Data-driven and LCA-based Framework for environmental and circular assessment of Modular Curtain Walls

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Abstract

To assist the sustainable development of the building sector, designers require tools illustrating the most viable design options. This paper, starting by presenting the opportunities and limitations of the Life Cycle Assessment (LCA) methodology and Digital Product Passport (DPP) instrument when applied to Custom Modules for Curtain Walls, proposes a Semantic Data-driven Framework to facilitate the design of low-carbon and circular façade modules. Based on literature and the practical outcome of the H2020 project Basajaun, this framework integrates computer-aided technologies that manufacturing companies commonly employ to automate an efficient sustainability assessment process using primary data. This solution innovates industrial process management and architectural design and supports the creation of greener products. It also facilitates the output of documents supporting end-of-life scenarios. The development methodology involves investigating required quantitative project data, environmental factors, and circularity information, as well as the definition of flowcharts for the Life Cycle Inventory, extending a best practice for the façade module's DPP. Furthermore, the methodology implicates data collection and IT implementation and organisation. This is through the definition of an ontology conceived for interconnection between digital systems. The findings shall contribute to implementing the LCA and DPP practices for custom prefabricated façade modules and suggest areas for further development. Challenges include obtaining and sharing data on environmental impacts and circularity, but involving stakeholders and addressing technical limitations can improve sustainability.

Keywords

Custom prefabricated Modules for Curtain Walls (CMCW), Life Cycle Assessment (LCA), Digital Product Passport (DPP), Semantic Data Framework, Eco-design tool, Production Management and Innovation

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1 INTRODUCTION

Among the most critical sustainability requirements that will have to be addressed in the coming decades, a renewer transformation of the building sector is inevitable (IPCC, 2023; UNEP & GABC, 2021). While the construction industry is hopefully moving in the green direction, it still needs to evolve to tackle the challenges of climate change, endurable use of resources, and water shortage. Therefore, it is fundamental to have a clearly defined picture of the design options that architects and designers own to minimise the environmental impact of their project's life cycle. However, current design tools are often limited in providing an accurate and comprehensive environmental and circular assessment. This study explores a data-driven approach to life cycle strategies in the sector of architectural building envelopes, which integrates the IT tools of Industry 4.0 for innovation, optimisation, and management of resources and processes.

Building façades are intricate components of architecture that interact with various disciplines and stages of the value chain. They have a shorter lifespan compared to the primary structure of a building (WGBC, 2019, p. 23). Consequently, it is both difficult and crucial to address the principles of the Circular Economy (CE) in façades. This transition is vital for shifting from the linear approach of take-make-waste to a more sustainable approach of reduce-reuse-recycle (Kragh & Jakica, 2022). This finding becomes even more stimulating in the case of prefabricated façade modules. Machado and Morioka (2021) systematically reviewed the literature to identify how modularity can contribute to a circular and sustainable economy. Fifteen advantages of commutability have been identified, which can positively impact the adoption of CE strategies, and five barriers have been recognised that may delay the process of incorporating these benefits. Examples of these advantages applicable to modular façade systems are reducing CO_2 emissions, assembly time, and production waste. Moreover, they facilitate disassembly, maintenance, product durability, and the entire reverse logistic process (López-Guerrero et al., 2022). However, a general assessment of these advantages remains challenging.

Considering all these factors, this paper will present the development and validation process of a Semantic Data-driven Framework (SDF) based on the Life Cycle Assessment (LCA) methodology for the environmental and circular evaluation of Custom prefabricated Modules for Curtain Walls (CMCW). This SDF is conceived to be integrated with manufacturing companies' software, such as computer-aided technologies, to automate the environmental assessment process using primary data. It can also facilitate better-defined product passports for End-of-Life (EoL) scenarios. Moreover, it can be perceived as a fundamental framework that can aid in corroborating software development of eco-design façade support tools. This type of circular construction necessitates the use of a novel set of design tools that can be seamlessly integrated into existing workflows (Heisel & McGranahan, 2024). Lastly, its connectivity could be further integrated with sensors and digital models, creating a framework for primary data towards supply chain stakeholders' collaboration and the work built on cross-platform unified standards.

The semantic data model proposed is being developed and tested within the European project H2020 Basajaun, one of the outcomes of which has been an industry 4.0 platform to ensure traceability and transparency of the engineering process. The method and the SDF have been applied to use-case in-line produced modules for an experimental building envelope (FIG. 1-3) to validate its development. The findings could contribute to implementing the LCA practice for CMCW and suggest areas for further development.

FIG. 1 In-line production of Basajaun's curtain wall modules (credit: Basajaun H2020, picture by Vandi, L.)

FIG. 2 *Basajaun's completed curtain wall modules (credit: Basajaun H2020, picture by Vandi, L.)*

FIG. 3 Basajaun's curtain wall modules' inner part installed on construction site. (credit: Basajaun H2020, picture by Vandi, L.)

2 STATE OF THE ART AND OPPORTUNITIES OF SDF

Ecological issues are driving market actors to pay more attention to the environmental impacts of their products. Since its definition, the LCA method has seen a growing diffusion in regulations and scientific research. Despite a lack of binding legislation, the European Union increasingly refers to LCA in its communication and policies (Sala et al., 2021). Generally, the LCA method applied in construction – intended as attributional in this research paper (Hauschild et al., 2018) – considers the environmental effects of resource usage associated with the lifespan of a building and its components. It also constructs a model of the analysed system based on these impacts, assisting in decision-making and identifying eco-design alternatives with a slighter environmental impact (Stijn, 2023). Succeeding in this field has notable expected impacts on the research and innovation of construction products that struggle to exhaustively implement the LCA method, such as the Custom prefabricated Modules for Curtain Walls (CMCW).

