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Digital information and data flow management for building envelope solutions: the MEZeroE BIM dataset tool as an Open Innovation Service

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ABSTRACT

Data inconsistency and limited interoperability among various stakeholders compromise data uniformity and hinder digitalization across all stages of the construction life cycle, thereby inhibiting effective collaboration in the development of innovative envelope construction solutions. To address these challenges, the MEZeroE project developed a novel standardized Building Information Modeling (BIM) dataset tool that enables stakeholders to access consistent, high-quality and application-specific data in a unified digital environment. This study presents the development and implementation of the MEZeroE standardized digital dataset tool, which introduces a structured and interoperable framework for data flow management specifically tailored to innovative building envelope solutions. By combining a systematic literature review with a Grounded Theory approach, the study identifies critical gaps in current practices and defines nine Construction Segments and fourteen envelope parameter categories, which represent a new standardized data structure for envelope solutions. The tool is integrated into the MEZeroE Virtual Marketplace, providing a practical digital infrastructure that supports BIM object creation, facilitates Digital Product Passport compliance, and enables real-time collaboration among designers, manufacturers, and other stakeholders. This integration enhances decision-making processes and accelerates the adoption and deployment of innovative building envelope technologies in real-world construction projects.

1. Introduction

The Architecture, Engineering, Construction, and Operations (AECO) industry has long faced inefficiencies related to fragmented data management practices and limited interoperability among the multiple stakeholders involved in building projects. These issues represent significant barriers to productivity, cost efficiency and sustainability [1–4], particularly for innovative construction products that require multidisciplinary collaboration across different development phases, from prototyping and performance testing to certification and market uptake. The success of such processes strongly depends on the availability of reliable, structured, and consistent data, as well as on transparent information flows among actors [5]. Among innovative construction solutions, building envelope systems play a central role in improving energy efficiency and overall building sustainability [6]. Comprising multiple components, such as façades, roofs, windows, thermal and insulation materials, envelope system regulate the interaction between indoor and outdoor environments and directly influence thermal comfort, energy performance, environmental impacts [7–9]. As envelopes increasingly integrate advanced technologies and multifunctional materials, the complexity of related the need for a clear and shared data management process is becoming more important than ever. Yet, the adoption of these solutions is often hampered by fragmented and inconsistent data exchange among stakeholders, leading to errors, unexpected delays, and increased project costs [10,11].

In this context, the increasing adoption of Building Information Modelling (BIM) across the AECO industry creates opportunities for addressing challenges related to interoperability and data management of building products and solutions [3,12,13], but it also highlights the importance of having standardized, digitalized datasets to facilitate interoperability, not only during the construction phases, but along the entire value chain of building products and solutions [14–16].

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In the last decades, BIM has progressively evolved from a simple 3D modeling tool into a comprehensive nD platform that integrates parametric data and advanced analysis features [14,17], which allowed improved clash detection, better coordination, and more accurate decision-making across building solutions lifecycle, helping to reduce errors, control costs, and streamline data sharing [18]. BIM also represents an important enabler for the transition towards a more circular construction industry, supporting energy analysis, environmental assessments [19], and the development and implementation of Digital Product Passports (DPPs) [20–22]. DPPs act as digital identity documents for materials and products, providing detailed information about their technical specifications and lifecycle characteristics [23].

Despite the recognized potential of BIM to enhance the design, construction, and management of buildings, the lack of standardized protocols for data management remains a major limitation in its widespread implementation, especially for building envelope solutions [10,24]. These require strict coordination between different actors, from manufacturers providing technical specifications to architects integrating these products into building models and contractors ensuring correct on-site installation [7]. The data necessary for the activity's coordination, among the various actors, are often fragmented, irregularly formatted, and insufficient, causing increased project costs and impacting building performance [11,25,26].

Recent regulatory developments and sustainability-oriented policies [27,28], including the growing emphasis on DPPs and lifecycle transparency, further highlight the urgency of structured and interoperable product data. While these frameworks increase the demand for high-quality digital information, they also expose the current lack of shared, envelope-specific datasets capable of supporting compliance, interoperability, and performance-driven decision-making within BIM-based workflows [20,22].

In recent years, several international initiatives and studies have focused on developing protocols and formats to support the digitalization process in the construction sector [29–31]. One of the most significant contributions in this context is the definition and development in 1996 of the o IFC (Industry Foundation Classes) by buildingSMART [32], an open, standardized file format designed to enable the exchange of BIM data across the architecture, engineering, and construction domains. The IFC format ensures interoperability between different BIM software platforms, allowing professionals from various disciplines to share and access project information without data loss [33]. However, the adoption of such formats remains variable, especially when it comes to the integration of complex components such as building envelope solutions [34]. The fragmented organization of product data formats, coupled with differences in national and regional building codes, emphasizes this problem, continuing to limit the potential of fully interoperable, data-driven practices across the building envelope solutions value chain [35].

The scientific literature reflects this gap. Although numerous studies address BIM-based performance analysis, energy simulation, or interoperability at the building level [36–38], limited attention has been given to the definition of standardized, scenario-based datasets specifically tailored to building envelope products. In particular, there is a lack of approaches that systematically structure envelope-related data according to different use scenarios, such as marketing, testing, certification, and operation, while ensuring consistency, interoperability, and applicability across different construction segments.

To address these challenges, it is fundamental to develop a specialized and standardized dataset for envelope solutions, not only to more easily meet the regulatory standards, but to also enhance technological advancements and data knowledge framework, based on an Open Innovation (OI) approach for industrial cooperation [39].

In this context the European H2020 project titled: "Measuring Envelope systems for Zero Energy buildings" (MEZeroE) operates with the final main goal to create an ecosystem accessible via a single-entry point based on a web Virtual Marketplace (VM) structured into 9 Pilot Measurement & Verification Lines (PM&VLs) and 3 Open Innovation Services (OISs) for developing nearly Zero Energy Buildings (nZEB) Enabler Envelope technology solutions and promoting cross-fertilization between actors of the construction sector. Within this broader framework, one of the project's tasks focuses on the development of a standardized and digitalized tool, the so-called MEZeroE BIM dataset tool, to provide a unique solution, available as part of the OIS3 from the MEZeroE VM, able not only to increase the data management by raising the level of consistency and quality, but also boosting the OI path for building envelope products.

This paper presents the activities conducted for the definition and development of the MEZeroE BIM dataset tool. The objective of this study is twofold: first, to conduct a state-of-the-art on BIM readiness level of envelope solutions based on the analysis of existing literature, databases and surveys performed by industries in the sector to understand the current state of the topic and the need and/or barrier to develop a tool who can boost their entrance in the market. The second objective, directly linked to the first, is the definition of a standardized protocol for managing a BIM-based Dataset model of building envelope products and solutions. The dual objectives of the study were subsequently formulated into the Research Question (RQ), which served as the guiding framework for the entire research process:

"How the digitalization of building envelope products data sets can support various target groups along the entire value chain towards the decarbonization target and DPP implementation:

(i) *to facilitate interoperability and a common language for boosting their market uptake?;*
(ii) *to boost new Open Innovation solutions development?".*

The manuscript is organized into 6 sections: after the introduction, Section 2 reports the overview of the applied methodology. Section 3 provides firstly a comprehensive state-of-the-art on data flow management for building envelope solutions, and secondly a state-of-the-practice on the BIM readiness level of envelope solutions through a survey performed by industries in the sector. In parallel, existing databases for envelope solutions have been analysed. Based on the state-of-the-art and state-of-the-practice results, Section 4 illustrates the development and validation of the MEZeroE BIM dataset tool for envelope solutions and its implementation into the MEZeroE VM as a user-friendly tool called "BIM Package Configurator". Section 5 describes a real experimental application of the developed tool to an innovative building envelope solution. Finally, Section 6 summarizes the conclusions of the study, presenting outcomes, limits, and future research directions for further development and broader implementation of the MEZeroE BIM dataset tool for the stakeholders of the construction industry.

