperature fluctuations in classrooms often occur due to **external weather conditions, occupancy density, and heat generated by electronic devices**. Traditional HVAC systems struggle to adapt to **rapid changes in thermal loads**, leading to **overcooling, overheating, or inefficient energy use**. IoT-enabled climate control systems, integrated with Digital Twins, allow for **dynamic thermal adjustments** based on **real-time occupancy and weather forecasts**. Smart thermostats and **AI-driven predictive analytics** ensure that **heating and cooling systems adjust in response to real-time data**, maintaining an **optimal learning environment** while **reducing energy consumption and carbon emissions**.

Lighting also plays a fundamental role in **educational building performance**, influencing **visual comfort, alertness, and energy efficiency**. Smart lighting systems equipped with **occupancy sensors and daylight harvesting technology** automatically adjust **artificial lighting levels** based on **natural daylight availability and room usage**. IoT-integrated lighting controls ensure that **unoccupied classrooms automatically switch to energy-saving modes**, significantly reducing **unnecessary energy waste**. When paired with **Digital Twin simulations**, lighting performance can be analyzed over time, allowing facility managers to **identify inefficiencies, optimize luminaire placement, and enhance overall energy savings**.

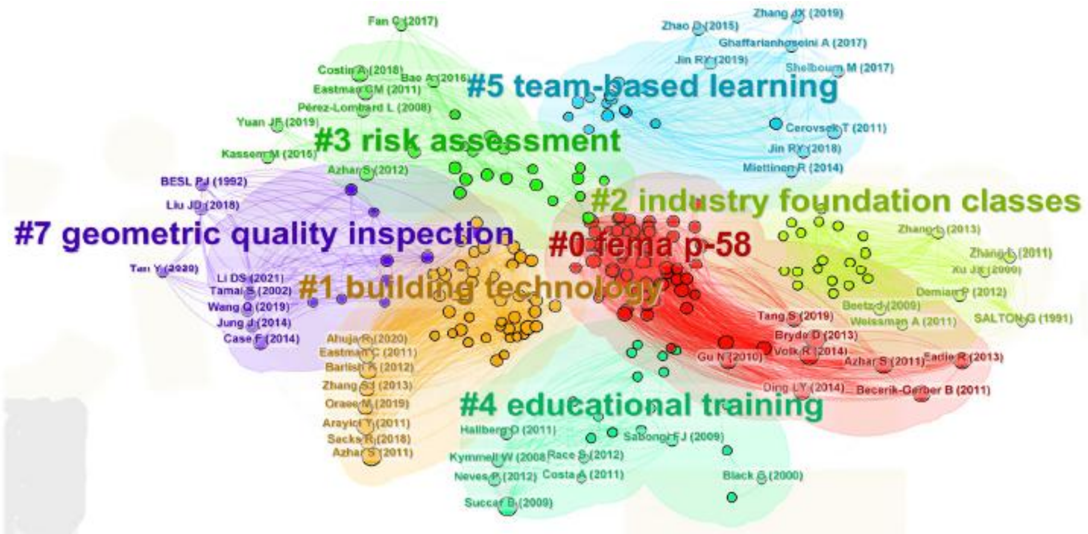

Figure 13. CiteSpace visualisation of the multidimensional fields of BIM and cluster analyses for SLR research.

The implementation of **predictive maintenance strategies** within IoT-enhanced educational buildings further contributes to **sustainability and operational efficiency**. HVAC systems, air filtration units, and lighting fixtures in educational buildings are subject to **high usage levels**, leading to **wear and tear, performance degradation, and**

increased energy demand. Traditional maintenance strategies rely on **fixed schedules**, often resulting in **delayed repairs or premature servicing of equipment**. By integrating **real-time equipment performance data** with Digital Twin models, IoT-enabled monitoring systems detect **early warning signs of system malfunctions**, allowing for **proactive maintenance scheduling**. Predictive maintenance not only **reduces downtime and repair costs** but also **extends the lifespan of building systems**, minimizing **resource consumption and overall operational impact**.

The use of Digital Twin simulations for **occupant behavior modeling and space utilization analytics** provides additional insights into **educational building performance optimization**. IoT sensors track **occupancy trends, classroom utilization rates, and movement patterns**, allowing facility managers to **allocate spaces more efficiently** and **optimize HVAC, lighting, and ventilation strategies** accordingly. Digital Twin-enabled occupancy forecasting ensures that **resources are allocated based on real demand**, preventing energy waste in underutilized areas. This level of **intelligent space management** contributes to **significant energy savings** while maintaining **a comfortable and adaptive learning environment**.

Health and well-being considerations are becoming increasingly important in the assessment of **educational building performance**, particularly in light of global concerns regarding **indoor air pollution and airborne disease transmission**. IoT-based IAQ monitoring plays a **critical role in maintaining safe and healthy learning environments**, particularly in high-density educational settings. By integrating **real-time air quality analytics with adaptive building control systems**, smart educational buildings can **automatically implement air purification measures, adjust ventilation rates, and enforce indoor air safety protocols**. This proactive approach not only improves **occupant health outcomes** but also aligns with **global sustainability and wellness standards**, such as the **WELL Building Standard and the EU Green Deal's Healthy Buildings Initiative**.

The combination of **IoT, Digital Twins, and AI-driven analytics** in educational building assessments represents a major step forward in **intelligent infrastructure management and energy-efficient design**. By continuously monitoring **IAQ, thermal comfort, lighting efficiency, and system performance**, smart buildings ensure that **learning environments remain safe, healthy, and optimized for productivity**. As educational institutions increasingly adopt **data-driven sustainability strategies**, the role of **IoT-integrated Digital Twins in smart building performance optimization** will continue to expand, driving **energy efficiency, occupant well-being, and environmental responsibility** across the sector.