As mentioned, it is difficult to measure and compare the green and circular benefits of complex and custom systems due to the lack of comprehensive standards and benchmarks, difficulties in accessing correct data from suppliers and organisations, and the diversification of the certification schemes. Figure 4 summarises the promising sustainability requirements that façade engineers and manufacturers will have to demonstrate in the coming years in Europe, according to the

Commission's and WBCSD's view (European Commission et al., 2020; European Commission, 2021; WBCSD, 2023). This is a challenge for the CMCW industry, which needs to show its contribution to sustainable development. At this time, there are few examples of comprehensive analyses of these products on the market, merely some rare independently verified exceptions achieved after the installation (Scheldebouw, 2022), but even fewer regarding circularity. Moreover, to meet the demands of stakeholders who want to verify environmental targets, the industry needs a digital strategy that can quickly and accurately evaluate buildings using data analysis. The value proposition for companies is depicted by an improvement in process management and architectural design, with a gain in terms of time and economy beyond the creation of more virtuous and environmentally friendly products (Bach et al., 2019; Zaffagnini & Morganti, 2022).

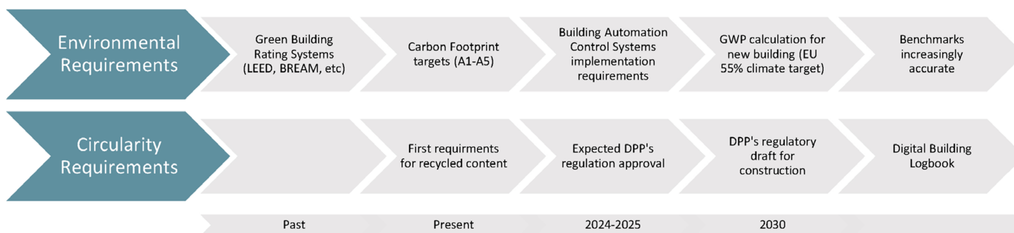

FIG. 4 Timeline of some of the upcoming possible environmental and circular requirements in the European construction sector (European Commission et al., 2020; European Commission, 2021; WBCSD, 2023)

That is why a Semantic Data-driven Framework (SDF) is proposed. It can help achieve these targets by enabling real-time data sharing among distinct departments with LCA-required data (e.g., quality and technical departments) and other data users (such as tender departments, project management, and design managers). In this way, the quantitative project data and environmental factors are always up to date when consulted (McAvoy, 2021) and related to relevant circularity information. The ultimate aim is to create optimal conditions for automatically linking the data across the existing computer-aided technologies, such as Enterprise Resource Planning (ERP) and Product Lifecycle Management (PLM) technologies, Common Data Environment (CDE) platforms and other specialised business databases if available.

Implementing this kind of SDF in support of companies' digital processes to perform data-driven LCA and DPP would offer several advantages:

A It would allow measuring the product's environmental impact using primary data based on the ISO EN standards. For that purpose, primary data are considered a key factor for accuracy (Silva et al., 2020). Moreover, it would aid in assessing and achieving other market requirements, such as using defined quantities of recycled materials or providing Environmental Product Declarations (EPDs) for the prefabricated modules. That rule-based compliance can be constantly verified during the project development.

B It would support ecological decision-making during several project stages, such as design, engineering, production, logistics, supply chain definition, assembly, and disassembly, by evaluating the impact of different options beforehand. In the future, this approach could also have the capacity to analyse the costs throughout the life cycle (Zeng et al., 2020).

C It would help create new and better strategies for the EoL of CMCWs to promote their circularity (Viscuso, 2021) and to enhance value creation after the dismantling stage. Moreover, by blending the entire supply chain within its digital framework and operation, it would be capable of integrating and supporting production monitoring, shipping and transportation, delivery, inspection, and site installation monitoring for data traceability and reliability (Jang et al., 2022).

D It would help visualise LCA and circularity-related data, assisting managers and workers in extending the know-how of the processes in which they are involved, such as the production process, identify problems and opportunities, and make informed decisions. Visualisation instruments, such as dashboards, charts, and graphs, can present the data clearly and intuitively, highlighting the most relevant and actionable information (Uchil & Chakrabarti, 2013).
It is claimed that data-driven digital tools, plans that prioritise circularity and monitoring of dismantling are the most crucial categories for developing economies in construction (Oluleye et al., 2023). Despite being slow to adopt, these tools have the potential to revolutionize building design and construction (Sangiorgio et al., 2024). Comprehensively, developing instruments to make LCA practice and circular design the fastest and most accurate has considerable importance and value in the design and production of CMCW.

Furthermore, focusing on research and innovation beyond business development, the study of these digital systems would contribute to the redefinition of the main limits of the currently used LCA method and CE models for customised products:

E It would support the insufficient "what if" scenarios, updating the integration with BIM models in the environmental assessment and investigating the lack of time-dependent data for EoL stage management (Fnais et al., 2022). Besides LCA being a time-consuming method, there is a discrepancy between resolution detail and building description level, and results lack reproducibility (Jusselme et al., 2018). SDF can make these analyses faster and more reliable.