2. Methodological framework

This section presents the objectives and activities performed within the study to conduct a state-of-the-art on BIM readiness level of envelope solutions and to define a standardized protocol for managing BIM-based datasets model related to such solutions.

The overall research method has been structured into six consequential and interconnected phases, as graphically represented in Fig. 1. The starting point, phase 1, corresponds to the Research Framework, the MEZeroE project, and the RQ definition, from which emerges the need to conduct an overall state-of-the-art on the topic, considering all existing sources of data or initiatives for building envelope products. For this reason, phase 2 foresees, on one hand, a systematic review of the existing literature on the topics of the RQ, and on the other, an extensive review of existing databases and standards for building envelope products. The literature review enables the classification of envelope solutions into nine distinct Construction Segments (CSs), facilitating improved data management and interoperability, while the analysis of existing databases and standards allows for the clustering of BIM

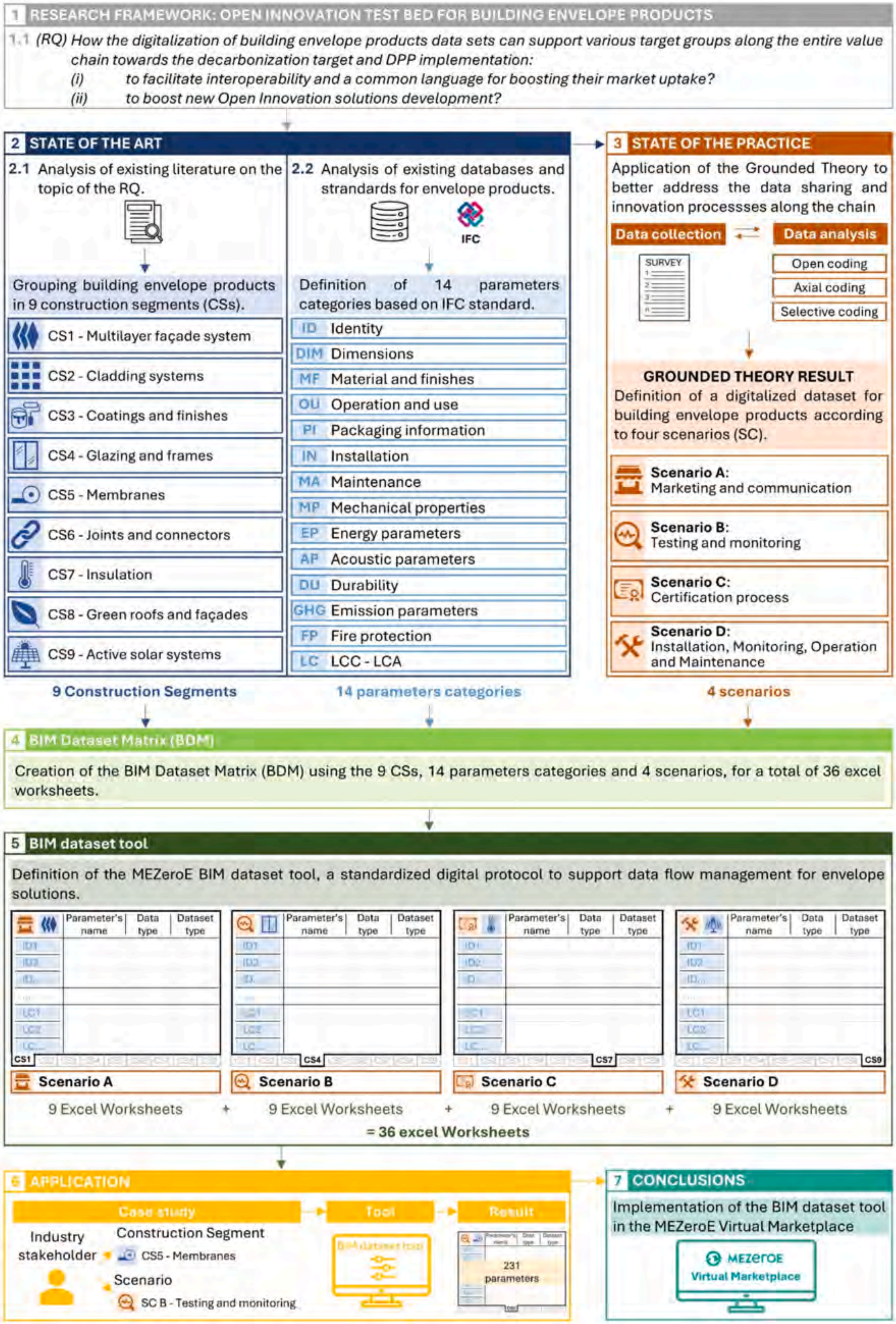

Fig. 1. Graphical overview of the methodological approach adopted in the study, organized into six sequential and interconnected phases. Source: elaboration of the authors.

parameters for envelope products and solutions into 14 distinct categories, based on the IFC standard classification.

The state-of-the-art analysis reveals a significant lack of common data references and standardized methods for building envelope products. Therefore, in phase 3, the Grounded Theory Methodology (GTM) is applied to investigate the state-of-the-practice on the topic, focusing on the perspectives and experiences of stakeholders within the construction sector. Surveys are distributed across selected stakeholders of the AECO industry to gather insights on the current awareness and knowledge of digitalized data for building envelope products. The results of the GTM application highlights the need for a standardized and digitalized BIM dataset to enhance the management and sharing of BIM-based information between actors of the construction sector, especially regarding building envelope products and solutions.

Following the results of the previous sections, phase 4 presents the process followed for the definition, structuring and validation of the MEZeroE BIM Dataset Matrix (BDM) as operative content of the MEZeroE BIM dataset tool. Within the BDM, the building envelope solutions are divided in 9 CSs, following the clustering presented in the state-of-the-art phase. Four scenarios are defined to validate the applicability of the BDM in practical contexts: (1) marketing and communication; (2) testing and monitoring; (3) certification processes; and (4) installation, monitoring, operation, and maintenance. Phase 5 presents the application of the MEZeroE BIM dataset tool to a real use case involving a membrane manufacturer. Finally, phase 6 describes the integration of the MEZeroE BIM dataset tool into the MEZeroE VM as part of OIS3, enabling its adoption by various stakeholders and supporting the development of innovative envelope solutions.