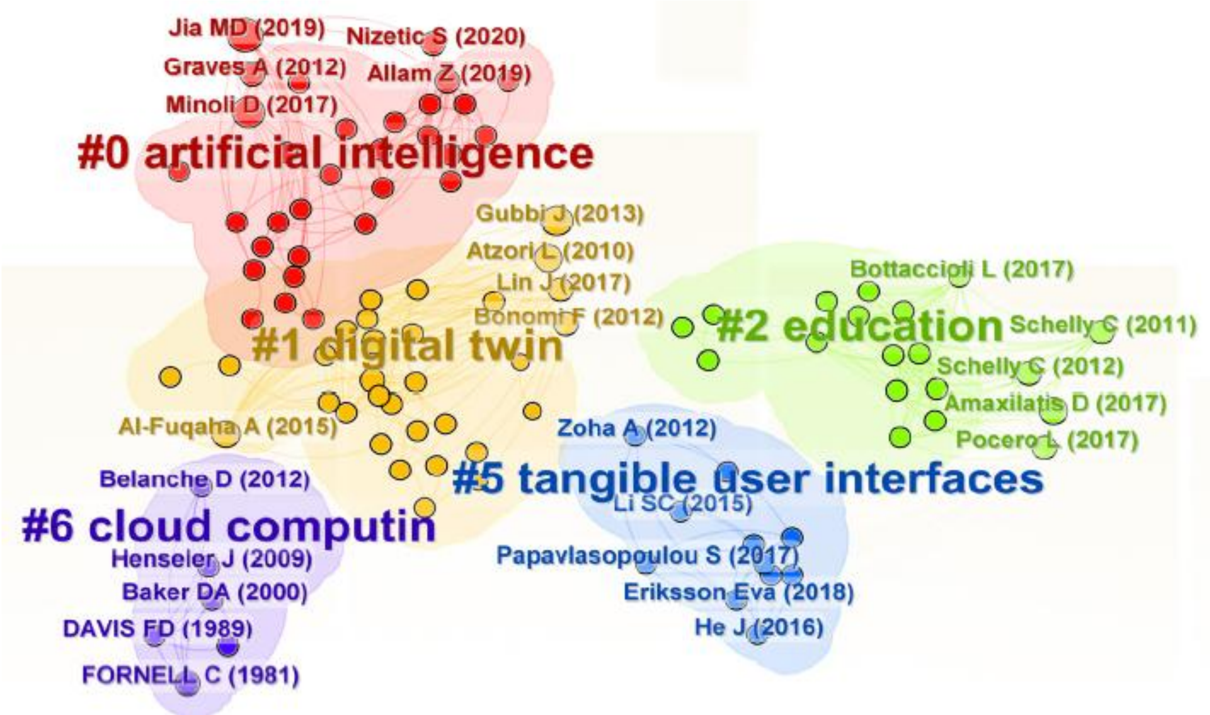

Figure 14. CiteSpace visualisation of the multidimensional fields of IoT and cluster analyses for SLR research.

4. Gained Knowledge by KTU

4.1. Contributions to LCA Modeling for Smart Buildings

The research conducted under SmartWins Task 1.1, has significantly enhanced the **Life Cycle Assessment (LCA) capabilities of Lithuania's Kaunas University of Technology (KTU)**, enabling it to strengthen its role in the field of **sustainable building assessments**. Through its participation, KTU has gained new insights into **building stock classification, sustainability benchmarking, and the integration of digital tools into LCA workflows**, positioning itself as a key player in the transition toward **low-carbon, high-performance buildings in the Baltic region and beyond**.

One of the major benefits of the research has been the ability to **enhance building stock classification methodologies**, allowing for a more structured and precise way of benchmarking **environmental performance across different building typologies**. Traditional sustainability assessments often relied on **generic datasets** that failed to capture the **regional variations in construction practices, climate conditions, and material choices**. By refining these classifications, KTU has developed **more context-sensitive benchmarking frameworks**, enabling detailed **comparisons between different building types and their sustainability potential**. This is particularly relevant for Lithuania, where the **building stock includes a mix of Soviet-era structures, modern developments, and historic buildings**, each with unique **embodied carbon profiles and energy performance characteristics**. The ability to distinguish between these categories has allowed KTU to generate **more targeted sustainability strategies**, ensuring that LCA findings are applicable to **real-world policymaking and building renovation initiatives**.

The integration of **digital tools and machine learning algorithms into LCA methodologies** has been another key area of advancement. Traditional LCA workflows were often **static and data-intensive**, requiring **manual input and limited adaptability** to changing sustainability regulations. Through the Twinning Widening collaboration, KTU has been able to **adopt more dynamic, data-driven approaches**, improving the accuracy and efficiency of sustainability assessments. By leveraging **automated material tracking, real-time energy simulations, and AI-driven analytics**, researchers at KTU have significantly reduced the **time required to conduct LCA studies**, making these assessments **more scalable and accessible for both research and industry applications**. This shift toward **automated LCA modeling** has strengthened KTU's ability to contribute to **national and EU-wide climate goals**, positioning it as a leading institution for **sustainability-driven digital transformation in the built environment**.

A deeper understanding of the role of **regional climate variations in sustainability benchmarking** has also emerged from the research. Buildings in **Northern and Baltic climates** face distinct challenges in terms of **thermal performance, heating energy**

demand, and material resilience, making it essential to tailor **LCA methodologies to these specific conditions**. By incorporating **climate-sensitive data into LCA models**, KTU has been able to develop more **accurate energy performance projections**, allowing for the identification of **best-practice strategies for insulation, passive solar design, and renewable energy integration**. This work has been particularly valuable for guiding **Lithuania's building renovation policies**, helping to ensure that **older building stock is upgraded in alignment with EU decarbonization targets while maintaining energy affordability**.