F It would contribute to achieving a CE in construction through the definition of metrics and key performance indicators to measure them, developing digitalisation initiatives and promoting materials passport, which are significant success factors for circular development (Oluleye et al., 2023).

G It would collect data that can be automatically organised in a Digital Product Passport (DPP) of the custom façade module to facilitate disassembly and reverse logistic actualisation in the future. For this purpose, blending STEP and BIM models offers possibilities for database integration and is increasingly being studied concerning data exchange solutions (Safari & AzariJafari, 2021). Moreover, it allows for complete tracking of the modules for the design and conception of the EoL (Llatas et al., 2022).

H It would help to implement a digital building logbook for construction collecting discussed data through time. This digital repository, or database, should contain comprehensive information about the building's materials and products throughout its lifecycle. The European Commission has recognised its potential as a tool to promote sustainability. Some experts believe that for the digital building logbook to be more widely adopted, there needs to be a systematic and improved approach to capturing, gathering, processing, exchanging, and storing information and data (European Commission et al., 2020).

All these issues and opportunities need to be addressed with a solution. Upon analysing the literature pertaining to digital tools, frameworks, or models that deal with data-driven circularity assessment approaches, as summarized in Table 1, it becomes apparent that some sources lay emphasis on circularity and concentrate solely on the requirements for DPP (or similar material passports), whereas others also focus on circularity but only address the requirements for Life Cycle Assessment (LCA).

TABLE 1 Summary of the literature reviewed regarding circularity assessment frameworks or models

Articles related to data-driven circularity digital tools, frameworks, or models						
References	Papers about tools, frameworks, or models					
	Generic Product Analysis	Related to construction, specifically:	Circular Assessment	Sustain-ability Assessment	Referred to DPP	Referred to LCA
Heinrich & Lang, 2019		Building products and buildings	x		x	
Jansen et al., 2023	x		x		x	
Mulhall et al., 2024	x		x		x	
Zabek et al., 2023		Mineral building materials	x	x		x
Klein et al., 2022		Building Products	x	x		x
Oluleye et al., 2023		Building construction industry	x			
Morganti et al., 2023		Building envelope components	x	x		x
Giovanardi et al., 2023a		Curtain Wall Façade	x		x	
Honic et al., 2024		Building products and buildings			x	
CWCT et al., 2022		Architectural Façades				x
European Commission et al., 2020		Built Enviromnent	x		x	x

Interestingly, to the best of the authors' knowledge, there is no framework available that aligns with the new EU requirements, which includes both DPP and LCA for façades. Recognising this gap, this paper proposes the development of a novel SDF to address these dual requirements comprehensively. The primary aim of the SDF is to bridge the current gap in frameworks and provide an integrated solution tailored to the evolving regulatory landscape and the challenges associated with modular façade design.

3 METHODOLOGY

In the last decade, the idea of developing a tool for automatic or semi-automatic LCA-based analysis of industrial products has grown. Various methodologies have been formed which involve the development of semantic data frameworks (or models) that integrate computer-aided technologies (e.g. CAD, PLM, ERP, etc.) with Life Cycle Inventory (LCI) data to develop eco-design and management tools (Morbidoni et al., 2011; Tao et al., 2017; Mandolini et al., 2019; Rovelli et al., 2022). More recently, they have also been related to construction and beyond LCA, including computational methods and circularity indicators that can aid in assessing the effectiveness of circular design strategies (Dervishaj & Gudmundsson, 2024). This paper's aim and originality are based on the implementation and application of those methodologies in the CMCW context, as well as the reorganisation and performance of CE aspects in data-driven practices.

Overall, the proposed methodology can be summarised in five practical development steps:

1 Preparation and collection of data:
   a Investigation of the required CMCW data for Environmental and Circular assessment.
   b Description of the LCI flowcharts of the module's single components and operations.
2 Reception and organisation of data for the Life Cycle Impact Assessment (LCIA) and Digital Product Passport (DPP):
   a Identification of the data sources (Business departments and software) and collection.
   b Definition of the ontology and semantics of the data-driven framework.
3 Finalization of the data input and output, results, and setting sharing modalities:
   a Validation of the Semantic Data-driven Framework through testing the ontology on façade-related datasets.

The framework's overall functioning can be visualised through the schematic representation depicted in Figure 5. This representation shows three distinct phases: preparation of data, reception and organisation, and visualisation of results. These phases will be explained in detail in Chapter 4, which is dedicated to research and results analysis.

