GREENBIMXELS: A DATA SPACE UNLOCKING ENVIRONMENTAL VALUE FOR PUBLIC FACILITIES IN THE CONSTRUCTION SECTOR

Gordo-Gregorio, Paula[1]; Coloma Picó, Eloi[1]; Martínez Ibañez, Manel[1]; Macarulla Martí, Marcel[1]; Angulo, Cecilio[1]

[1]Polytechnic University of Catalonia, Barcelona,Spain

Abstract

Public administration buildings generate vast operational data, which is rarely used for environmental purposes. GreenBIMxels, a research project led by the Polytechnic University of Catalonia, explores how Data Spaces support environmental assessments in public facilities.

This paper defines environmental services for BIM models within a Data Space named UPCxels. The study addresses the interests of public administrations and private-sector stakeholders, examining how Data Spaces can respond to their needs. Three use cases are designed by combining participatory workshops and a questionnaire survey. The use cases include energy-efficiency, water-consumption optimization and carbon-footprint assessment, each operationalized through KPI sets and BIM/IFC-based properties.

Introduction

Building Information Modeling (BIM) is increasingly used to manage building and infrastructure assets by means of shared digital representations that support decision-making across design, construction and facility management throughout the asset lifecycle. By consolidating geometric, technical and operational information into a single model, BIM improves coordination among stakeholders and provides a data-rich foundation for operation and maintenance activities (Gordo-Gregorio et al., 2025). Despite this potential, BIM is still frequently applied in a construction-centric way, which constrains the systematic reuse of information for environmental performance monitoring or long-term portfolio planning, particularly within public administrations (Akbari et al., 2024; Kivits & Furneaux, 2013).

In parallel, the European data strategy and recent work on Data Spaces propose federated infrastructures where data holders remain sovereign over their assets while enabling controlled sharing and cross-organizational analytics and demand alignment with the international data-space principles (the Data Spaces Support Centre (DSSC), Gaia-X, and the International Data Spaces Association (IDSA)) (Enes, 2025; Valk & Ryan, 2025). Sectoral Data Spaces define common governance, trust and interoperability frameworks so that heterogeneous datasets can be securely combined and analyzed without centralizing sensitive information (Kovach et al., 2026). For the built environment, this paradigm is particularly relevant, because public owners, operators and service providers need to cooperate around services such as energy demand, while respecting contractual constraints, privacy and institutional autonomy (Janev et al., 2021).

At the same time, research in BIM-based sustainability assessment shows the importance of harmonized, object-level data structures to integrate building models with environmental information such as life-cycle assessment (LCA) datasets and operational performance indicators (Klumbyte et al., 2023). Several authors have proposed BIM-centered workflows for energy analysis or water-use evaluation, but these approaches often rely on project-specific schemas, ad hoc integrations or proprietary platforms, which hampers scalability (González et al., 2021; Sameer & Bringezu, 2021). There is therefore a need for an open semantic framework that connects BIM, standardized data dictionaries and environmental datasets within a data-space architecture, so that AI-based services can perform analytics on public facilities.

To demonstrate the practical impact of this approach, GreenBIMxels develops three use cases focused on environmental performance of public facilities (energy, water and carbon footprint). For each case, structured data from BIM models of public facilities are combined with external data bases and IoT data within the Data Space, enabling advanced analytics and AI-based services without exposing raw operational data outside their institutional boundaries. These use cases are defined in this paper to evaluate how a BIM-based Data Space can unlock environmental value from existing BIM datasets of public facilities, support evidence-based decision-making, add value and reduce fragmentation between administrations in the management of building and infrastructure assets.

Methodology

The three use cases were developed with companies and public administrations, within the Catalan context, through a structured, multi-stage Co-Creation Method that combined participatory workshops and a formalized questionnaire-based survey targeting future data consumers. This approach ensured that the selected use cases were not only technically feasible within the GreenBIMxels data-space architecture but also aligned with real market needs, operational practices, and governance expectations. The process started with a series of dedicated workshops with data providers, aimed at identifying priority environmental challenges, and feasible analytical services that could be realistically deployed within a data-space context. The development of these collaborative workshops is aligned with the guidelines of the DSSC (Data Spaces Support Centre), which define the Co-Creation Method with the aim of ensuring that the evolution process of any Data Space is carried out in an appropriate and structured manner. This process, as shown in the following figure, consists of three stages: the exploratory phase, the preparation phase and the implementation phase (Fauth et al., 2024; Weiss et al., 2025). This paper includes the exploratory and preparatory stages.