3. BIM based information flow and datasets for building envelope products

In line with the research methodology and in response to the defined Research Question, this section provides a comprehensive overview of the current landscape about BIM-based information flow and datasets for building envelope solutions. It combines both the state of the art and the state of practice to offer a holistic analysis of existing knowledge and industry implementation. Subsection 3.1 presents the state of the art, based on a critical review of scientific literature and existing datasets about data interoperability, management and standardization in the context of building envelope solutions. Subsection 3.2 focuses on the state of practice, addressing the empirical gaps identified during the literature review. Given the lack of available data, a Grounded Theory Method (GTM) was applied to collect and analyse insights from stakeholders in the construction sector.

3.1. State of the art

The management of BIM-based information flow in the development, market uptake and diffusion of innovative building envelope solutions is a critical aspect of modern construction and design practices. As the industry moves towards more integrated and digital approaches, the need for standardized protocols and efficient data management becomes increasingly important. This shift is driven by the need to enhance interoperability, improve collaboration among various stakeholders, and streamline the entire lifecycle of building projects, from design to maintenance.

Numerous studies [40–42] have highlighted that while digital technologies like BIM, cloud computing, and the Internet of Things (IoT) have been adopted at various stages of construction, there is still a significant gap in their integration between different platforms and stakeholders.

In this context, Fan et al. [43] in their study emphasize that current digital solutions often remain stand-alone, with minimal interoperability across different phases of construction projects. This fragmentation, common in the construction sector, prevents effective data sharing, leading to delays, inefficiencies, and a lack of uniformity in information management. Studies conducted by Bui et al. [44] and Evans et al. [45] also underscore the importance of creating common data environments and shared digital platforms to reduce these gaps and stimulate collaboration.

A central theme in recent literature is the need for standardized data sets and processes to support the exchange of technical information between stakeholders. Although digital tools are widely studied and increasingly adopted in various phases of building design and construction, there is still a lack of comprehensive, sector-wide databases specifically focused on building envelope solutions [42,46]. BIM models are commonly used to model envelope components, but their application is often limited to specific use cases, such as seismic testing or performance simulation, rather than offering a standardized approach to managing envelope data across the supply chain. Moreover, Gerbino et al. [42] noted that the data fragmentation and inconsistent use of BIM for building envelope solutions affect the overall efficiency of information management.

As noted by Sampaio and Gomes [47], existing standards like IFC offer a potential framework for data interoperability, but their adoption is not sufficiently widespread, particularly in the building envelopes context. This lack of integration is particularly negative given the complex, multi-disciplinary nature of building envelope projects, which often require data sharing across various experts and organizations throughout a project's lifecycle. In this regard Tabrizikahou et al. [48] promote the development of specialized digital tools to address the unique challenges posed by envelope products, which often involve complex material interactions and performance criteria.

The literature also highlights the need to cluster building envelope products into distinct Construction Segments (CS) to facilitate better data management and digital interoperability. Studies by Kheiri [49] and Peters [50] identify common segments within the envelope domain, including multilayer façade systems, cladding systems, and glazing and frames. Other research, such as that by Ragheb et al. [51], emphasizes the role of green roofs, insulation, and active solar systems as key components of modern, sustainable envelope designs. By clustering building envelope products into specific Construction Segments, the literature highlights the potential for a more structured and interoperable data exchange. This approach not only facilitates the integration of advanced digital tools but also establishes a common language for stakeholders, supporting a holistic understanding of building envelope systems. Fig. 2 provides a summarized view of these construction segments, reflecting their functional roles [52–57].

The review of existing structured formats, datasets and classification systems further highlights these gaps, identifying the fragmentation of data management practices and the limited interoperability of digital tools as significant barriers.

Multiple international initiatives have been focused in recent years in the definition and structuring of formats, datasets and classification systems, to facilitate data standardization and exchange between stakeholders. One of the most known results is the Industry Foundation Classes (IFC), defined by buildingSMART [32] as a standardized file format that provide an open schema for data interoperability, supporting global adoption across various software platforms. The format’s lifecycle coverage and extensive connection between different BIM objects make it an important resource for BIM applications [58]. Similarly, the USA Construction Engineering Research Laboratory (CERL), proposed in 2007 the Construction Operations Building Information Exchange (COBie) [59], a standardized, non-proprietary data format used to organize and deliver crucial building asset data throughout the design, construction, and operation phases of a building project [60].

OmniClass [61] and Uniclass [62] are two other classification systems developed in recent years. They serve as hierarchical classification systems designed to organize construction products and solutions information comprehensively, tailored to the specific regional requirements of North America and the United Kingdom, respectively

Fig. 2. Literature-based classification framework of building envelope products into Construction Segments (CSs). Source: elaboration of the authors.

[63]. Both classification systems are aligned with ISO 12006–2:2015 [64] and are designed to facilitate the organization and retrieval of information throughout the lifecycle of a construction project, ensuring consistency and interoperability between different software platforms and stakeholders [65]. In Europe, the European Technical Information Model (ETIM) [66] standard specializes in the classification of technical product data, with multilingual support and precise specifications that facilitate international collaboration [67]. Finally, UniversalTypes [68] integrates product standardization for sales and procurement, offering real-time data for enhanced e-commerce and commercial activities [69]. Table 1 presents a comparative analysis of these formats, databases and classification systems based on characteristics and functionalities. The analysis of these formats, datasets and classification systems enabled a possible classification of building envelope solutions indicators in multiple categories. The IFC and COBie formats presents indicators classification based on identity, dimensions, and mechanical properties, while also considering operational categories such as installation, maintenance, and operation and use [70,71]. OmniClass and Uniclass classification systems, supported the clustering of construction products and solutions in: types of material and finishes, level of fire protection and durability [72–74]. ETIM standard provided specialized performance categories including energy parameters, acoustic parameters, and emission parameters [67], while UniversalTypes' commercial orientation provided the inclusion of more practical categories like packaging information [69].

These formats, databases and classification systems collectively address different needs within the construction information ecosystem. However, their application to building envelope solutions remains limited. For instance, while IFC enables broad interoperability, its use in addressing the complex performance requirements of building envelopes is not yet widespread [33]. Similarly, COBie's focus on facility management overlooks the multidisciplinary interactions and considerations relevant in building envelope solutions development and implementation [71]. These gaps underscore the need for integrated systems capable of supporting the unique challenges posed by building envelopes, such as material interactions, performance criteria, and sustainability metrics.

3.2. State of the practice

In the context of building information and data flow management for building envelope systems, one of the main challenges is the lack of standardized methods for sharing product and solutions data across the supply chain. The review of existing literature and standards revealed a significant gap in unified data references and a general absence of common approaches for the categorization and interoperability of building envelope solutions. These gaps prevent the efficient exchange of information, fundamental for development, market uptake and

Table 1
Comparative analysis of building information classification systems. Source: elaboration of the authors.