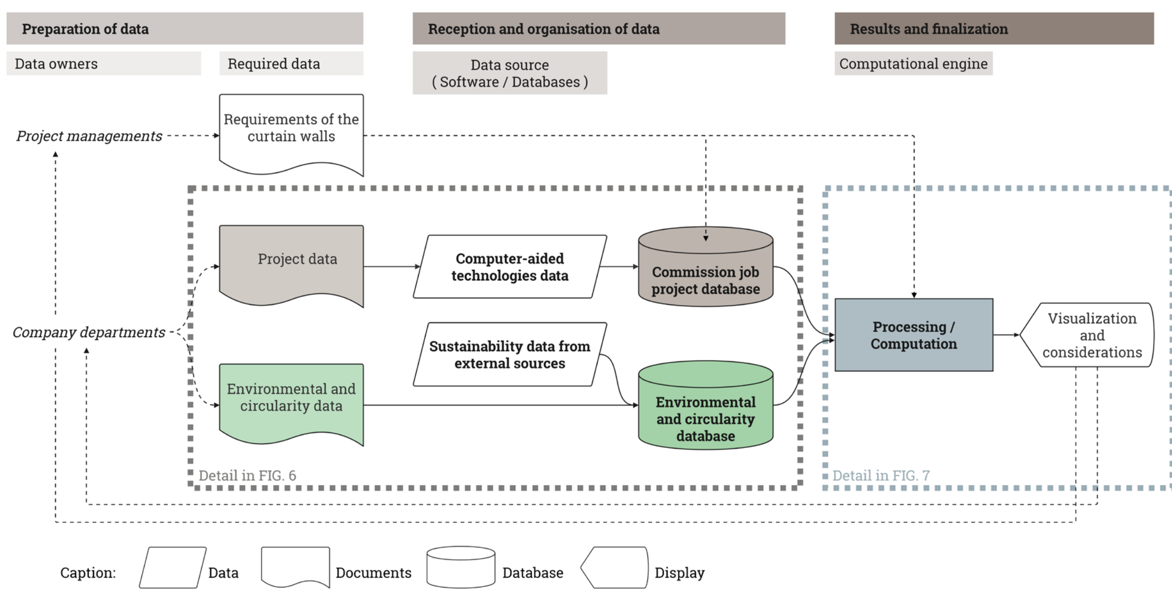

FIG. 5 *Schematic flowchart of the entire data processes according to the proposed semantic data-driven framework, from data preparation to finalisation. Figures 6 and 7 provide more detailed views of some steps.*

4 RESEARCH AND RESULTS

This chapter presents the methodology employed in the research and the consequential results that have emerged.

4.1 INVESTIGATION OF THE REQUIRED DATA

The first step involved in developing a Semantic Data-driven Framework (SDF) must be the definition of the information required to achieve its purpose, meaning assessing CMCWs according to their design. The concept of data here refers to a set of particular values that communicate information, such as those that characterise the subject of evaluation, for example, the weight of aluminium profiles or the surface area of glass. Additionally, it encompasses data that describes the environmental impact of these materials, such as the amount of carbon dioxide emitted per unit of aluminium or the percentage of recycled content present in the glass. To define the requirements, it is necessary to consider LCA impact categories, scoped label-specific rules and requirements of the most prevalent rating systems, as well as other certifications requested by clients (Rovelli et al., 2022; Zaffagnini & Morganti, 2022). These can serve as benchmarks for best practices defining products' impacts on the environment and circularity declarations. In addition, it should collect data that includes related input and output values from past events, actual sources or models (Venkatraj & Dixit, 2022). Lastly, organising these parameters in a hierarchy aids in assessing both short-term and long-term sustainability roadmaps. Once the SDF is operative, implementing target cascading makes it possible to seamlessly integrate innovative components and systems into parametric simulations. This approach tackles the challenge of exhaustively exploring diverse alternatives, as it allows for specific targets to be set at the system level (Jusselme, Rey & Andersen, 2018).

For the implementation of the SDF, three categories of data have been identified and collected: Project data, Environmental data, and Circularity data.

1. Project data describe the physical dimension of the construction module and its components and materials. Examples of project data can be the mass (kg) and surface (m^2) of the CMCW and the quantities of its framings, as well as architectural features. Beyond their related transportation distances (km), embodied electricity consumptions (kWh), and lifespan periods (years).
2. Environmental data represent the extent of the environmental damage related to each designed quantity. For instance, the Embodied Carbon Factors ($kgCO_2eq$/Functional Unit), water consumption (litre), or the Grid Carbon Factor ($kgCO_2eq/kWh$).
3. Circularity data are aimed at facilitating the assessment and communication of end-of-life scenarios, such as describing materials composition, percentages of pre- and post-consumer recycled content (%), or proposal for a reverse logistic stream.

For each data category, the annexes' tables A1-A4 concisely describe the identified project and environmental and circularity data to be collected that were identified in the research. The following subsections examine the necessary environmental and circularity data in more depth to conduct an effective analysis of these factors.

4.1.1 Required environmental assessment data for CMCW

Past literature reviews have examined the sustainability of industrialised building systems, primarily focusing on environmental factors and qualitative indicators. The primary reported indicators in evaluating the sustainability of building systems include Global Warming Potential (GPW) or Embodied Carbon (mass of equivalent CO_2 emitted), water consumption, waste generation, construction time, and productivity (López-Guerrero et al., 2022).

The Embodied Carbon Committee of the Centre for Window and Cladding Technology (CWCT) released a new type of report to introduce a peer-reviewed methodology for assessing specifically the embodied carbon of façades (2022). This procedure focuses on the GWP environmental impact indicator outlined in BS EN 15804 (2019) and aligns it with whole-life carbon assessment documents from other construction industry bodies. This proposed methodology, also aligned with BS EN 15978 (2011), has been considered a starting point for selecting the required environmental data for the presented research, considering the specific circumstances and requirements.