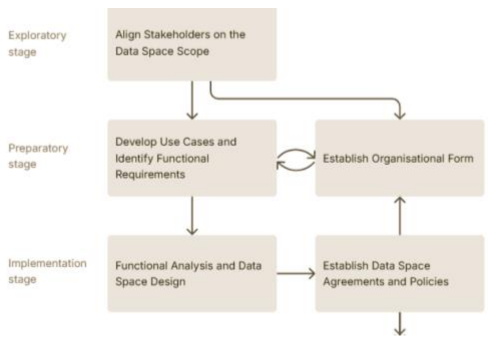

Figure 1 Workflow of the Co-Creation Method. Source: DSSC

A total of ten public administrations participated, including municipalities, regional government departments, public institutes, and public bodies responsible for infrastructure and transport, with technical staff drawn from energy services (end users with in-depth knowledge of operational processes), maintenance representatives (end users with process expertise), and organizational managers and BIM specialists acting as data providers or decision-makers. During these workshops, participants discussed current practices related to energy management, water consumption monitoring, and carbon-footprint assessment, as well as limitations in accessing, sharing, and reusing BIM and operational data across organizational boundaries. The workshops combined exploratory and convergence-oriented activities. First, they gathered information on environmental data services by examining the types of BIM models and IFC datasets currently available, the environmental functionalities that data providers aim to enable through the Data Space, and the key performance indicators (KPIs) used or anticipated for decision-making. Building on these discussions, the workshops converged on three representative, high-impact domains (energy efficiency, water consumption optimization, and life-cycle carbon-footprint assessment) which are common across multiple public administrations and closely aligned with policy-driven sustainability objectives. In parallel, the workshops focused on defining the implementation process, identifying the main barriers that administrations expect to face during the project, and outlining the required technological approach for effective deployment. To complement the qualitative insights with quantitative rigor, workshop contributions from public administrations were analyzed using co-occurrence network analysis and text mining techniques implemented in the R programming language (Amancio et al., 2025).

Furthermore, a structured questionnaire survey was subsequently distributed to prospective data consumers, including architecture and engineering firms, technical consultancies, software providers, and sustainability-oriented service companies. The questionnaire was designed to capture a detailed profile of data consumers, their typical data usage patterns, integration challenges, and required update frequencies. In addition, the survey explored perceived value and priority of different environmental use cases, expectations regarding AI-based analytical services, preferred levels of data processing, and requirements related to data governance, quality and security. This method enables a thorough assessment by integrating multiple data sources, thereby strengthening the reliability of results in applied research contexts (Mayo-Wilson et al., 2018). Consumer surveys provide structured quantitative and qualitative feedback on perceived outcomes, while workshop Post-it notes offer spontaneous, context-rich reflections from providers directly involved in delivery.

The results of the workshops and surveys were jointly analyzed to define the scope, data requirements and KPIs. For each case study, a clear mapping was established between the proposed analytical services, the required data properties and IFC-based data elements, and the KPIs used to assess environmental performance and impact. As part of the preparatory stage, the definition of indicators was carried out by translating the co-created use cases into measurable parameters. This process aimed to operationalize the needs and analytical requirements identified during the workshops into a structured set of indicators suitable for implementation within the data-space architecture.

The development of these indicators followed an iterative approach. First, candidate parameters were derived from workshop discussions, reflecting their data needs and decision-making criteria. Second, these parameters were refined through two complementary activities, an analysis of the digital tools and information systems currently used to ensure alignment with existing data availability and formats and validation through expert consultations and literature review to assess completeness and relevance.

During this process, some parameters initially identified were discarded due to their limited contribution to the proposed services, while additional parameters emerged as necessary to ensure analytical feasibility and robustness. The final set of parameters was then structured into KPIs and mapped to BIMxel properties and IFC-based data elements, forming the basis for the KPI tables presented in the Results section.

As a result, the methodology ensured coherence between stakeholder needs, available and shareable data, and the analytical capabilities supported by the GreenBIMxels infrastructure, thereby increasing both technical robustness and adoption potential.

Results and discussion

The results presented in this section derive from the combined analysis of two complementary empirical sources, a series of structured workshops with public administrations and data providers, and a questionnaire-based survey addressed to prospective data consumers from the construction, engineering, digitalization, and sustainability sectors. This approach simultaneously provided feedback on the project implementation and supported the definition of the three use cases, including their associated KPIs.

On the questionnaire survey most respondents operate as direct data consumers but also express a strong interest in developing data-based services or advisory products, indicating that data consumption and value creation are closely linked in their business models. From a digital readiness perspective, 87% of respondents reported a medium to high level of maturity in managing BIM/IFC data. This finding is consistent with the workshop results, where public administrations demonstrated the availability of IFC models, monitoring systems, and sectorial platforms (such as BMS, SCADA or energy monitoring tools), albeit in a fragmented and heterogeneous manner. Together, these results suggest that both providers and consumers possess a sufficient baseline of digital capabilities to engage with a data-space-based solution, while still facing significant integration challenges.