Beyond new construction, the project has enabled KTU to **expand its LCA modeling expertise to assess existing buildings**, providing a framework for evaluating the **sustainability potential of retrofitting and adaptive reuse**. While many LCA studies traditionally focus on **newly built structures**, a significant share of Europe's carbon footprint is tied to **existing buildings**, necessitating a **comprehensive approach to whole-life sustainability**. By integrating **embodied carbon assessments into retrofitting evaluations**, KTU has been able to compare the **long-term environmental impact of renovation strategies versus new construction**, ensuring that decision-makers have access to **evidence-based sustainability metrics**. These insights are critical for shaping **national renovation strategies and EU-wide building decarbonization efforts**, reinforcing the importance of **lifespan extension and material efficiency** in achieving carbon neutrality.

One of the most impactful findings has been the **variation in embodied carbon across different building typologies**, underscoring the need for **differentiated sustainability strategies** based on **construction methods and material compositions**. The research has shown that **low-rise residential buildings, high-density urban developments, and mixed-use commercial buildings** each have unique **environmental performance profiles**, necessitating tailored **LCA approaches**. By refining classification metrics and developing **data-backed sustainability benchmarks**, KTU has established **standardized reference values for embodied carbon and operational energy performance**, allowing for more **precise regulatory compliance checks and voluntary sustainability certifications**.

Another significant outcome has been the **integration of LCA modeling with energy performance certification frameworks**, allowing for **cross-referenced assessments of whole-life carbon impacts and operational energy efficiency ratings**. In many cases, sustainability regulations and energy certifications operate in **parallel but disconnected systems**, limiting the ability to **assess buildings holistically**. Through the Twinning Widening collaboration, KTU has worked on **hybrid assessment models** that link **LCA methodologies with energy benchmarking tools**, ensuring that sustainability assessments account for both **embodied and operational carbon**. This has positioned KTU as a **regional leader in energy performance and carbon accountability research**, strengthening its influence in shaping **policy-driven sustainability initiatives**.

The adoption of **circular economy principles within LCA modeling** has also been a major milestone. Traditionally, LCA assessments have focused primarily on **energy use and emissions**, with less emphasis on **material circularity, resource recovery, and design for disassembly**. By expanding LCA frameworks to include **material lifecycle tracking**, KTU has developed methodologies for assessing **the recyclability, reuse potential, and waste reduction impact of different construction materials**. This work aligns with **Lithuania's growing focus on circular construction**, providing **scientific evidence to support material recovery strategies, deconstruction planning, and waste minimization policies**.

Beyond individual building assessments, the research conducted has contributed to **urban-scale sustainability evaluations**, providing insights into **district-level energy efficiency trends, carbon mitigation potential, and large-scale renovation priorities**. By applying LCA at a **broader urban scale**, KTU has been able to support **regional planning initiatives**, ensuring that **policy interventions are data-driven and aligned with EU sustainability objectives**. The ability to assess **building stock sustainability on a city-wide basis** has empowered **municipal governments, urban planners, and energy policymakers** with the tools needed to **prioritize high-impact renovation projects and district-level decarbonization strategies**.

As KTU continues to strengthen its role in **sustainable building research**, the knowledge gained through this Twinning Widening project will serve as a **foundation for further advancements in LCA methodologies, digital sustainability modeling, and climate-responsive building assessments**. The integration of **data-driven tools, automated benchmarking frameworks, and regional adaptation strategies** has positioned KTU at the forefront of **smart building sustainability research**, enabling it to contribute to **both national and European climate action goals** in the years to come.

Table 4.1:Key Findings from Section 4.1 – Advancements in LCA Modeling for Smart Buildings at KTU

Main Achievements	Description
Enhanced Building Stock Classification	Developed refined methodologies for classifying building stock, improving sustainability benchmarking across different typologies.
Integration of Digital Tools for LCA	Adopted machine learning and automated digital tools to improve LCA modeling accuracy and scalability.
Climate-Sensitive Sustainability Benchmarking	Integrated climate adaptation factors into LCA assessments, ensuring region-specific sustainability strategies.
Assessment of Existing vs. New Buildings	Expanded LCA modeling to assess existing buildings, emphasizing retrofitting strategies alongside new construction.

Variation in Embodied Carbon Across Typologies	Identified variations in embodied carbon across different building types, informing differentiated sustainability policies.
LCA Linked with Energy Performance Certifications	Developed hybrid assessment models linking LCA with energy certification frameworks for comprehensive sustainability evaluations.
Incorporation of Circular Economy Principles	Enhanced LCA modeling to track material lifecycle potential, reinforcing circular economy strategies in construction.
Urban-Scale Sustainability Assessments	Applied LCA methodologies to district-wide sustainability planning, contributing to urban carbon reduction strategies.
Standardization of LCA Benchmarking	Established standard methodologies for benchmarking LCA sustainability performance, ensuring consistency across building assessments.
Alignment with Future Climate Policies	Aligned LCA advancements with emerging EU climate policies, strengthening regulatory compliance and policy impact.

4.2. Advancements in Integrating Digital Twins with RFID and IoT

Research conducted in SmartWinshas significantly contributed to strengthening **Lithuania's Kaunas University of Technology (KTU)** in the field of **Digital Twin integration with Radio Frequency Identification (RFID) and Internet of Things (IoT) technologies**. TOne of the most impactful advancements has been the ability to **seamlessly integrate Digital Twin platforms with IoT sensors and RFID systems**, enabling **real-time data acquisition and automated decision-making**. Traditionally, **building monitoring and facility management** have relied on **static models and periodic inspections**, limiting the ability to detect **system inefficiencies, equipment failures, or deviations from expected performance levels**. Through the adoption of **IoT-enabled Digital Twins**, KTU has gained the capability to **create dynamic building models that continuously update based on real-time environmental conditions, occupant behavior, and operational data**. This transition from **static to dynamic monitoring** has vastly improved the ability to **predict maintenance needs, optimize HVAC operations, and refine sustainability performance in educational, residential, and commercial buildings**.