Even if, as a principle, designers and assessors must consider as many life cycle modules as possible, CWCT highlighted the minimum life cycle stages that must be included in the façade assessment. I.e. product stage (A1–A3), construction process stage (A4–A5), replacement stage (B4), and EoL stage (C1–C4). Table A2 in the annexe, named CMCW Environmental Data, presents a list of the information that must be retrieved for each project data depending on the stage of the façace's life cycle. In addition, further in the tool application, an off-site waste rate and a site waste rate must be defined. These are corrective factors (percentages) to be multiplied by the A3 and A5 façade GWP to consider the waste's impacts on the manufacturing and construction process. Furthermore, in developing the described SDF, it was decided not to exclude any component in the corporate IT system's bill of materials and components. This was due to the decision to validate the system with all the primary data relating to the use cases analysed.

4.1.2 Required circular assessment data for CMCW

Many circularity assessment methods and tools already exist not only in the construction field but are widespread in various manufacturing sectors. However, they often remained fragmented (Sassanelli et al., 2019) and focused on a single or a limited number of indicators. Thus, a comprehensive and quantitative assessment method is needed in the construction industry. An analysis of existing literature by Sposito and Scalisi (2020), focused on assessing the life cycle of materials and buildings, has shown limited research on the process-related aspects. Furthermore, Cambier et al. (2020) found that while there are general guidelines for building circular design, there is still a lack of specific policies for construction components.

This encompasses various types of façade-related data, including static and dynamic information such as administrative documents (e.g., assembly and use and maintenance manuals), building detail drawings describing the technical systems, components and material characteristics, performance data, and connections to building ratings and certificates.

When assessing complex building components, such as CMCW, it is important to inventory them as a combination of different parts and materials. This inventory should differentiate materials with varying use cycles and lifespans. Additionally, all value retention processes and use cycles should be documented (Stijn, 2023; Kedir et al., 2021; McDonough & Braungart, 2013). This can facilitate the end-of-life management of the module and its components. For that reason, the data collection of components processing information of the LCA must be designed in such a way as to collect the data not only considering their impact as a component of the façade module but also as a future element/material that can be repaired, reused, recycled or efficiently disposed of. As a digital repository, the Digital Product Passport (DPP) report is being proposed by the European Commission to increase transparency and promote circularity throughout the product lifecycle. Moreover, the construction sector is one of the eight priority industries with a Commission's Action Plan, which should end with the definition of a DPP by 2030. Nonetheless, further development is required for data storage, carrier, access, and governance requirements (WBCSD, 2023)

Mulhall et al. (2022) and Jansen et al. (2023) identified the requirements for a DPP system through stakeholder involvement, consultations with industry experts, and current literature science. They conducted a state-of-play analysis and developed an overview of the current discussion on requirements. In addition, they formulated problem statements based on the analysis and created a template and guidance to improve circularity data sharing efficiency. Furthermore, Heinrich & Lang (2019) and Zabek et al. (2023) incorporated performance indicators derived from legal frameworks and LCA methodology. They summarised these indicators, including a description and recommended actions for product manufacturers to achieve the targets. Nevertheless, all of them provide a foundation for further research on DPP system requirements.

The research results present a best practice summary of the required circularity data for generic CMCWs and their possible DPP in the annexe section, table A3-A4.

4.2 DESCRIPTION OF THE LCI FLOWCHARTS

To move forward with this semantic framework development, the second step of the methodology consists of creating a clear and simplified Life Cycle Inventory (LCI) plan. This plan has to include all possible flowcharts for each component and operation within the analysed productive processes and the required environmental and circular design details for an accurate LCA. That implies defining categories of components and operations through the life cycle. Some will denote physical product elements (e.g. extruded profiles, glass), and others will denote the operations and organised activities (e.g. manufacturing, varnishing) associated with the product entity (Tao et al., 2017). This is by identifying physical dimensions compatible with the calculation of the impact categories of the LCA that will characterise the following data collection (Famiglietti et al., 2022; Rovelli et al., 2022). This methodological step is important in the development of the SDF because it aims to lay the basis for the forthcoming executive structure of the data to be collected and suggests the ontology with which the data are to be related to each other.

Afterwards, once the SDF is integrated into a performing tool, design parameters must be established by designers based on their interests or on the impact of the outcome, either through research or previous use of the method. Each parameter's values should be qualified or quantified within specified boundaries, chosen in accordance with the designer's expertise (Jusselme et al., 2018). Moreover, considering the scope of the tool, in the first phase, it is also important to identify the standards that the customer and general contractor have requested, which must be considered during all the further project stages.

4.3 IDENTIFICATION OF THE DATA SOURCES AND COLLECTION

At this stage of development, the preparatory phase is considered complete, and the data collection necessary for the analyses can begin. To do this, the first step consists of the breakdown and analysis of project commission jobs, identifying the business departments that manage the required data for the assessment and the departments that need the data. It is crucial to determine the pieces of information that can be directly obtained from business commissioning management systems and through databases, spreadsheets and documents from the company (Zaffagnini & Morganti, 2022; Rovelli et al., 2022). Instead, data that cannot be acquired directly from these systems must be implemented from literature and external databases or estimated using average values (Famiglietti et al., 2022). Typical data references for any required information have been identified and listed in tables A1 to A4 in the annexes.

The method proposed in this paper involves a data retriever from different sources in two feature-based databases to support the SDF, prepared for integration according to the LCI (Tao et al., 2017), which has been developed in the second step. This can also be done through ETL processes (Extract, Transform, Load), which involve extracting data from one or more sources with different structures or formats, transforming it as needed, and loading it into a unified target database. This replication approach is useful when real-time synchronisation or high availability is required.