Project implementation

The findings reflect consumers' perspectives as captured through questionnaire responses and providers' viewpoints as emerging from the workshop discussions. The questionnaire survey was completed by 8 organizations out of 15 invited (response rate ≈ 53%). The questionnaire sample could be acknowledged as modest in absolute terms, yet it can still be considered adequate for the exploratory and descriptive aims of this study. In survey methodology, sample adequacy is not determined solely by size but by its ability to capture the relevant heterogeneity of the target population (Erdogan & Baker, 2002; Fosnacht et al., 2017). From this perspective, the present sample covers micro, small, and medium-sized organizations involved in different stages of the building and infrastructure life cycle, which enhances its structural similarity to the population of interest and supports its analytical representativeness. Post-it notes collected during co-creation workshops were analyzed to identify emerging themes and stakeholder concerns.

As a result, a co-occurrence network (Figure 2) was built based on the content of the post-it notes, which were generated in response to two guiding questions addressing the needs and challenges related to the sustainable management and equipment maintenance of their building assets. Each post-it note was systematically coded to extract key terms. The network was then developed by mapping the frequency with which these terms co-occurred across responses, enabling the identification of the following thematic clusters:

- Need for research: Participants highlighted gaps in applied knowledge on data-space integration for BIM, calling for more pilot studies and evidence on ROI.
- Need for interoperability: Frequent mentions of heterogeneous formats, proprietary tools, and semantic standardization.
- Data and models availability/sharing from administrations: This emerged as the dominant cluster, reflecting frustrations with fragmented access, outdated datasets, and bureaucratic silos.
- Lack of human resources: Capacity constraints, including skilled BIM personnel and training, were recurrent, limiting sustained adoption.

The diagram's visual prominence of the data-sharing cluster signals broader sector challenges like platform fragmentation. Both data consumers and public data providers highlighted that access to operational consumption data (energy and water) and geospatial information remains uneven and often constrained by organizational or technical barriers.

A key convergent result concerns the main barriers to effective data use (Figure 3). Respondents gave greatest importance to practical and structural barriers, especially the cost or time required to obtain data, along with interoperability and incomplete data. In contrast, lack of knowledge was considered less important. This perception mirrors the workshop findings, where public administrations repeatedly emphasize platform fragmentation, dependency on proprietary systems, and difficulties in maintaining up-to-date and consistent datasets across multiple tools and departments.

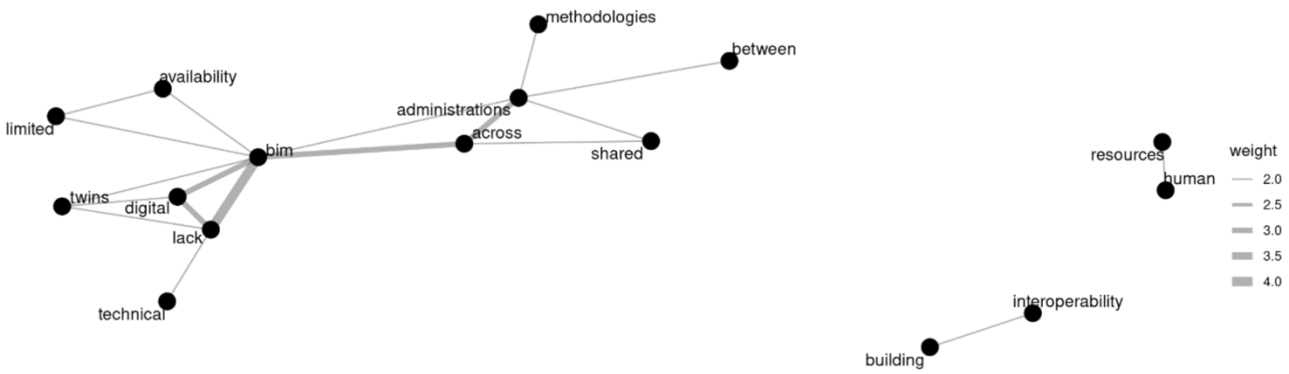

Figure 2 Co-occurrence network of implementation barriers identified in the public administration workshops

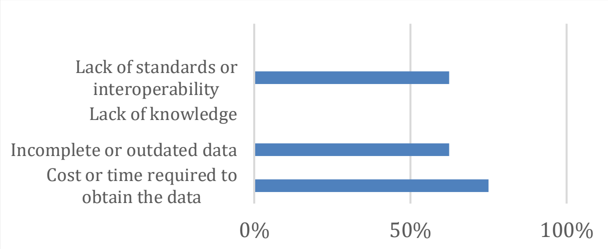

Figure 3 Main difficulties in integrating facility management information into data-consumers workflows (n=8 Companies).

Regarding adoption, consumers emphasized that technical feasibility alone is insufficient, uncertainty about return on investment remains the main barrier (Figure 4). Expected benefits are framed primarily in terms of market differentiation and access to new business opportunities, rather than purely internal efficiency gains (Figure 5).