Characteristics	Database IFC [32]	COBie [5958]	OmniClass [61]	Uniclass [62]	ETIM [66]	UniversalTypes [68]
Primary Function	Open data model for BIM interoperability; Schema for building and construction industry data	Data exchange format specifically for facility management handover	Hierarchical classification system for North American construction industry	Unified classification system for UK construction industry	Technical product classification and data exchange	Product specification and sales platform
Standards or specifications	ISO 16739–1:2024 [82].	NBIMS-US standard.	ISO 12006–2:2015 [64].	ISO 12006–2:2015 [64].	European standards.	bSDD specification.
Main Focus	Data exchange and interoperability within BIM models;	Structured facility data delivery for operations phase	Organization of construction data across all phases	Unified approach to organizing project information	Technical product specifications and characteristics	Product data standardization for sales
Key Strength	Vendor-neutral, open standard; Extensive object relationships; Global adoption	Simplified spreadsheet format; Clear data requirements; FM focus	Comprehensive coverage; Multiple table structure; Industry acceptance	Dynamic updates; Digital-first approach; Integration capability	Precise technical specifications; Multi-language support	Real-time data; E-commerce integration; Search optimization
Data Scope	Geometry; Properties; Relations; Processes; Materials	Equipment; Spaces; Maintenance; Documents; Contacts	Facilities; Spaces; Elements; Products; Materials; Phases.	Complexes; Entities; Activities; Systems; Products	Product properties; Technical details; Performance data	Product attributes; Commercial data; Sales specifications
Diffusion	Globally.	Primarily USA, UK.	Primarily USA.	Primarily the UK.	Primarily Europe.	Globaly.

diffusion of innovative building envelope solutions.

Given the lack of standardized approaches, this section presents the adoption of the Grounded Theory method (GTM) to develop a conceptual framework directly based on the experiences and insights of industry stakeholders. The GTM is a systematic qualitative research methodology that generates a theory through data collection and analysis, making it ideal for contexts where existing theoretical frameworks are limited or non-existent [75–78].

Following the methodological structure presented by several studies [79–81], the interview process involves 9 steps leading up to the definition of the grounded theory, as shown in Fig. 3.

Following the RQ identified in Section 1, the application of the GTM aims to explore how digital interoperability in building envelope systems can be improved, particularly considering the significant barriers related to non-standardized data formats. The study seeks to understand the challenges that stakeholders in the supply chain face when dealing with digital datasets and to propose solutions based on their actual experiences.

The first step of the GTM is the development of semi-structured surveys, which have been carefully designed to understand the perspectives of stakeholders interviewed. These surveys have been structured considering key performance indicators (KPIs), including the current BIM readiness of the stakeholders, their openness to future BIM development, the level of resources that they dedicated to BIM implementation, and their knowledge of BIM-based data management. To ensure effectiveness and clarity, the survey questions underwent iterative refinement, based on preliminary feedback received from the MEZeroE industrial partners.

The data collection phase has been executed in multiple stages. The initial survey targeted industrial partners within the MEZeroE consortium to assess their general level of BIM readiness and the financial and organizational resources dedicated to digitalization. Ten semi-structured interviews were conducted, capturing insights into the responders' availability and intended development of BIM objects, their achieved or targeted Levels of Detail (LOD), the types of data they supplied through BIM objects, and the primary challenges that they faced in the BIM development process. This phase employed a snowball sampling method to ensure a diverse representation of perspectives across various types of building envelope products.

The responses from this first data collection have been analyzed using open coding, which revealed critical themes and patterns in the data. For instance, while many partners lacked BIM objects for their products, they expressed an intention to develop these resources in the near future. The analysis also highlighted varying levels of BIM readiness, ranging from conceptual design (LOD 100) to fully detailed as-built models (LOD 500). The survey further identified common data attributes in BIM objects, such as dimensions, weight, installation time, and end-of-life reuse potential, underscoring the need for standardized approaches to data interoperability.

To validate and expand upon these findings, the following phase involved engaging external SMEs through a similar survey. This effort included direct outreach, social media dissemination, and participation in the MEZeroE stakeholder event. Ten additional SMEs, primarily headquartered in Europe and spanning various market areas, participated in this phase. Analysis of their responses revealed limited BIM readiness, with most SMEs lacking dedicated roles, training programs, and a strategic vision for leveraging BIM across product development and certification processes.

The data analysis proceeded through axial coding, where the codes identified in the open coding have been synthesized into central themes, emphasizing common challenges such as insufficient internal resources, a lack of standardized practices, and difficulties in keeping pace with technological advancements. A subsequent in-depth survey of selected industrial partners provided further granularity, focusing on company profiles, BIM readiness levels, and the use of BIM-based datasets. The results of this final data collection, underscored the variability in BIM practices across the industry and the critical need for structured training programs and workflow standardization, allowing to the definition of a Grounded Theory: the construction sector needs a dedicated digitalized dataset of BIM-data for building envelopes products and solutions according to the most common scenarios of use of such data and information.

4. The MEZeroE BIM dataset tool

The review of the state of the art and state of the practice allowed the development of a dedicated MEZeroE BIM dataset tool, with the goal of establishing a common and standardized protocol for managing BIM-based datasets of envelope products and solutions. The process that has been followed for that purpose can be broken down in three main actions, presented in this section: (i) definition of the base structure of the so-called "BIM Dataset Matrix" (BDM) as content of the BIM dataset tool, to include all possible CSs as refers to envelope products and solutions, and populating of such structure also with the support of the MEZeroE Consortium partners (Section 4.1); (ii) standardization of the previous activities, finalizing the MEZeroE dataset in compliance with the relevant standards if applicable (Section 4.2); and (iii) validation of such MEZeroE BIM dataset tool (Section 4.3).

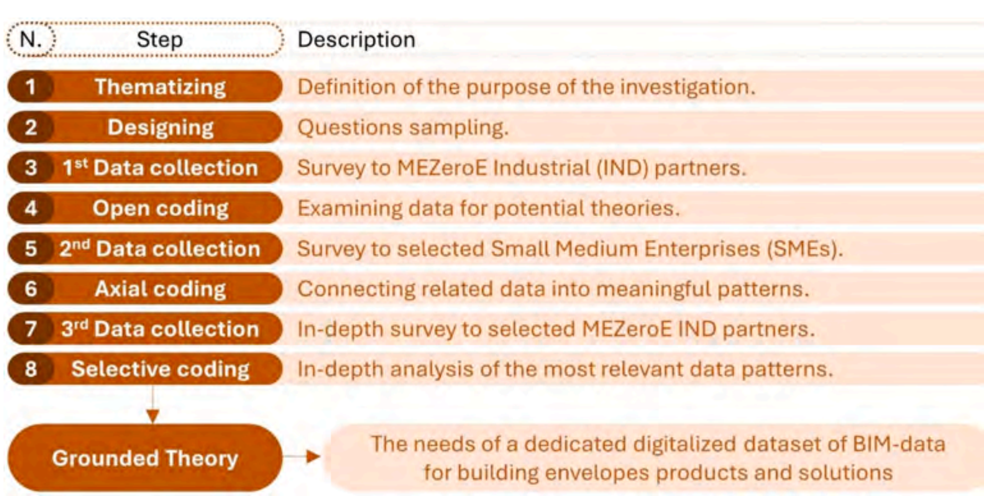

Fig. 3. Methodological structure of the Grounded Theory approach adopted to define the conceptual framework of the study. Source: elaboration of the authors.