The integration of **RFID tracking within Digital Twin environments** has also been a major breakthrough, allowing for enhanced **asset management, material traceability, and lifecycle monitoring of building components**. In traditional construction and facility management workflows, **tracking the movement of materials, equipment, and energy-consuming devices** is often labor-intensive and prone to errors. By embedding **RFID tags into key building components**, KTU has developed new methodologies for

real-time material tracking, ensuring that **building assets can be continuously monitored from construction through to operation and eventual deconstruction**. This has led to a more **data-driven approach to resource allocation, material recovery, and circular economy adoption**, supporting **Lithuania's sustainability agenda** by reducing **construction waste and enhancing material lifecycle planning**.

One of the key challenges addressed through this research has been the **interoperability of Digital Twins with multiple data sources**. Digital Twin platforms require **continuous input from IoT sensors, RFID trackers, BIM models, and real-time energy monitoring systems**, yet ensuring that these **disparate data streams** function cohesively has historically been a challenge. Through the **Twinning Widening collaboration**, KTU has developed expertise in **API-based interoperability frameworks**, allowing different sensor systems and digital models to **exchange data seamlessly**. This has significantly **improved the accuracy and responsiveness of Digital Twin simulations**, ensuring that **building performance data remains up to date, synchronized, and actionable in real time**.

Another critical area of advancement has been the **calibration and optimization of IoT sensor networks** for **real-time environmental monitoring**. IoT sensors deployed in **smart buildings must maintain high levels of precision and reliability**, yet external factors such as **sensor drift, network interference, and environmental variations** can impact data accuracy. Through its research efforts, KTU has **developed methodologies for IoT sensor calibration**, ensuring that **temperature, humidity, air quality, and energy consumption sensors deliver consistently accurate data over long-term monitoring periods**. This capability has strengthened KTU's role in **sustainable building performance assessments**, allowing researchers to produce **high-resolution environmental datasets that support advanced sustainability modeling**.

By integrating **Digital Twin technologies with predictive maintenance frameworks**, KTU has been able to explore **new strategies for optimizing building operations and reducing energy waste**. Traditionally, **building maintenance relies on reactive strategies**, where equipment failures are only addressed **after** they cause **significant inefficiencies or downtime**. Through Digital Twin-enabled **predictive analytics**, it is now possible to **identify potential system failures before they occur**, allowing for **proactive interventions** that extend the lifespan of building infrastructure while reducing maintenance costs. HVAC systems, for example, can now be **monitored in real-time**, with Digital Twins detecting **patterns of inefficiency or gradual performance declines**. If anomalies are detected—such as **unexpected energy spikes or airflow irregularities**—the Digital Twin can **automatically trigger maintenance alerts**, ensuring that **equipment is serviced before failure occurs**.

A major benefit of this research has been the **integration of Digital Twins with occupant behavior modeling**, allowing for **smarter building adaptations based on real-**

time user interactions. In many cases, **energy inefficiencies arise due to human factors**, such as **overuse of heating and cooling systems, inefficient lighting usage, and poorly managed ventilation strategies**. Through IoT-enabled occupancy tracking, Digital Twins can now **analyze movement patterns, detect room utilization rates, and optimize HVAC and lighting schedules accordingly**. If a classroom or office space remains **unoccupied for an extended period**, the Digital Twin can **automatically adjust climate control settings**, reducing unnecessary energy consumption. This **adaptive control strategy** ensures that buildings **maintain energy efficiency without compromising occupant comfort**, reinforcing **Lithuania's commitment to climate-conscious building management**.

Beyond individual buildings, the research conducted has also supported the **scaling of Digital Twin applications to district-wide and city-scale infrastructure projects**. Smart city initiatives are increasingly reliant on **Digital Twin ecosystems** that coordinate **building performance data, energy grid stability, and distributed renewable energy resources**. Through its work in **Digital Twin-enabled urban analytics**, KTU has developed methodologies for **aggregating multi-building sustainability data**, enabling urban planners and municipal authorities to **optimize resource distribution, improve grid reliability, and enhance large-scale energy resilience**. This capability is particularly valuable for **Lithuania's efforts to integrate smart energy management strategies into national climate policies**, ensuring that **buildings contribute to broader decarbonization goals** at the district and regional levels.

As with any advanced technology, the integration of **Digital Twins with RFID and IoT** has also raised **important cybersecurity concerns**, particularly regarding **data privacy, network vulnerabilities, and unauthorized system access**. Since these systems **collect and process vast amounts of real-time data**, protecting sensitive information has been a key research priority. Through the Twinning Widening project, KTU has **gained expertise in secure data encryption, AI-driven threat detection, and blockchain-enabled cybersecurity frameworks**, ensuring that **Digital Twin ecosystems remain resilient against cyber threats**. This research has not only **enhanced the security of smart building infrastructures in Lithuania** but has also positioned KTU as a key contributor to **EU-wide cybersecurity policies for digital sustainability technologies**.

The advancements in **Digital Twin integration with RFID and IoT** have fundamentally transformed KTU's ability to conduct **high-precision sustainability assessments, predictive energy optimizations, and dynamic building performance monitoring**. The knowledge gained through this research ensures that KTU remains a **regional leader in digital sustainability modeling**, allowing it to contribute actively to **smart building innovations, national energy strategies, and EU-wide sustainability initiatives**. With the continued expansion of Digital Twin applications, KTU is now well-positioned to lead future research in **self-regulating smart buildings, adaptive climate resilience,**

and circular economy-driven construction strategies, reinforcing its role as an emerging center of excellence in sustainable building technology.