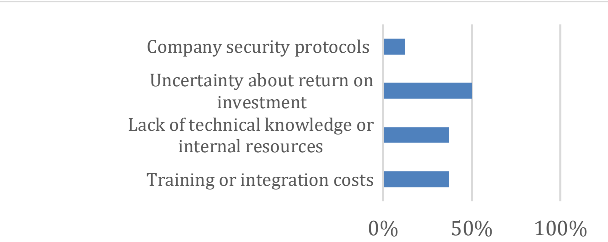

Figure 4 Identified barriers by data-consumers on connecting to the Data Space (n=8 Companies).

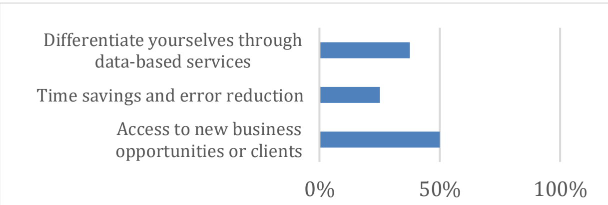

Figure 5 Identified benefits by data-consumers on connecting to the Data Space (n=8 Companies).

Trust-related aspects emerged as critical enablers of participation in the GreenBIMxels Data Space. Data consumers identified confidentiality, secure access, and ease of integration as essential guarantees, with data traceability and clear licensing conditions also playing an important role (Figure 6). These expectations align closely with the governance concerns expressed in the workshops, where compliance with European data-space principles and security requirements was considered a prerequisite for institutional adoption.

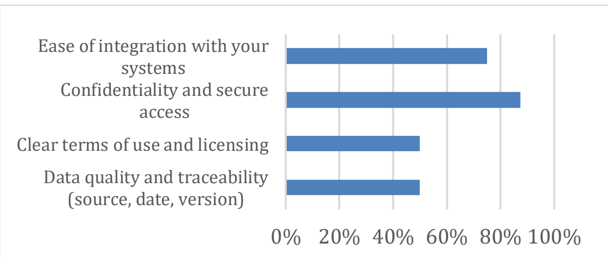

Figure 6 Key guarantees required for data consumers to connect to the Data Space (n=8 Companies).

These results underscore the importance of demonstrating concrete, replicable value through the selected use cases.

Definition of use cases

The network graph in Figure 8 visualizes the thematic clustering of post-it notes from workshops, where node size reflects frequency of mentions, colors denote domains (orange: energy, purple: water, green: carbon, gray/black: transversal), and edges indicate interconnections that directly informed the definition of GreenBIMxels use cases and KPIs.

Gray central nodes dominate the core including "data", "comparison", "monitoring", "consumptions", "IFC", forming a highly repetitive and interconnected hub that underscores these topics as transversal KPIs essential to all three use cases. Their prominence and repetition signal that reliable, standardized access to BIM/IFC models and operational consumption metrics constitutes the primary analytical foundation, enabling portfolio-scale visualization, anomaly detection, and benchmarking across energy, water, and carbon domains.

Energy emerges as the most prominent use case, with the largest orange cluster showing high frequency and dense connections to gray transversals, indicating it as the top stakeholder priority for KPIs like power curves, efficiency patterns, and predictive interventions. This priority is also reflected among consumers in the questionnaire survey (Figure 7). Strong orange-green linkages reveal a tight relationship between energy and carbon footprint, particularly for renovation decisions, material choices, and lifecycle optimizations, positioning combined energy-carbon KPIs (such as CO_2eq reductions via efficiency upgrades) as high-impact composites. Water stands apart with fewer blue nodes, mostly peripheral and linked to monitoring, highlighting leak detection and usage patterns (liters) as a more niche but still a relevant use case with lower overall emphasis. The graph's density confirms stakeholder consensus on actionable, data-space-enabled indicators rather than exploratory ones.

With respect to consumers, all proposed functionalities were considered important by the respondents. However, automatic simulations and predictions stood out as the most demanded feature (Figure 7).

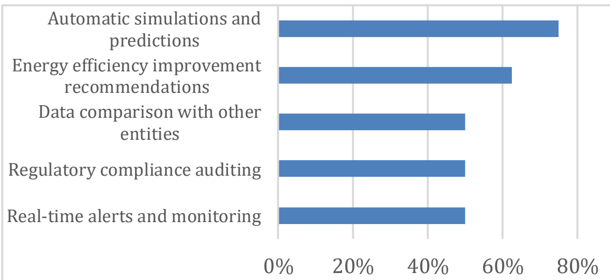

Figure 7 Identified useful domains by data-consumers on connecting to a Data Space (n=8 Companies).