There were various reasons for transferring the data to the two different databases instead of linking the SDF directly to the identified sources, such as computer-aided technologies:

1. It allows for more user-friendly management by operators who may need to interact directly with this data but do not have the necessary technical skills to understand all the sources from which these data come (e.g., an IT technician who is unable to comprehend a complex technical drawing).
2. It allows the customisation of data collection databases to be compatible with the unique semantic languages production companies utilise in their operational processes. Additionally, the database architecture, storage capacity, and processing power can be adapted to handle the growing volume and complexity of data without relying on external providers.
3. It allows for consolidating data from external databases and private production datasheets, which may contain confidential information, e.g. about suppliers. By creating a dedicated database, companies can implement necessary compliance measures to ensure control over data privacy and meet requirements imposed by data protection laws and intellectual property rights.
4. It allows for more protection than relying on third-party solutions. With a dedicated database, companies can implement encryption techniques and access controls and authentication protocols to safeguard sensitive information.
5. It allows for the necessary measures to be taken to meet legal standards, particularly for production companies that deal with sensitive information and must comply with strict regulations within their respective industries.

As mentioned, the proposed methodology implies the development of two databases, one to organise the project data related to each production company's commission job and the other to collect the environmental and circularity data in one single place (FIG. 6). The environmental and circularity database is designed to be unique for each production plant or industry and contains at least four datasets. (1) The first dataset must contain information about each possible single component of CMCWs relating to phases A1, C3, and C4 of the life cycle. Likewise, (2) the dataset related to the construction site options must contain data about all the working activities that the module can refer to. (3-4) The transport and production data can be stored in two different datasets.

On the other hand, project data needs to be separated into different databases for each commission job. That is due to the need for datasets for each type of CMCW designed, containing its bill of materials, components, and processes. Moreover, a dataset for each module is needed to contain information on its construction activities. The other two datasets related to project data are unique for commission jobs and contain information about the logistics and production of the modules.
In order to ensure the effective management of data in various datasets, each data string is assigned a unique code (@id) associated with the relevant information. This code may also coincide with the alphanumeric codes utilized by the manufacturing companies in their computer-aided technology systems. Such a practice is crucial for accurate data identification and retrieval, thereby enhancing the overall efficiency of data management processes.

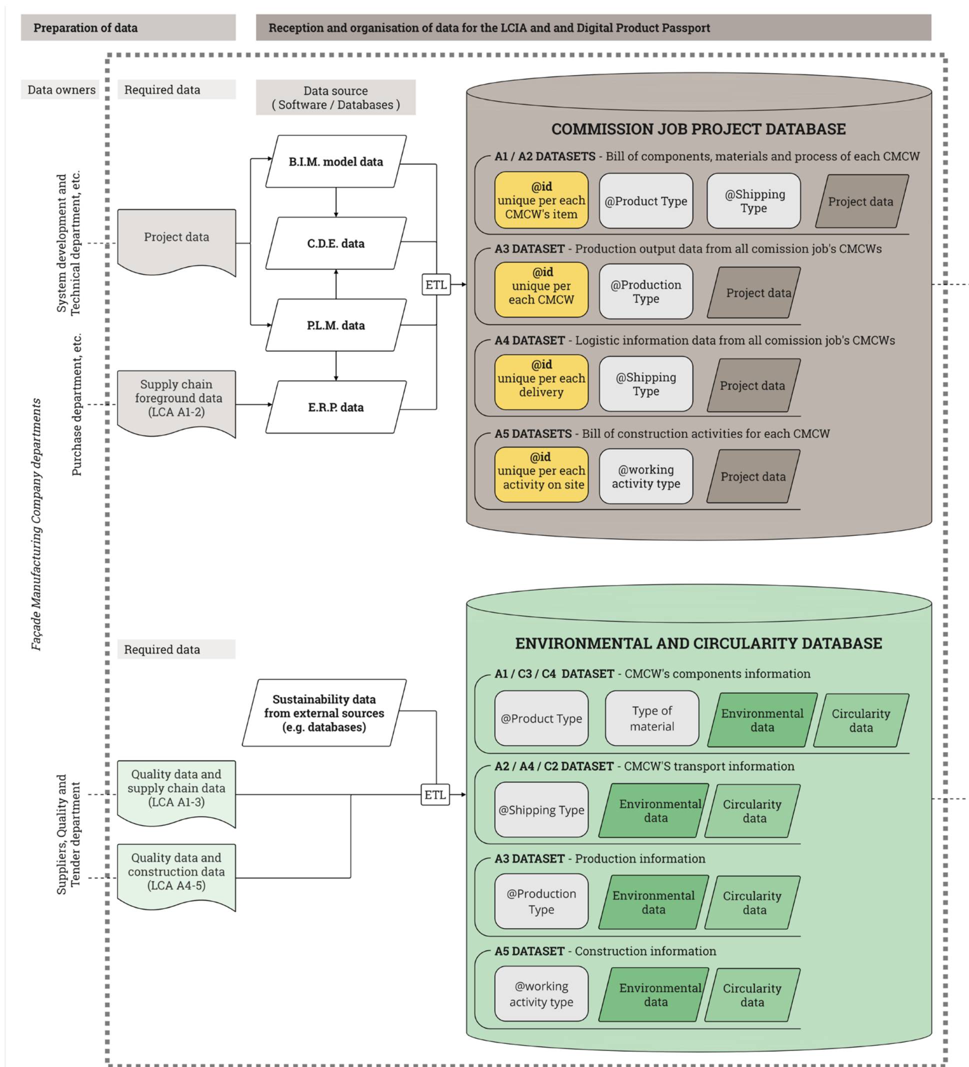

FIG. 6 Schematic flowchart of Project, Environmental, and Circularity data flow to the databases and their related datasets on which the SDF is based. It is a more detailed representation of Figure 5 concerning the stage of receiving and organising data.