Table 4.2: Key Findings from Section 4.2 – Advancements in Digital Twin Integration with RFID and IoT

Table 4.2: Key Findings from Section 4.2 – Advancements in Digital Twin Integration with RFID and IoT

Main Finding	Description
Seamless Integration of Digital Twins with IoT and RFID	Developed methodologies for integrating Digital Twin platforms with real-time IoT sensor data and RFID tracking systems.
Real-Time Asset Tracking and Lifecycle Monitoring	Enhanced asset tracking and lifecycle monitoring through RFID-based material traceability in construction and facility management.
Improved Data Interoperability in Digital Twin Environments	Implemented API-based frameworks to enable seamless data exchange between Digital Twin models and diverse data sources.
Optimization of IoT Sensor Networks for Environmental Monitoring	Refined IoT sensor calibration techniques to improve the accuracy of real-time environmental monitoring and building automation.
Advancements in Predictive Maintenance Strategies	Developed predictive maintenance strategies using Digital Twin analytics, optimizing equipment performance and reducing failures.
Occupant Behavior Modeling for Energy Efficiency	Integrated occupant behavior modeling into Digital Twins, ensuring energy optimization strategies align with real-world interactions.
Scaling Digital Twin Applications to Urban Infrastructure	Expanded Digital Twin research from individual buildings to district-level and city-wide smart infrastructure applications.
Strengthening Cybersecurity for Digital Twin Ecosystems	Developed secure data encryption, AI-based threat detection, and blockchain-enabled verification for Digital Twin systems.
Automated Resource Allocation in Smart Buildings	Enhanced data-driven decision-making for dynamic resource allocation, improving HVAC efficiency and material management.

Alignment with EU Smart Building and Digitalization Strategies	Aligned Digital Twin research with EU smart building policies, reinforcing Lithuania's role in digital transformation initiatives.

4.3. Innovations in BIM-Enhanced LCA Workflows

KTU has also significantly advanced its expertise in **integrating Building Information Modelling (BIM) with Life Cycle Assessment (LCA)**. This collaboration has strengthened KTU's ability to develop **automated sustainability assessment frameworks**, ensuring that **smart buildings in Lithuania and the broader widening region can achieve higher levels of environmental efficiency, material optimization, and carbon reduction**. The integration of **BIM-enhanced LCA workflows** has provided KTU with the tools needed to **streamline sustainability calculations, improve regulatory compliance, and scale up life cycle modeling capabilities** for both new and existing buildings.

One of the most important advancements in **BIM-LCA integration** has been the **implementation of automated data extraction**, eliminating the need for **manual sustainability calculations** and significantly **reducing inconsistencies in environmental assessments**. Traditionally, LCA relied on **static datasets**, requiring researchers and building professionals to **manually input material inventories, operational energy estimates, and embodied carbon values**. This process was not only time-consuming but also prone to **human error and data discrepancies**. Through the **integration of BIM with automated sustainability assessment tools**, KTU has developed **more precise and scalable methodologies**, ensuring that **material selections and energy performance indicators are automatically extracted from BIM models and linked to LCA databases**.

A key innovation in this process has been the **use of APIs (Application Programming Interfaces) to facilitate real-time data exchange between BIM platforms and LCA tools**. APIs allow BIM models to be **dynamically linked with external sustainability databases**, ensuring that **LCA calculations are continuously updated based on the latest material specifications, energy benchmarks, and regulatory requirements**. Through this Twinning Widening collaboration, KTU has developed expertise in using **cloud-based sustainability APIs**, which enable real-time synchronization between **BIM platforms such as Autodesk Revit and LCA tools like OneClickLCA and SimaPro**. This **automated data flow** has streamlined **whole-life carbon accounting**, ensuring that buildings are designed, constructed, and maintained in alignment with **EU sustainability directives and national climate targets**.

Another key area of advancement has been the **integration of BIM-enhanced LCA models with real-time energy simulations**, allowing for **multi-scenario sustainability**

assessments. Traditionally, LCA methodologies assessed a building's environmental performance **only after** the design phase was completed, making it difficult to incorporate **carbon reduction strategies at early decision-making stages**. Through this research, KTU has gained the ability to conduct **predictive sustainability modeling**, enabling designers to **test multiple material configurations, construction techniques, and operational strategies** before finalizing building specifications. This innovation has significantly improved **decision-making processes in sustainable architecture**, ensuring that environmental impacts are considered **from the earliest stages of design**.

One of the most transformative applications of **BIM-enhanced LCA workflows** has been the ability to **link sustainability assessments with real-time building operations**, ensuring that **post-occupancy performance data continuously refines life cycle models**. The integration of BIM with **IoT-enabled energy monitoring systems** allows KTU to track **actual energy consumption, occupant behavior, and system efficiency**, comparing real-world data against initial LCA predictions. This process, known as **dynamic LCA modeling**, has helped KTU refine **sustainability benchmarks for different building typologies**, ensuring that **future designs incorporate lessons learned from real operational conditions**.

A major outcome of this research has been the ability to **automate compliance checks for environmental regulations and energy performance certifications**, ensuring that **buildings meet stringent sustainability standards without additional manual processing**. By embedding **regulatory constraints and sustainability criteria into BIM-based LCA workflows**, KTU has enabled project teams to **automatically detect non-compliant materials, excessive carbon footprints, or inefficient system configurations**. This has allowed designers, engineers, and policymakers to **make more informed decisions**, ensuring that buildings comply with **Lithuania's national sustainability policies as well as EU-wide standards, such as the Energy Performance of Buildings Directive (EPBD) and the EU Taxonomy for Sustainable Activities**.

The ability to **streamline life cycle cost (LCC) and life cycle impact (LCI) assessments** within **a unified digital environment** has also been a crucial advancement. Traditionally, economic and environmental assessments were conducted **independently**, making it difficult to align **financial considerations with sustainability targets**. Through this Twinning Widening collaboration, KTU has adopted **new BIM-integrated LCA workflows that assess both economic feasibility and environmental impact simultaneously**. This ensures that **carbon reduction strategies remain cost-effective**, helping project teams make **data-driven decisions that balance sustainability with affordability**.

Beyond individual building assessments, the research has supported the **scaling of BIM-enhanced LCA methodologies to urban planning and district-wide sustainability evaluations**. Through large-scale modeling initiatives, KTU has gained expertise in applying **automated LCA workflows to entire building portfolios**, allowing municipalities and urban planners to **prioritize high-impact renovation projects, optimize district-level energy strategies, and assess regional carbon reduction potential**. This capability has strengthened KTU's ability to contribute to **Lithuania's national climate goals**, ensuring that the research findings are applicable at **both the building and urban scales**.