4.1. Structuring and populating the MEZeroE BDM

The development of the BDM started from the definition of its structure by identifying the relevant content to include and the methods for retrieving it. Since the main goal of the BDM is to facilitate the management and sharing of BIM data among various stakeholders involved in building envelope products and solutions, a clustering process has been carried out to ensure a comprehensive and specific dataset tailored to different types of products and solutions. This clustering has been based on the nine CSs identified through the literature analysis presented in Section 3.1 and illustrated in Fig. 2, as they already represent the main typologies of envelope products and solutions on the market.

In addition to the nine CSs, which constitute the columns of the BDM, the next step in structuring the matrix involved the identification of the main property categories used to gather and cluster all relevant information and attributes related to the products and solutions. The selection of these categories has been informed by the classification systems, databases, and data formats reviewed in the state-of-the-art section, as well as by consultations with industry professionals. Moreover, existing BIM objects for building envelope products available on online platforms such as bimobject.com, bimstore.com, and nationalbimlibrary.com have also been examined. This process led to the definition of 14 property categories, divided into two typologies: attributes categories, which describe the intrinsic, descriptive, and static characteristics of products and solutions, and performance categories, which include quantifiable indicators used to assess and compare their functional behaviour and effectiveness with respect to specific performance objectives. Fig. 4 illustrates the fourteen property categories classified into attributes and performance categories, reporting the number of indicators included in each category. In total, the BDM comprises 326 indicators.

Among the identified categories, performance-related groups such as energy parameters and Life Cycle Assessment (LCA) play a transversal role within the dataset, as they are potentially reused across multiple scenarios and phases. In the MEZeroE BIM Dataset Matrix, these parameters are not analysed independently, but structured to ensure consistency, traceability, and reusability of envelope-related performance data along the value chain.

This approach allows different stakeholders to access coherent information according to their specific needs, while avoiding fragmentation or reinterpretation of data when moving from design-oriented activities to testing, certification, or operational phases. By structuring building energy performance and/or life cycle–related information within a standardized dataset, the tool boosts the data workflows more efficiently and consistently, it reduces uncertainties due to missing or inconsistent data, and it facilitates comparison between alternative envelope solutions. This indirectly contributes to more informed decision-making and, consequently, to the potential reduction of environmental impacts over the lifecycle of envelope products.

Once the rows (properties) and columns (CSs) of the BDM have been identified, the structured matrix has been extended to multiple

ATTRIBUTES CATEGORIES		
ID	**Identity** Unique identification attributes of the product, such as name, model, and manufacturer.	16
DIM	**Dimensions** Geometrical attributes including size, shape, and spatial configurations.	36
MF	**Materials and Finishes** Composition of the product, including raw materials used, coatings, and surface finishes.	4
OU	**Operation and Use** Intended application, usability aspects, and operational requirements.	21
PI	**Packaging Information** Details regarding how the product is packaged for transport, including weight and dimensions of packaging.	9
IN	**Installation** Requirements and guidelines for the correct installation of the product.	16
MA	**Maintenance** Maintenance needs, frequency, and specific procedures to ensure the product's longevity.	13

PERFORMANCE CATEGORIES		
MP	**Mechanical Properties** Mechanical behavior such as strength, elasticity, and load-bearing capacity.	57
EP	**Energy Parameters** Energy performance indicators, U-value and insulation efficiency.	53
AP	**Acoustic Parameters** Sound insulation and acoustic performance of the product.	14
DU	**Durability** Information on product lifespan, resistance to wear, and environmental degradation.	10
GHG	**Emissions Parameters** Emissions related to product use, including VOC and other pollutants.	15
FP	**Fire Protection** Fire resistance ratings and relevant certifications.	10
LC	**Life Cycle Cost (LCC) and Life Cycle Assessment (LCA)** Economic and environmental impacts over the product's entire lifecycle, including energy consumption, raw material sourcing, end-of-life considerations, and EPD dataset information.	52

Fig. 4. Categories of parameters included in the MEZeroE BIM dataset tool, grouped into attributes and performance categories; the number of indicators associated with each category is reported. Source: authors' elaboration.

scenarios, as suggested by the grounded theory defined in Section 3.2. Four main scenarios have been selected, according to the most common uses of the BIM data and information within the building envelope products and solutions supply chain: (i) marketing and communication, (ii) testing and monitoring, (iii) certification process, and (iv) installation, monitoring, operation and maintenance. This scenario-based structure enables a targeted selection and filtering of product information, ensuring that only relevant data are shared according to the specific use cases and the intended end users. The scenario-based structure of the MEZeroE BIM dataset is summarized in Fig. 5, providing for each of them, relative scope and main characteristics.

These four key scenarios of the dataset tool help themselves streamline the workflow, covering not just different applications, but also all the phases of the construction value chain, from the design to the operation and maintenance, till the end-of-life with the final goal to improve the energy performance of the building. Indeed, information initially defined during early design and communication activities (Scenario A) can be progressively refined through testing and monitoring (Scenario B) and formalized during certification processes (Scenario C). The same structured dataset supports installation, monitoring, operation, and maintenance activities (Scenario D), ensuring that envelope-related performance assumptions defined during design are not lost, but remain accessible and usable during the operational phase.

4.2. Development of the MEZeroE BIM dataset tool

Once the BDM has been structured and populated, the second step was its standardization through the collection of feedback from the MEZeroE partners and their infrastructure, specifically structured as: 10 industrial partners (INDs) operating along the supply chain of building envelope products and solutions; 9 Pilot Measurement and Verification Lines (PM&VLs), which are the experimental infrastructures designed to characterize the performance of either non-standard products or market-ready products lacking standardized assessment methods; and 3 Living Labs (LLs), a network of real-world sites where innovative solutions are tested and evaluated in occupied buildings, enabling collaboration among building owners, manufacturers, and research institutions to assess performance and occupant satisfaction. To support a consistent interpretation of the feedback and to reflect the different roles of the partners within the consortium, each partner typology has been explicitly associated with the scenario(s) for which its contribution has been considered most relevant. As illustrated in Fig. 6, this association has been operationalized by asking partners to assign a value ranging from 1 to 4 to each parameter of the BDM, according to a shared legend that reflects data availability, relevance, and expected use within each scenario.

The results of the feedback campaign have been filtered according to the 9 CSs, leading to the creation of a series of working matrices, one for each segment. For every working matrix, the parameters relevant to the development of the MEZeroE BIM dataset tool have been identified through a cross-comparison of the feedback provided by the partners. All parameters for which at least two partners assigned a value other than 3, according to the legend in Fig. 6, have been considered for inclusion in the MEZeroE BIM dataset tool, while parameters not meeting this condition have been excluded.

To clarify how the filtering criteria has been applied in practice, Fig. 7 provides an example of a working matrix referring to Scenario B (Testing and Monitoring) for Construction Segment CS1. The figure illustrates how the feedback collected from the relevant partners has been translated into a binary decision for each parameter. In particular, the rightmost column explicitly indicates whether a given parameter has been retained or excluded from the MEZeroE BIM dataset tool, based on the value-assignment logic described in Fig. 6 and the cross-comparison criteria adopted for the standardization process.

The cross-comparison of the feedback for Scenario A revealed that the IND partners primarily provided parameters for the categories of Identity and Energy. Instead, the category with fewer parameters, Acoustic Property, is requested to be included in the standardized dataset. Conversely, in Scenarios B and C, the majority of indicators were deemed relevant by the PM&VL leaders for the standardization of the MEZeroE BDM.