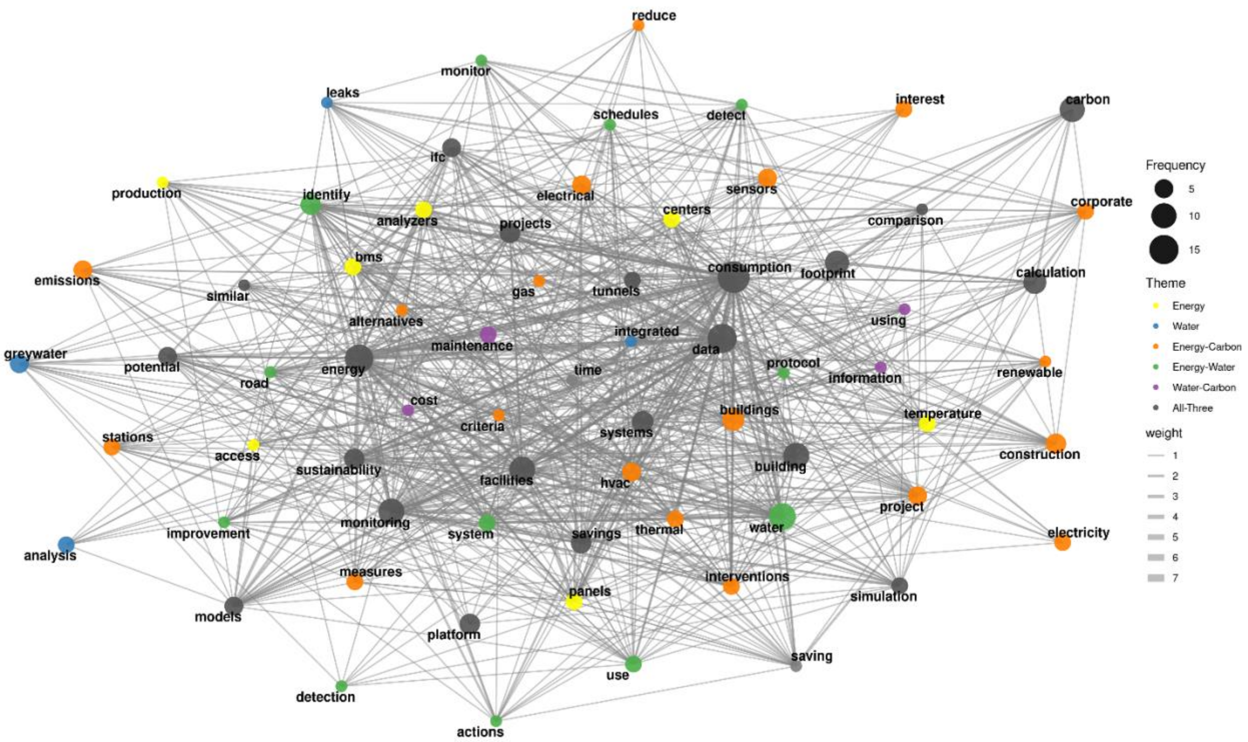

Figure 8 Co-occurrence network of the use cases requirements identified in the public administration workshops

Figure 9 shows that respondents mainly aim to use the Data Space for decision-making in design or planning, followed by developing digital products or services and only a few respondents are uncertain about which data to consume, indicating generally clear expectations.

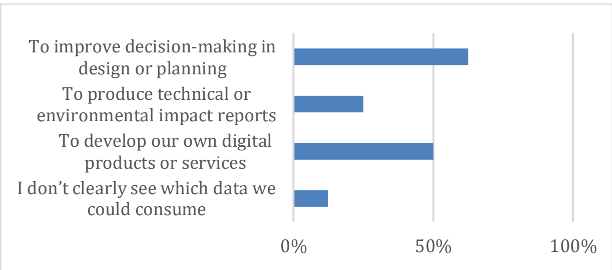

Figure 9 Identified data use by data-consumers on connecting to the Data Space (n=8 Companies).

The results show strong alignment between workshop insights and user expectations. Transversal data elements such as monitoring, comparison and predictions, form the core foundation across all use cases, highlighting the importance of standardized, accessible and interoperable data. Energy emerges as the main priority, closely linked to carbon, while water plays a more secondary role. From the consumer side, the proposed functionalities are well received, with a clear preference for simulations and predictive analytics. Overall, the findings confirm that the Data Space approach is relevant and valued, particularly for decision-making and advanced, actionable insights.

KPIs Definition

The KPI tables presented in this section are the result of the properties-definition process described in the preparatory stage of the methodology. The defined KPIs are directly linked to BIMxel properties that are systematically derived from IFC databases, external reference sources (such as Datadis for consumptions or AEMET for temperatures), and operational data obtained from IoT systems. Detailed KPI tables for each service are provided in Appendix 1[1].

The correlation network built from the workshop post-it notes showed that stakeholders perceive standardized access to BIM/IFC models, asset identification, geometry, space–system mapping and basic consumption metrics as prerequisites for any environmental analysis. The transversal data properties repeated across the KPI tables (IfcBuilding, IfcSpace, asset codes, consumption and anomaly properties) operationalize those clusters by turning the most frequent and central post-it notes topics into reusable, object-level data requirements shared by all three services. Based on the needs from the participants and the existing literature review the KPIs and their properties have been defined as shown in Appendix 1 (Table 1: Energy KPIs, Table 2: Water KPIs and Table 3: Carbon Footprint KPIs).