A major focus of the research has been on advancing **circular economy principles within BIM-enhanced LCA workflows**, ensuring that sustainability assessments extend beyond **energy performance metrics** to include **material recovery potential, design for deconstruction, and waste reduction strategies**. Through API-driven BIM-LCA integration, KTU has developed methodologies for **automated material lifecycle tracking**, allowing for **detailed assessments of recyclability, reuse potential, and carbon savings from circular construction approaches**. This work aligns with **Lithuania's growing focus on circular building strategies**, ensuring that the research findings contribute to **national and EU-wide sustainability policies** aimed at reducing **material waste and promoting resource efficiency**.

The advancements in **BIM-enhanced LCA workflows** gained through this Twinning Widening project have positioned KTU as **a regional leader in digital sustainability modeling**, enabling it to **support national regulatory development, contribute to EU policy implementation, and foster further research in automated environmental impact assessment**. As Lithuania continues its transition toward **low-carbon, data-driven building practices**, the ability to integrate **real-time sustainability analytics into BIM workflows** will be crucial in achieving **climate-neutral construction and smart building innovation**.

The research conducted has demonstrated that **BIM-LCA automation is not just a tool for improving sustainability calculations—it is a transformative methodology that enables continuous learning, adaptation, and improvement**. By strengthening its expertise in **automated sustainability assessments, real-time energy simulations, and dynamic carbon tracking**, KTU has developed a **future-proof approach to smart building sustainability**, ensuring that **digital tools and data-driven decision-making remain at the heart of Lithuania's built environment transformation**.

Table 4.3: Key Findings from Section 4.3 – Innovations in BIM-Enhanced LCA Workflows

Main Finding	Description
Automation of LCA Data Extraction from BIM Models	Developed automated workflows for extracting material and energy performance data from BIM models for LCA calculations.

API-Enabled Real-Time Sustainability Assessments	Implemented API-based integrations for continuous sustainability benchmarking and compliance monitoring.
Integration of BIM-Enhanced LCA with Energy Simulations	Enhanced LCA capabilities through BIM-integrated energy modeling, allowing for dynamic multi-scenario analysis.
Predictive Sustainability Modeling for Early Design Stages	Developed predictive sustainability modeling techniques to assess environmental impacts at early design stages.
Automated Compliance Checks for Sustainability Regulations	Established rule-based automation for detecting material and energy inefficiencies based on regulatory constraints.
Linking Life Cycle Cost (LCC) and LCA Evaluations	Linked financial and environmental assessments in a unified BIM-LCA framework for optimized decision-making.
Scaling BIM-Enhanced LCA to Urban Planning	Applied BIM-enhanced LCA methodologies to large-scale urban sustainability assessments and district-level planning.
Incorporating Circular Economy Strategies in BIM-LCA Workflows	Developed methodologies for tracking material reuse potential and waste reduction strategies in LCA workflows.
IoT-Connected BIM-LCA for Post-Occupancy Monitoring	Integrated IoT-based energy monitoring into BIM-LCA models, ensuring real-time post-occupancy performance analysis.
Alignment with Emerging EU Carbon Neutrality Targets	Ensured that BIM-LCA workflows align with evolving EU regulations on whole-life carbon accountability and net-zero targets.

4.4. Findings on Building User Interaction and Performance Monitoring

The research conducted on **building user interaction and performance monitoring** has provided **Kaunas University of Technology (KTU)** with valuable insights into how **occupants influence indoor environmental quality (IEQ), energy efficiency, and overall building sustainability**. With a focus on **educational buildings**, the study examined how **real-time monitoring, IoT-enabled data collection, and Digital Twin**

integration can improve the understanding of **indoor air quality (IAQ), occupant behavior, and adaptive building performance strategies**. The findings from this research have strengthened KTU's expertise in **data-driven building management**, ensuring that **smart educational environments** in Lithuania and other widening regions can be **optimized for health, cognitive function, and energy efficiency**.

One of the most critical findings from this research has been the **direct correlation between IAQ and student performance**. Prior to the implementation of **real-time air quality monitoring**, many educational buildings relied on **fixed ventilation rates and static assumptions about occupancy patterns**, often failing to account for **fluctuations in CO_2 levels, humidity, and airborne pollutants**. Through the deployment of **IoT sensors and Digital Twin analytics**, it became evident that **IAQ conditions varied significantly throughout the day**, with peak occupancy hours leading to **higher CO_2 concentrations and reduced ventilation effectiveness**. The research demonstrated that when CO_2 levels exceeded **1000 ppm**, students experienced **noticeable declines in concentration, cognitive function, and overall well-being**, reinforcing the need for **adaptive IAQ management strategies** in smart educational buildings.

The ability to **continuously monitor and dynamically adjust IAQ conditions** has been one of the most important advancements made possible through this project. By integrating **sensor networks with Digital Twin models**, KTU has gained expertise in **developing automated IAQ optimization strategies**, where **ventilation rates are adjusted in real time based on occupancy levels and environmental data**. This has led to the **development of smarter, more responsive HVAC systems**, ensuring that educational buildings maintain **optimal air quality while minimizing unnecessary energy consumption**. The knowledge gained through this research has positioned KTU as a **leader in IAQ optimization strategies**, ensuring that future educational building designs in Lithuania incorporate **real-time air quality feedback loops** as a standard feature.

Beyond IAQ, the research has highlighted the importance of **thermal comfort and lighting conditions in shaping student productivity and overall building efficiency**. Traditional heating and cooling strategies often **fail to account for real-world variations in occupant preferences, weather conditions, and space utilization rates**, leading to **inefficient energy use and discomfort among building users**. The findings demonstrated that **overheating in winter and excessive cooling in summer** were common issues, often exacerbated by **rigid thermostat settings and a lack of dynamic climate control mechanisms**. By leveraging **IoT-based climate control systems and Digital Twin simulations**, KTU has developed expertise in **adaptive thermal regulation**, ensuring that **temperature adjustments align with real-time occupancy data and external climate conditions**. This has significantly **improved energy efficiency while maintaining occupant comfort**, contributing to Lithuania's broader **climate resilience and energy-saving initiatives**.