The difference between the proposed databases and a data warehouse–in computing known as a reporting system used for data analysis essential in business intelligence–is that their data cannot be "read-only", because for some kind of components or processes, an update or delete action could be necessary for that step (Dedić & Stanier, 2016).

4.4 ONTOLOGY AND SEMANTICS OF THE DATA-DRIVEN FRAMEWORK

To best describe the next step of the methodology, it is helpful to examine the flowchart concerning the processing and computation of the collected data (FIG. 7).

The SDF is designed to start with the input of the identification module code of the CMCW that has to be analysed. In the computer-aided technology software typically used by companies operating the code of a CMCW, it is possible to trace back all its life cycle characterisations. As an illustration, the aforementioned module code may be utilised to identify the CMCW in the corporate Product LifeCycle Management (PLM) software. But also its components and processes, how it will be produced, how it will be shipped, and what activities it will be subjected to on the construction site. All attributes of these pieces of information must be related to the correct environmental data. Under the designer's supervision, this can be done automatically if there is an unambiguous correspondence or manually if the database contains more than one option. To develop this system, it is necessary to define ontology classes for the procedure, both during the collection of information in the respective databases and later during the development of the framework.

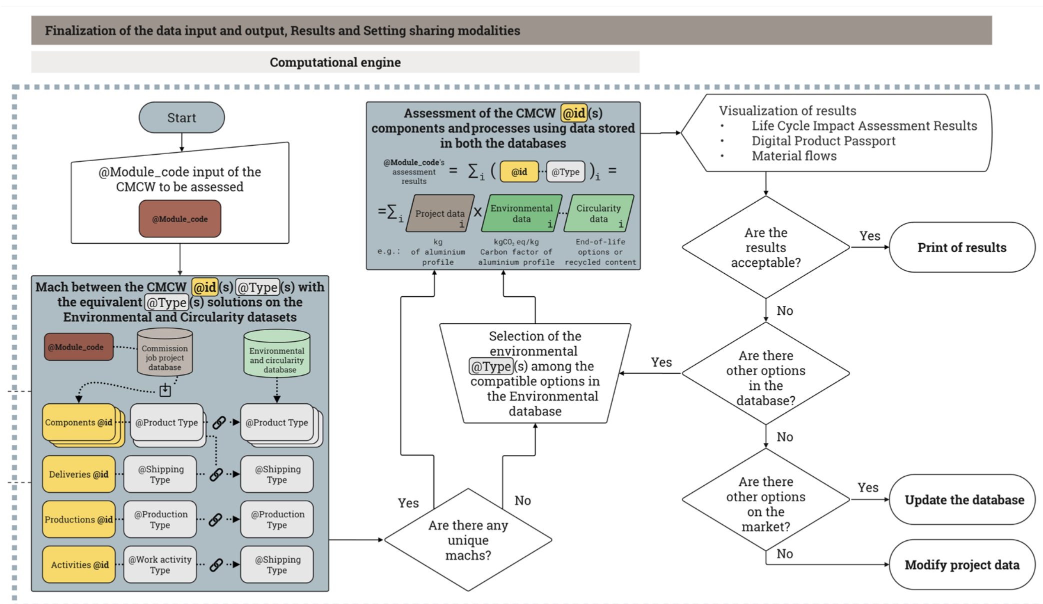

FIG. 7 *Schematic flowchart of the final stage of the SDF, in which data are correlated to obtain the results of the analysis. It is a more detailed representation of Figure 5 concerning the stage of finalisation and results visualisation.*

Ontologies are conceptual vocabularies used to represent knowledge and facilitate data exchange and interoperability across multiple databases. They provide a level of abstraction above specific database designs, enabling data to be exported, queried, and unified across independently developed systems (Gruber, 2008).

In order to achieve efficient management and evaluation of project and environmental data, it is crucial to comprehend their interconnection. This stage establishes the groundwork for acquiring valuable insights. During the SFD creation, it is essential to opt for features and advancements that correspond with the metrics the designer intends to analyse (Jusselme et al., 2018). This applies not only to LCA engines but also to circularity assessment tools. Moreover, regarding circular aspects, Kedir et al. (2021) have developed an ontology-based framework to gather DPP-related information for industrialised construction products. They have found that it is essential to identify the functional levels of buildings and collect their property attributes at each level. Additionally, property attributes may have varying values during different stages of the building's life cycle, so it is crucial to fill in the corresponding life cycle for each value. Typically, representational primitives comprise classes, attributes, and relationships among class objects. Therefore, for each dataset included in project and environmental databases must be defined classes that facilitate database integrations through their attributes and the definition of rules depending on the kind of component or material.