The correlation graph showed energy as the dominant cluster, the most interconnected, highlighting stakeholder priority for immediate value in monitoring, anomaly detection, and benchmarking. This aligns with

[1] Detailed KPI tables are provided in Appendix 1 and are available in: https://doi.org/10.5281/zenodo.19912259

questionnaire findings favoring AI-driven energy services (simulations, predictions, recommendations). Consequently, the energy KPI (Appendix 1: Table 1) emphasizes portfolio-level and pattern-oriented indicators (including total and seasonal consumption, normalized intensities, PV share, number, frequency and duration of anomalies, and seasonal HVAC efficiency) supported by the transversal data properties needed for pattern analysis (stable IDs, geometry, use, occupancy, meter–asset mapping), directly reflecting the central topics in the correlation network.

Regarding water, surveys and workshop notes pinpoint specific barriers such as uneven access to operational data across municipalities, high costs and time delays for data acquisition, and incomplete datasets lacking historical depth. Therefore, administrations prioritize short-term services like leak detection, consumption anomaly alerts, and basic usage pattern analysis using existing smart meters and sectorization data. This is reflected in the water KPI (Appendix 1: Table 2).which focuses on seasonal consumption, consumption by use type, irrigation and external uses, regenerated water ratio, anomaly counts and resolution times, normalized intensities, monitoring coverage and tank capacity, all grounded on a minimal but coherent set of BIMxel properties (space/use classification, meter linkage, reuse flags, etc.) mirroring the main nodes in the correlation graph.

For carbon footprint, the network shows strong energy-material linkages around renovation and lifecycle impacts, framing it as a composite of operational and embodied decisions rather than standalone. Workshops and surveys reinforce this through emphasis on regulatory compliance, portfolio-scale assessment, and urban context factors like density and street canyons. Accordingly, the carbon KPI (Appendix 1: Table 3). extends the energy and material KPIs to include total and operational CO2eq reductions, PV-related avoided emissions, urbanization interventions, embodied carbon by material, share of low-carbon and circular materials and mobility-related emissions, all parameterized with the same transversal building and consumption data plus additional indicators correspond to the green and transversal nodes in the network. For carbon footprint services, regulatory and taxonomy compliance checks (aligning with frameworks like EPBD, GENERCAT 2023-2027, EU Taxonomy, and DNSH criteria) did appear in stakeholder discussions but will require location-specific development. Thus, they are excluded from the main required properties, though they will be incorporated during implementation by mapping operational/embodied carbon KPIs, and metadata (such as YearOfConstruction, Phase, PrincipalUse) against local regulatory thresholds for automated eligibility screening and portfolio compliance reports.

The three KPI tables specify only those BIMxel properties that can be consistently exposed through a shared object-level layer (IFC entities, classification codes, environmental properties, governance attributes), making it possible to deliver the requested AI-enabled services (anomaly detection, benchmarking, predictive analysis, renovation-support KPIs) through a service-layer architecture where raw BIM and time-series data remain with providers. In this way, the KPIs emerge as a direct translation of the most central and recurrent patterns in the correlation network.

Services definition

Consequently, the AI-based services defined in this work focus on three main families, each leveraging the co-created KPIs and BIMxel properties to deliver actionable environmental analytics within the Data Space.

- Anomaly detection and monitoring services automatically identify abnormal energy and water consumption patterns at both asset and portfolio levels. These services process time-stamped meter data linked to BIM elements (via AssetManagementCode, IfcSpace mappings and Subdiscipline flags) to compute anomaly counts, mean durations and deviation scores against historical baselines or seasonal patterns, enabling early fault detection and prioritized maintenance interventions (Zhang et al., 2023).
- Benchmarking and portfolio comparison services normalize KPIs by floor area (GrossFloorArea), user occupancy or functional use across energy, water and carbon domains. By comparing normalized energy intensity (kWh/m²/year), water intensity (m³/m²/year) or total CO_2eq reductions between comparable public facilities, these services identify efficiency outliers, best practices and intervention priorities at scale (Martínez-Rocamora et al., 2021).
- Predictive performance analytics services forecast future consumption trends, efficiency degradation and carbon trajectories. These integrate KPI time series with BIM-derived context (climate via TerritorialScope/LatitudeLongitude, occupancy patterns, envelope U-values, material properties) and external baselines using time-series models or multivariate learning to simulate intervention impacts and risk profiles (Billanes et al., 2025; Cheng et al., 2020).