Another key area of investigation has been the **role of occupant behavior in influencing energy efficiency and IAQ**. While automated building systems can **optimize environmental conditions**, human behavior remains **a crucial factor in determining overall performance**. The research found that **occupants often unknowingly contribute to inefficiencies**, such as **leaving windows open while HVAC systems are running, adjusting thermostat settings to extreme levels, or blocking ventilation pathways with furniture**. By integrating **occupancy tracking data with Digital Twin learning algorithms**, KTU has developed methodologies to **predict and mitigate these user-driven inefficiencies**, ensuring that **building automation systems account for real-world occupant interactions**. This has led to the **development of targeted behavioral interventions**, such as **occupant feedback interfaces, energy awareness programs, and AI-driven climate recommendations**, fostering **more energy-conscious user behavior** in smart educational buildings.

The research has also provided valuable insights into **personalized environmental control systems**, demonstrating how **user-adaptive climate, lighting, and ventilation settings** can enhance **occupant satisfaction and cognitive performance**. By allowing **students and faculty to provide real-time feedback on indoor environmental conditions**, Digital Twin models can learn from **occupant preferences**, refining **automated control strategies to balance sustainability with comfort**. This **user-centered approach** to building performance monitoring ensures that **sustainability interventions do not compromise human well-being**, reinforcing the importance of **adaptive smart building design**.

Through this project, KTU has also gained expertise in **leveraging IAQ and performance monitoring data for large-scale policy recommendations**. By analyzing **longitudinal IAQ datasets across multiple educational buildings**, researchers have been able to identify **patterns in air quality deficiencies, ventilation effectiveness, and student performance correlations**, leading to the development of **evidence-based recommendations for national IAQ standards in schools and universities**. This research supports **Lithuania's alignment with EU-wide building health regulations**, ensuring that future educational buildings adhere to **higher air quality and comfort standards**.

The scalability of these findings extends beyond educational buildings, offering **valuable insights for broader smart building applications**. The ability to **track real-time occupant interactions, optimize environmental conditions dynamically, and integrate IoT-driven performance monitoring** can be applied to **commercial, residential, and public sector buildings**, reinforcing KTU's role as a **leader in sustainable building management research**. The methodologies developed through this project provide **a replicable framework for integrating IAQ optimization, behavioral modeling, and climate-responsive control systems into a wide range of smart building environments**.

Through its involvement in the **Twinning Widening project**, KTU has strengthened its **capacity for advanced building performance analysis**, ensuring that **Lithuanian educational institutions and smart buildings benefit from the latest research-driven innovations in IAQ monitoring, adaptive building automation, and data-driven energy optimization**. The expertise gained through this initiative positions KTU as a **regional knowledge hub for sustainable building performance research**, ensuring that future developments in **smart educational infrastructure** are informed by **scientific evidence, real-world user interactions, and cutting-edge digital modeling techniques**.

Table 4.4 :Key Findings from Section 4.4 – Building User Interaction and Performance Monitoring

Main Finding	Description
Correlation Between IAQ and Cognitive Performance	Demonstrated the impact of indoor air quality on student concentration, cognitive function, and overall well-being.
Implementation of Real-Time IAQ Monitoring and Adaptive Ventilation	Developed real-time IAQ monitoring strategies with automated HVAC adjustments based on occupancy and pollutant levels.
Integration of IoT Sensors for Dynamic Climate Control	Refined IoT-based climate control methodologies to optimize energy efficiency while maintaining thermal comfort.
Behavioral Modeling for Energy Optimization	Integrated Digital Twin-driven occupant behavior analysis to minimize energy inefficiencies linked to user interactions.
Development of Personalized Environmental Control Systems	Developed adaptive climate, lighting, and ventilation controls to balance sustainability with individual occupant preferences.
Data-Driven IAQ Benchmarking for Educational Buildings	Created IAQ benchmarking methodologies tailored to educational buildings, ensuring optimal ventilation and air quality standards.
Scalability of IAQ Monitoring to Other Smart Buildings	Demonstrated the applicability of IAQ monitoring techniques across residential, commercial, and public smart buildings.
Automated Feedback Loops for IAQ and Occupant Comfort	Established feedback loops between IAQ sensors, HVAC controls, and user preferences for continuous environmental optimization.

Policy Implications for IAQ Standards in Educational Buildings	Provided data-driven recommendations for national IAQ policies in schools and universities, supporting improved air quality standards.
Alignment with EU Healthy Buildings and Well-Being Policies	Aligned research findings with EU-wide initiatives promoting healthy indoor environments and occupant well-being in smart buildings.

5. Conclusions

The **SmartWins project** has contributed significantly to advancing the research and development of **smart, energy-efficient, and carbon-neutral buildings**. Through an interdisciplinary approach that integrates **LCA, BIM, Digital Twins, IoT, and RFID-based tracking**, this deliverable has laid the foundation for more **data-driven, automated, and holistic whole-life cycle assessments of buildings**. These advancements not only support **sustainability goals** but also ensure that **smart buildings are optimized for energy efficiency, material use, occupant well-being, and long-term environmental impact reduction**.

One of the primary achievements of this deliverable is the integration of **LCA methodologies with digitalization tools**, which has allowed for more **accurate, real-time sustainability assessments** across all building life cycle stages. Traditionally, LCA has been constrained by **static datasets** and **manual inventory processes**, limiting its ability to **adapt to changing building conditions and material innovations**. However, by incorporating **BIM and Digital Twin platforms**, LCA modeling has become **dynamic and predictive**, enabling **automated calculations, real-time environmental impact assessments, and improved material tracking**. These advancements contribute to the **optimization of embodied carbon accounting, operational energy efficiency, and end-of-life material recovery strategies**.