Once all the contributions have been analyzed, an Excel file was created in which all the results have been merged to optimize and successfully standardize the MEZeroE BIM dataset tool. Different worksheets were dedicated for each scenario and each CS.

As part of the standardization process, an additional mapping of the compiled parameters to open standards has been carried out, to ensure compatibility with existing BIM authoring software, formats, databases, and classification systems. The key aspect of this is the comprehensive mapping of these parameters to the IFC library, which serves as the primary open standard for building data model exchange. For parameters with direct counterparts in the IFC 4.0 schema, the mapping process has been straightforward. However, some product-specific parameters identified in the MEZeroE BDM could not be directly referenced to the IFC standard.

To address this, a decision-making process was implemented, involving the following steps: (1) evaluation of existing IFC parameters and their applicability; (2) cross-referencing with other industry formats and classification systems such as ETIM, Uniclass, OmniClass and UniversalTypes, when IFC did not cover a specific parameter; (3) creation of custom parameters for unique product attributes, adhering to consistent naming conventions and clear definitions; (4) consideration of future-

Fig. 5. Scope and main characteristics of the four key scenarios of the MEZeroE BIM dataset tool. Source: elaboration of the authors.

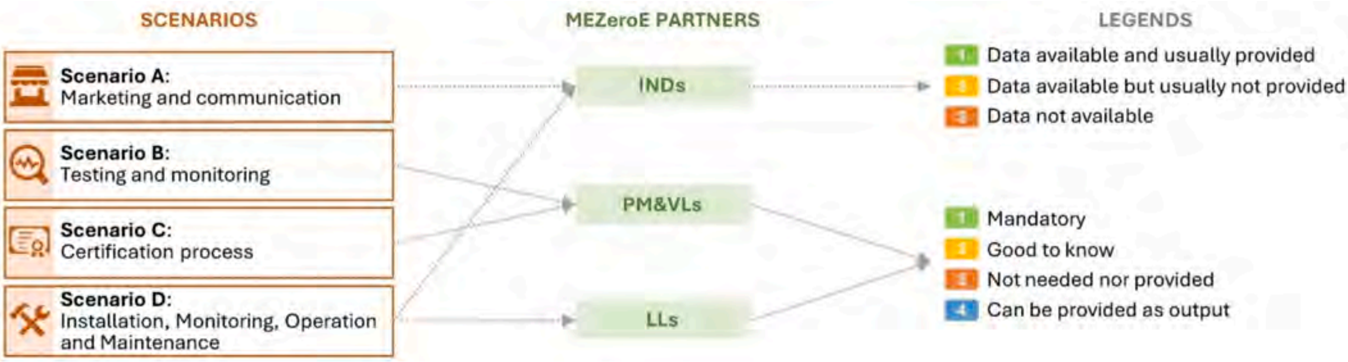

Fig. 6. Connection between MEZeroE partner typologies, application scenarios, and value-based criteria adopted for the BDM standardization process. Source: elaboration of the authors.

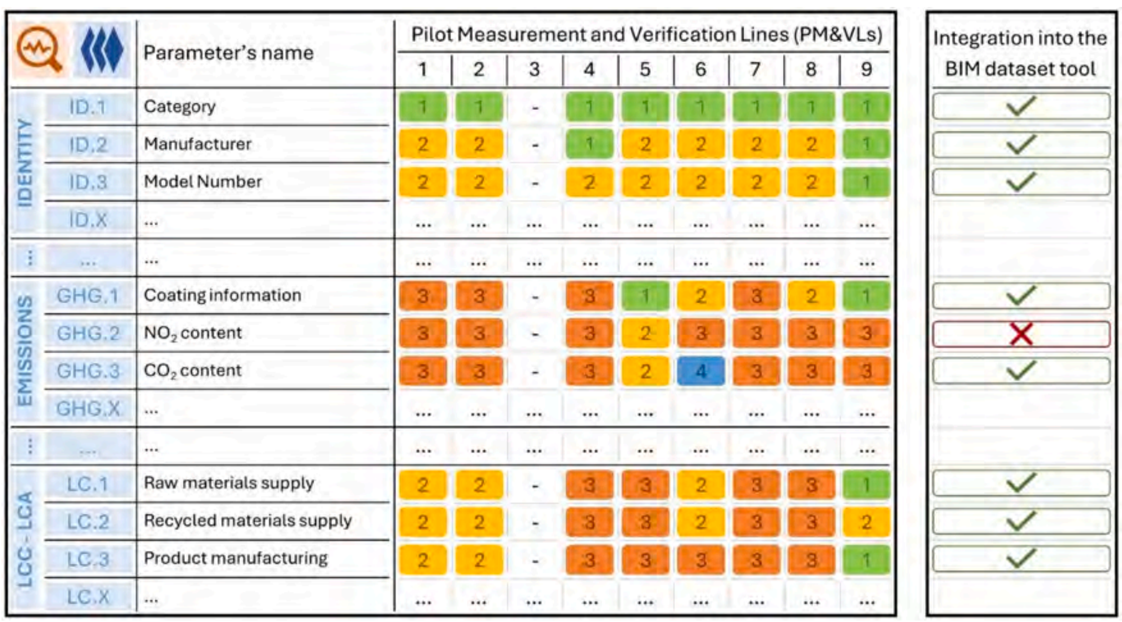

Fig. 7. Example of the working matrix standardization process for scenario B and CS1. Source: elaboration of the authors.

proofing strategies to ensure regular updates in line with evolving BIM standards; and (5) comprehensive documentation of the decision-making rationale to ensure transparency and facilitate understanding among internal teams, collaborators, and clients.

This holistic approach to parameter mapping and standardization ensures that the resulting protocol not only aligns with current BIM standards but also remains adaptable to future industry requirements. By combining existing standards with custom parameters and maintaining flexibility for updates, the protocol aims to create a robust framework for integrating building envelope products and systems into existing BIM environments. This standardization effort ultimately contributes to improved data exchange, enhanced collaboration, and more efficient project management across the entire building lifecycle, from initial design concepts to long-term facility management.

4.3. Validation of the MEZeroE BIM dataset tool

The third and final step of the MEZeroE BIM dataset tool development has been its validation, to ensure its reliability, usability, and applicability across multiple scenarios and construction segments both with a real use case and a simulated condition, confirming its capacity to meet the diverse needs of stakeholders across the AECO industry. To this end, a dual validation approach was adopted, combining both a real use case (applied) and a digital (virtual) method.

The applied approach involved the MEZeroE partners LLs, which conducted the physical testing on real buildings. This approach allows for conducting a comprehensive assessment of the MEZeroE BIM dataset tool in relation to current real construction cases, and it enables stakeholders to observe how the BIM dataset facilitates on-site decision-making, testing, and data management. The digital approach, on the other hand, using building archetypes and virtual models to simulate real buildings, allows the validation of the MEZeroE BIM dataset tool in scenarios where physical tests were not otherwise feasible. By using digital models, the validation could cover a wider range of boundary conditions and evaluate how the MEZeroE BIM dataset tool supported simulation studies and other virtual testing methods.