These AI-based services collectively address key gaps identified in the workshops (the need for streamlined access to standardized BIM/IFC data, reliable anomaly alerts, cross-asset benchmarking and actionable compliance insights) while respecting data-sovereignty principles through federated processing within the GreenBIMxels Data Space. By operationalizing stakeholder-defined KPIs via BIMxel properties, they enable public administrations to transition from fragmented, project-centric environmental monitoring to scalable, portfolio-wide decision support that aligns with European data-space architectures.

At the current stage of the project, GreenBIMxels is in the implementation phase, where the proposed approach is being developed and tested through pilot deployments. These pilots are being conducted using real-world datasets, BIM models, and operational information from public buildings, primarily from the Universitat Politècnica de Catalunya and a collaborating municipality. This allows the validation of the approach under realistic conditions, including heterogeneous data availability and existing system constraints.

The three use cases are being implemented through two main development streams. Energy and water management services are being developed within a shared analytical environment, as both rely on similar data sources (such as consumption data from monitoring systems) and analytical logic, particularly anomaly detection and performance monitoring. In parallel, the carbon footprint use case is being developed in a separate tool, currently focused on material-based analysis and comparison, reflecting its different data requirements and methodological approach.

For all three use cases, an initial Minimum Viable Product (MVP) has been defined and is currently under development and testing. This MVP is based on the KPI framework and BIMxel properties defined in this study. However, at this stage, only a subset of the defined properties is being actively used, corresponding to the functionalities implemented in the MVP. The full set of KPIs and properties represents the target model to be progressively integrated as the implementation phase advances. The pilot implementations have already highlighted several practical issues. First, a substantial share of the required BIMxel property values is missing or incomplete in the source BIM models, confirming the relevance of the harmonized property set. Second, energy and water consumption data are currently distributed across heterogeneous platforms (including DEXMA, Datadis and other provider-specific systems), which has motivated the ongoing development of dedicated connectors to federate these sources within the Data Space. Third, temporal and semantic gaps in consumption records have emerged as recurrent, reinforcing the need for analytical services capable of handling incomplete, noisy or inconsistent data. Finally, to address interoperability challenges, a tool for the automated conversion of IFC parameters into BIMxel properties has been developed and integrated into the workflow, reducing manual effort and improving consistency in the preparation of KPI-ready datasets.

Limitations include the focused size and geographical scope of the empirical sample, limiting behavioral insights to the Catalonian context. The paper also concentrates on the exploratory and preparatory stages of data-space implementation, so future work should examine the long-term performance and maintenance effort of the proposed services in operational deployments, thereby improving and complementing the properties set in subsequent steps.

Conclusions

The study concludes that a BIM-based Data Space can effectively unlock underused environmental information from public facility portfolios, enabling administrations and service providers to implement AI-based services for energy, water and carbon management while maintaining data sovereignty. It demonstrates that co-created KPIs, encoded as BIMxel properties and systematically derived from IFC models, external databases and operational data, provide a robust semantic backbone for anomaly detection, benchmarking and predictive analytics. The three use cases prove to be strongly aligned with stakeholder priorities, with energy-related services emerging as the dominant entry point. Results from workshops and surveys indicate that both public administrations and data consumers possess sufficient digital maturity to engage with data-space-based solutions but require harmonized data structures, reduced integration friction and clear governance guarantee to translate this potential into operational value.

This paper confirms the dual-sided value proposition, public data providers in Catalonia gain scalable portfolio insights without data centralization, while engineering firms and sustainability consultants access validated KPIs and analytics foundations to build commercial services. By implementing a service-layer architecture that processes data locally and exposes aggregated indicators via harmonized APIs, GreenBIMxels unlocks environmental value from existing BIM models of public facilities and demonstrates stakeholder's interest in data-space adoption.

Acknowledgments

We thank the public administrations and private stakeholders for their participation, and the Spanish Ministry for Digital Transformation and the Civil Service for funding through the 2024 Call for Demonstrators and Use Cases of Sectoral Data Spaces.

References

Akbari, S., Sheikhkhoshkar, M., Pour Rahimian, F., El Haouzi, H. B., Najafi, M., & Talebi, S. (2024). Sustainability and building information modelling : Integration, research gaps, and future directions. *Automation in Construction*, *163*, 105420. https://doi.org/10.1016/j.autcon.2024.105420

Amancio, D. R., Machicao, J., & Quispe, L. V. C. (2025). Leveraging word embeddings to enhance co-occurrence networks : A statistical analysis. *PLOS ONE*, *20*(7), e0327421. https://doi.org/10.1371/journal.pone.0327421

Billanes, J. D., Ma, Z. G., & Jørgensen, B. N. (2025). Data-Driven Technologies for Energy Optimization in Smart Buildings : A Scoping Review. *Energies*, *18*(2), 290. https://doi.org/10.3390/en18020290

Cheng, J. C. P., Chen, W., Chen, K., & Wang, Q. (2020). Data-driven predictive maintenance planning framework for MEP components based on BIM and IoT using machine learning algorithms. *Automation in Construction*, *112*, 103087. https://doi.org/10.1016/j.autcon.2020.103087

Enes, G. (2025). The Common European Data Space (s). A Governance Model "the European Way". *A Digital*

Europe for Citizens: Data Governance, Data Markets, Data Services, 35.