The research has also underscored the **importance of Digital Twins in enhancing smart building performance monitoring**. The ability to create **real-time, data-rich digital replicas of physical buildings** has transformed how sustainability performance is evaluated. Unlike conventional assessment methods that rely on **periodic audits and static models**, Digital Twins provide **continuous, sensor-driven updates** that allow for **immediate performance adjustments, predictive maintenance, and proactive energy optimization**. This **real-time adaptability** ensures that **smart buildings can respond dynamically to occupant behaviors, environmental conditions, and system inefficiencies**, significantly improving **long-term sustainability performance**.

Another major finding from this deliverable is the **integration of RFID and IoT technologies** into **smart building asset management**. Traditional building maintenance, material tracking, and operational monitoring have often relied on **manual inspections and scheduled maintenance cycles**, which can lead to **inefficiencies, unnecessary resource consumption, and reactive maintenance strategies**. By embedding **RFID tags and IoT sensors into building systems and materials**, it is now possible to **automate real-time tracking, enable predictive maintenance algorithms, and ensure that sustainability indicators are continuously monitored and refined**. These innovations allow **facility managers, designers, and policymakers to make more informed decisions about resource allocation, energy consumption, and long-term building adaptability**.

The integration of **LCA and BIM workflows** has also been a key area of advancement. One of the primary challenges in sustainability assessments has been the **lack of interoperability between assessment tools and design models**, which has often resulted in **fragmented data, inefficiencies in material impact calculations, and disjointed regulatory compliance checks**. By embedding **BIM-based sustainability simulations and LCA plug-ins**, this research has demonstrated how **automated material tracking, carbon footprint calculations, and scenario-based simulations** can significantly **improve the accuracy, efficiency, and scalability of smart building assessments**. This development is particularly relevant for **ensuring compliance with EU sustainability directives such as the EPBD, EED, and RED**, which require **standardized sustainability benchmarking and whole-life carbon reporting**.

A critical insight from this deliverable has been the **benchmarking of building geometries and thermal performance**, which has provided valuable data on **how different architectural designs influence energy efficiency and life cycle sustainability**. The relationship between **building form, solar exposure, passive design strategies, and operational energy performance** is crucial for determining **optimal sustainability pathways for different climates and typologies**. By integrating **thermal simulations with LCA and Digital Twin data**, the research has demonstrated how **adaptive energy models and passive cooling strategies** can be used to **enhance sustainability while minimizing material and operational carbon footprints**.

The research has also emphasized the **importance of human-centric smart building design**, particularly in educational environments where **indoor air quality (IAQ), lighting conditions, and occupant comfort** play a significant role in **well-being and productivity**. Findings indicate that **real-time IAQ monitoring using IoT sensors** can lead to **improved learning outcomes, better health conditions, and more energy-efficient HVAC operations**. By incorporating **sensor-based IAQ tracking, adaptive ventilation, and predictive environmental modeling**, this deliverable has provided a roadmap for **how smart buildings can balance sustainability goals with user-centric design principles**.

The **role of Digital Twin technology in predictive maintenance and fault detection** has been another important area of focus. Traditional building maintenance often relies on **fixed inspection schedules** that do not account for **real-time system degradation or emerging inefficiencies**. Digital Twins, combined with **AI-driven analytics and IoT monitoring**, allow for **continuous tracking of equipment performance**, ensuring that **potential failures are detected before they escalate**. This approach not only **reduces maintenance costs** but also **extends the lifespan of building systems**, contributing to **long-term sustainability and resource conservation**.

A key policy-related takeaway from this deliverable is the **alignment of smart building sustainability strategies with EU directives**. The **Energy Performance of Buildings Directive (EPBD)** mandates the transition to **Zero Emission Buildings (ZEBs) by 2030**, requiring **LCA-driven sustainability assessments, Digital Twin-enhanced monitoring, and whole-life carbon reduction strategies**. The **Energy Efficiency Directive (EED)** emphasizes **building renovation strategies**, smart metering systems, and **real-time energy optimization**, all of which have been demonstrated through the findings of this deliverable. Meanwhile, the **Renewable Energy Directive (RED)** reinforces the **integration of on-site renewable energy sources**, which have been **analyzed through Digital Twin simulations and life cycle energy modeling**. These policy alignments demonstrate the **practical applicability of the SmartWins research** in **helping the EU achieve its long-term decarbonization goals**.

From an academic and capacity-building perspective, this deliverable has also strengthened **Lithuania's Kaunas University of Technology (KTU) in the field of sustainable building assessments**. As part of the **Twinning Widening initiative**, the research has enabled **KTU to enhance its expertise in LCA, BIM automation, Digital Twin modeling, and smart building analytics**, positioning it as a **key institution for climate-conscious digital transformation in the built environment**. By leveraging **cutting-edge methodologies**, KTU has improved its ability to **conduct large-scale sustainability assessments, contribute to EU policy development, and collaborate with international research networks on future sustainability innovations**.

Ultimately, the **SmartWins D1.1 deliverable** marks a **significant milestone in the evolution of whole-life sustainability assessments for smart buildings**. The integration of **digital sustainability tools, automated material tracking, real-time performance analytics, and AI-driven optimization** has **transformed how smart buildings are designed, operated, and maintained**. These advancements not only enhance **building efficiency and carbon footprint reduction** but also provide a **scalable, data-driven approach to ensuring long-term environmental resilience**.

As **research, policy, and technology continue to evolve**, the findings of this deliverable provide a **strong foundation for further innovation** in **sustainable smart buildings, digital construction workflows, and data-driven climate adaptation strategies**. The continued **advancement of Digital Twin technology, AI-powered LCA modeling, and IoT-enhanced monitoring** will play a **pivotal role in ensuring that smart buildings remain adaptable, sustainable, and aligned with global climate targets**.