The validation has been structured for the four key scenarios introduced in Fig. 5. Scenario A employed a virtual validation approach due to its focus on information dissemination, which is not related to specific building archetypes. For Scenario B, which emphasized testing and monitoring activities, the applied validation approach has been used, allowing PM&VLs to conduct real testing on selected construction segments. Scenario C involved a virtual approach, as obtaining actual certification data from PM&VLs posed challenges, whereas Scenario D combined both applied and virtual methods, integrating the validation activities with ongoing work in LLs.

Once the scenarios were established, each construction segment was assigned to a specific PM&VL, IND or LL partner for validation based on their expertise and the nature of their products. Each partner provided feedback on the working matrix containing the indicators selected specifically for the validation, indicating if they are essential, or suggested, or whether if corrections or integrations in the list were necessary. Feedback have been gathered from all partners, for each scenario and all construction segments to produce a finalized version of the MEZeroE BIM dataset tool. The validated version foreseen two groups of indicators: the minimum ones, which have been targeted as the minimum indicators needed to perform the activities described by the scenarios, for the specific construction segments, and the suggested ones, which have been considered as useful but not essential to perform the activities described by the scenarios, for the specific construction segments.

Fig. 8 presents an example of the finalized MEZeroE BIM dataset tool for Scenario B applied to Construction Segment CS1, to illustrate the outcome of the validation process. The figure shows how the validated indicators are organized and distinguished according to their classification as minimum or suggested, representing the final output of the standardization and validation workflow.

The cross-comparison of feedback revealed that the PM&VL partners generally consider multiple parameters from Scenarios B and C as non-essential for the BDM, particularly in the categories of Mechanical Properties and LCC-LCA. Additionally, for Scenario C, at least 21 new indicators have been identified by the PM&VL partners for each Construction Segment, with most of them for the "Identity" category.

After analyzing all the contributions, an Excel file has been created to compile and standardize the validated MEZeroE BIM dataset tool.

The validation activities presented in this section have been conducted on a limited number of construction segments and involved a selected group of stakeholders, primarily represented by MEZeroE industrial partners, PM&VLs, and Living Labs, as proof of applicability that could be replicated to a broader range of envelope solutions. This approach ensured a high level of technical relevance and allowed for an in-depth assessment of the MEZeroE BIM dataset tool within controlled and well-defined contexts. However, not all nine construction segments identified in the study have been validated through applied or real use cases, and the participation of external stakeholders beyond the project consortium remained limited. Consequently, the validation should be interpreted as proof of applicability and internal consistency of the proposed dataset structure, rather than as a comprehensive evaluation of its generalizability across the entire construction sector. Further validation activities involving additional construction segments and a broader range of independent stakeholders are therefore required to strengthen the scalability, transferability, and robustness of the MEZeroE BIM dataset tool.

Once the validation process has been completed, the MEZeroE BIM dataset tool has been integrated within the MeZeroE Virtual Marketplace (VM) as one of the services that it provides.

The MEZeroE VM is a web platform that offers to the actors of the construction sector a single-entry point to integrate cutting-edge technologies, collaborate with solution providers, and stay ahead of industry trends. It helps enhance product performance, meet sustainability goals, and maintain a competitive edge. Additionally, the platform provides tools and services to assess the environmental and economic impacts of innovations, ensuring informed decisions that align with regulations and customer expectations.

The platform aims to increase access to additional test lines, enabling providers to test their solutions in real, comprehensive scenarios. Moreover, solution providers can benefit from a rich network of experts and potential partners within the MEZeroE community.

5. Application of the MEZeroE BIM dataset tool to an innovative product for building envelope

The MEZeroE BIM dataset tool has been implemented within the MEZeroE VM through a user-friendly front-end interface and an Excel-based back-end, designed to facilitate accessibility and usability for various stakeholders. The tool provides manufacturers of building envelope systems with a standardized and digitalized dataset, offering minimum and suggested parameters according to the selected Construction Segment and one of the four predefined use scenarios.

This section presents the application and real use case of the MEZeroE BIM dataset tool to an innovative product for building envelopes, developed by a membrane manufacturer. The new sealing membrane developed by this company being an innovative solution for building façade component, has not already defined reference values or methodology for testing performances, so the SME decided to use the MEZeroE BIM dataset tool to firstly identify which parameters needs to be collected to conduct the test into a facility laboratory and then to use

		Parameter's name	Data type	Dataset type
IDENTITY	ID.1	Category	Alphanumeric	Minimum
	ID.2	Manufacturer	Alphanumeric	Minimum
	ID.3	Model Number	Alphanumeric	Minimum
	ID.X	...	...	...
⋮	...	...	...	...
EMISSIONS	GHG.1	Coating information	Alphanumeric	Suggested
	GHG.2	NO_2 content	Numeric (unit)	Suggested
	GHG.3	CO_2 content	Numeric (unit)	Suggested
	GHG.X	...	...	...
⋮	...	...	...	...
LCC - LCA	LC.1	Raw materials supply	Alphanumeric	Suggested
	LC.2	Recycled materials supply	Alphanumeric	Suggested
	LC.3	Product manufacturing	Alphanumeric	Suggested
	LC.X	...	...	...

CS1 | CS2 | CS3 | CS4 | CS5 | CS6 | CS7 | CS8 | CS9

Fig. 8. Example of evolution of the working matrix into the MEZeroE BIM dataset tool worksheet. Source: elaboration of the authors.

the MEZeroE BIM dataset results to create the digitalized BIM object of the new product.

The application of the MEZeroE BIM dataset tool followed four main steps.

1. Platform Access: the company accessed the MEZeroE Virtual Marketplace through the dedicated web interface.
2. Tool Selection: the MEZeroE BIM dataset tool, integrated into the BIM Package Configurator service, was selected as the appropriate resource to identify the necessary parameters.
3. Construction Segment and Scenario Definition: the company chose Construction Segment 5 – Membranes and Scenario B – Testing and Monitoring, as the most relevant to their product and objective.
4. Dataset Retrieval: the system generated an Excel worksheet that listed all relevant parameters—classified as minimum or suggested—for the selected segment and scenario.

To support the interpretation of the generated dataset, Fig. 9 illustrates the distribution of minimum and suggested parameters across the fourteen data categories included in the worksheet produced for this use case.

This process enabled the manufacturer to obtain a clear overview of the information requirements for digital modeling and testing of its membrane. The minimum parameters outlined in the worksheet were considered essential for conducting testing and monitoring activities, while the suggested ones provided additional data that could enhance interoperability and performance analysis.

The case study demonstrated how the MEZeroE BIM dataset tool not only guides manufacturers in structuring their product data but also ensures alignment with broader testing protocols and digital workflows. By enabling the automatic extraction of relevant parameters based on product type and intended application, the BDM effectively reduces uncertainty, increases data consistency, and accelerates the preparation of BIM-ready content.

6. Conclusions

This paper has presented a comprehensive strategy to develop, standardize, and validate a digitalized dataset for building envelope products within the framework of the H2020 MEZeroE project. The process followed a structured and sequential approach, beginning with an extensive state-of-the-art analysis to identify existing standards and languages in use. In addition to this, an analysis of the literature on the subject was carried out to identify and examine possible studies on the topic. The state-of-the-art analysis was followed by. Due to the lack of information from the literature analysis, Grounded Theory was subsequently performed to understand real-world contexts in the construction sector. These initial phases laid the groundwork for the development of the MEZeroE BIM dataset tool, which was further refined and standardized through collaborative efforts with project partners. Finally, the dataset underwent a validation phase using both real-world and simulation-based testing methods to confirm its utility and adaptability in real-world and simulated environments.