Erdogan, B. Z., & Baker, M. J. (2002). Increasing Mail Survey Response Rates from an Industrial Population : A Cost-effectiveness Analysis of Four Follow-up Techniques. *Industrial Marketing Management*, *31*(1), 65-73. https://doi.org/10.1016/S0019-8501(00)00117-6

Fauth, J., Strnadl, C. F., Brenner, M., Heitzhausen, H., & di Pascale, M. (2024). *A Digitalization Framework for Ecosystem-Based* Servitization *: The Use Case of the Building Permit Process* (SSRN Scholarly Paper No. 4827733). Social Science Research Network. https://doi.org/10.2139/ssrn.4827733

Fosnacht, K., Sarraf, S., Howe, E., & Peck, L. K. (2017). How Important are High Response Rates for College Surveys? *The Review of Higher Education*, *40*(2), 245-265.

González, J., Soares, C. A. P., Najjar, M., & Haddad, A. N. (2021). BIM and BEM Methodologies Integration in Energy-Efficient Buildings Using Experimental Design. *Buildings*, *11*(10), Article 10. https://doi.org/10.3390/buildings11100491

Gordo-Gregorio, P., Alavi, H., & Forcada, N. (2025). Decoding BIM Challenges in Facility Management Areas : A Stakeholders' Perspective. *Buildings*, *15*(5), 811. https://doi.org/10.3390/buildings15050811

Hamilton, A. B., & Finley, E. P. (2019). Qualitative methods in implementation research : An introduction. *Psychiatry Research*, *280*, 112516. https://doi.org/10.1016/j.psychres.2019.112516

Janev, V., Vidal, M.-E., Endris, K., & Pujic, D. (2021). Managing Knowledge in Energy Data Spaces. *Companion Proceedings of the Web Conference 2021*, 7-15. https://doi.org/10.1145/3442442.3453541

Kivits, R. A., & Furneaux, C. (2013). BIM : Enabling Sustainability and Asset Management through Knowledge Management. *The Scientific World Journal*, *2013*, 983721. https://doi.org/10.1155/2013/983721

Klumbyte, E., Georgali, P.-Z., Spudys, P., Giama, E., Morkunaite, L., Pupeikis, D., Jurelionis, A., & Fokaides, P. (2023). Enhancing whole building life cycle assessment through building information modelling : Principles and best practices. *Energy and Buildings*, *296*, 113401. https://doi.org/10.1016/j.enbuild.2023.113401

Kovach, A., Montalvillo, L., Lanza, J., Sotres, P., & Urbieta, A. (2026). Understanding Data Spaces : A Systematic Mapping Study of foundations, technical building blocks, and sectoral adoption. *Computer Science Review*, *59*, 100819. https://doi.org/10.1016/j.cosrev.2025.100819

Martínez-Rocamora, A., Rivera-Gómez, C., Galán-Marín, C., & Marrero, M. (2021). Environmental benchmarking of building typologies through BIM-based combinatorial case studies. *Automation in Construction*, *132*, 103980. https://doi.org/10.1016/j.autcon.2021.103980

Mayo-Wilson, E., Li, T., Fusco, N., Dickersin, K., & Investigators, for the M. (2018). Practical guidance for using multiple data sources in systematic reviews and meta-analyses (with examples from the MUDS study). *Research Synthesis Methods*, *9*(1), 2-12. https://doi.org/10.1002/jrsm.1277

Sameer, H., & Bringezu, S. (2021). Building information modelling application of material, water, and climate footprint analysis. *Building Research & Information*, *49*(6), 593-612. https://doi.org/10.1080/09613218.2020.1864266

Valk, O. M. C. van der, & Ryan, M. (2025). Data for the common good in the common European Data Space. *Data & Policy*, *7*, e32. https://doi.org/10.1017/dap.2025.5

Weiss, W., Russegger, S., Kozic, D., Cossa, A., Huber, A., Hofer, T., Draxler, S., Schützenhofer, E., & Schoiswohl, P. (2025). A Data Space for Accessible Multimodal Transport : Enabling Inclusive Mobility. *URBAN INNOVATION: TO BOLDLY GO WHERE NO CITIES HAVE GONE BEFORE. Medium Sized Cities and Towns as a Major Arena of Global Urbanisation. Proceedings of REAL CORP 2025, 30th Intl. Conference on Urban Development, Regional Planning and Information Society*, 53-64.

Zhang, Z., Chen, Y., Wang, H., Fu, Q., Chen, J., & Lu, Y. (2023). Anomaly detection method for building energy consumption in multivariate time series based on graph attention mechanism. *PLOS ONE*, *18*(6), e0286770. https://doi.org/10.1371/journal.pone.0286770