The resulting MEZeroE BIM dataset tool represents a standardized framework for organizing technical data for building envelope solutions, clustered into nine construction segments and applicable to four main scenarios. The modular structure of the dataset ensures that it can be tailored to diverse needs along the construction value chain, from marketing and communication to testing, certification, and maintenance. The validation activities conducted in Section 4.3 highlighted the MEZeroE BIM dataset tool's versatility and effectiveness, demonstrating its capacity to enhance data consistency and usability across different construction contexts. For instance, the case studies involving the validation of two different construction segments illustrated the practical benefits of using the BDM in assessing and improving the performance of cladding systems and membranes.

The creation of the MEZeroE BIM dataset tool has provided a clear and structured answer to the research question posed at the beginning of this paper. By developing a common and standardized protocol, the dataset facilitates seamless data exchange, ensuring that all stakeholders—from manufacturers to installers—can access, understand, and utilize product information consistently across the construction process.

The added contribution of the paper, therefore, concerns not only the formalization of the BDM tool for standardizing the datasets for analyzing, modeling and sharing digitalized envelope information but, more broadly, of an approach to boost and facilitate the performance and technical datasets of envelope products, by the potential application of the MEZeroE BIM dataset tool within the MEZeroE BIM Package

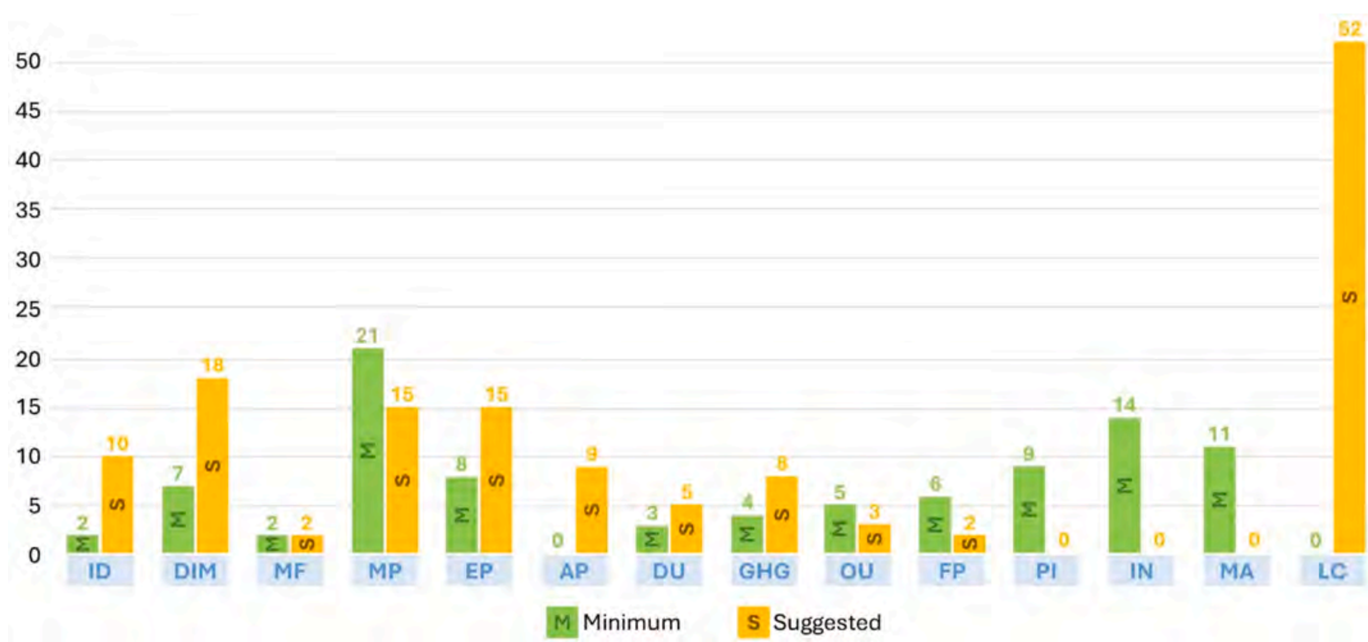

Fig. 9. Distribution of minimum and suggested parameters across the fourteen BDM data categories for Scenario B and Construction Segment CS5, as defined in Fig. 4. Source: elaboration of the authors.

Configurator service, part of the MEZeroE VM.

The BIM package configurator is the practical outcome of the research, and it serves as a tool to help manufacturers include the minimum standardized information required for their products, according to the construction segments and relevant scenarios. The MEZeroE BIM dataset tool forms the backbone of this service, providing a common language and structure for digitalizing product information that can be used to create BIM objects or evaluate BIM-readiness levels, as outlined in the MEZeroE platform. This integration into the OIS3 BIM Package Configurator is expected to facilitate the broader adoption of standardized digital datasets, ultimately leading to improved collaboration and data exchange across the AECO industry.

From a life cycle perspective, the MEZeroE BIM dataset tool acts as an enabling tool that improves the efficiency, reliability, and usability of LCA workflows for building envelope solutions, not to directly quantify environmental impacts or GHG emissions, but by structuring standardized LCA-related information, the tool supports the availability of consistent and traceable input data, reducing uncertainties related to data gaps and heterogeneous sources. The MEZeroE BIM dataset tool contributes indirectly to GHG emission reduction by improving data-driven decision-making across the entire lifecycle of building envelope products, from early design choices to long-term operational management.

However, there are limitations to this study that warrant discussion. Although the validation activities demonstrated the feasibility and usefulness of the MEZeroE BIM dataset tool, they were conducted on a limited number of construction segments and involved a restricted group of stakeholders, mainly within the MEZeroE consortium. As a result, the validation does not yet fully capture the diversity of building envelope products, market conditions, and organizational practices present in the construction sector. This limitation may affect the generalizability of the findings. Future research should therefore extend the validation to additional construction segments and engage a wider range of external stakeholders, including designers, contractors, certification bodies, and manufacturers operating outside the project consortium, in order to further assess the robustness and scalability of the proposed approach. Furthermore, while the dataset provides a standardized approach, the dynamic nature of construction technologies and standards implies that ongoing updates and adaptations will be necessary. Despite these limitations, the MEZeroE BIM dataset tool presents a significant step forward in digitalizing and standardizing data management for building envelope products, offering a foundation that can be built upon to support innovation and efficiency in the construction industry.

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CRediT authorship contribution statement

Marta Maria Sesana: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Graziano Salvalai:** Writing – original draft, Validation, Supervision, Methodology, Funding acquisition, Formal analysis, Conceptualization. **Paolo Dell'Oro:** Writing – review & editing, Writing – original draft, Visualization, Investigation, Data curation. **Akshit Gupta:** Writing – review & editing, Writing – original draft, Investigation, Data curation, Conceptualization.

Declaration of competing interest

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

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Data availability

Data will be made available on request.

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