A structured framework for data collection for comparative design evaluations defined by Mandolini et al. (2019) aims to manage and share life cycle information along the product development process. Their framework defines classes and attributes that represent the product structure. Attributes, describing relevant characteristics such as the data that have been previously identified and collected, define a list of features necessary to uniquely identify a class and allow mapping the relation with others linked. For instance, this can mean functional units with which to relate design data and carbon factors or end-of-life documents. Furthermore, the list of attributes can be customised by adding or removing attributes to suit the specific product and application context.
In this SDF, classes are called types (@type), which include @product type, @shipping type, @ production type, and @work activity type.

Interoperable connections between data sources internally and externally need proper semantic methods to ensure unambiguous and consistent mapping. Going towards automation in Industry 4.0, the interconnections between systems are central. One of the challenges facing the use of data templates and DPPs is the absence of standardisation, which could promote the implementation of passports, but aligning existing concepts and identifying overlaps remains challenging (Honic et al., 2024). Open Platform Communications Unified Architecture (OPC UA) evolved around companion information models to align the industry and create an extensible framework to enable continuous integrations. Furthermore, additions to the OPC UA standard (Part 14 "PubSub") promote IoT connectivity over the Internet, extending the Operational Technology (OT) from on-site factory data pipelines to distributed and decentralised architectures. Connections between OT and IT departments are increasingly common and unlock the potential to break up vertical silos for business operations and supply chain collaboration on the information system level. When OT connects to the channels of decentralised infrastructure, great opportunities emerge for data-driven solutions, such as dynamic value chain evaluation networks. This also increases the need for semantic interoperability using namespace prefixes as the semantic meaning of data payloads is likely different between systems or actors in an extended network and consequently cannot be controlled like the manufacturing company of CMCW itself. Several standards are emerging to leverage IoT messaging using semantic JSON payloads.
After thoroughly analysing IT-related protocols and their connection to OPC UA and industrial operations, a clear correlation has been established between the world of semantic web technology standards and various systems utilised in manufacturing operations, such as Computer-aided technologies (e.g. ERP, MRP, and CRM). The compatibility of many of these systems with the REST API over HTTP protocol using JSON serialisation has caused a recent surge in integration solutions, showcasing the potential for further development. Moreover, the concept of "context broker" is used in the area of connected digital twins as a concept of sharing the data with the metadata needed to distribute the context together with the universally identified mechanism required (W3C, 2020).

The JSON-LD standard is a way to contextualise JSON properties with namespaces to identify entities and their types. Looking at the @id and the @type handles to define identities and pointing to a specific instance is possible to further the semantic connections. Data from relational databases,

spreadsheets or graph data structures can be hooked into a mapping process of either "knowing" or "not yet knowing" item's identity, iteratively working towards an agreement between actors and data sources to formalise the connections. More significantly, in this framework, the semantic model is not modelled top-down but instead aims at an increasingly better understanding using data contexts. As the semantic structures of various processes become confident and additional data sources, actors, and products are incorporated into the decision-making process, automation can be extended to more tasks.
Using the @id and @type, a row in a database or spreadsheet is a well-defined entity in the context of well-known operations. The next step would be to harmonise and align with other datasets to see if this represents the same or similar thing in these vocabularies. Using ontologies, the formal definition of contextual descriptions, and machine-readable logic can assist with this validation. Furthermore, the ontologies must be made understandable by users as the conceptualisation of "real things". This is how workers from different departments or companies with different backgrounds will understand each other in the collaboration to improve the sustainability implications of operations, processes, and LCA between co-workers, executives, and stakeholders. Utilising pre-existing ontologies is highly desirable as it covers many domains and promotes better interoperability and automation with greater industry convergence. However, the human knowledge process in collaborative efforts is often overlooked as ontologies are typically created and used by a small group of experts, leading to accessibility issues for the industry. Hence, the proposed framework prioritises knowledge acquisition and collaboration through co-creating information models instead of mandating ontologies from the outset.

Moreover, emerging trends in ontology layering indicate a preference for starting at the first level closest to the application and moving towards strict formal descriptions using first-order logic. This approach enables the establishment of principles for ontology connections rather than the unnecessary expansion of ontologies. A modular approach can be taken, using domain-level ontologies to cover various phenomena along the supply chain. However, a local scope can be maintained at the application level to address specific problems and proposed solutions. The application-level ontologies can be connected to domain-level ontologies or the more abstract middle-level ontologies, which are aligned with top-level ontologies that are mathematically proven to be consistent.

4.5 VALIDATION OF THE FRAMEWORK TESTING THE ONTOLOGY

To validate the presented methodology and the SDF architecture, an assessment of CO_2eq emissions associated with the manufacturing, transportation, and installation of the modular façade system was carried out. The assessment was performed through the GWP A1-A5 calculation of some demo CMCWs and related circularity data collection. This phase aimed to evaluate the framework by defining the appropriate @type for each process category or component to be assessed and defining an ontology that binds them together in a workable manner.

The object of the analysis was the curtain wall modules façade of the demo house built during the H2020 Basajaun project, to be constructed in the village of Le Pian-Médoc (Nouvelle-Aquitaine, France). For this, eight different types of CMCWs were designed and fabricated for the building (Figure 8). Two of these were used to validate the proposed SDF: an Opaque Vertical Module without any glazing and a Window Module containing both glazed and opaque elements. Finally, a Glazed Vision Module, primarily composed of glass and designed for another demo building that was planned to be built, was also used to validate the framework.

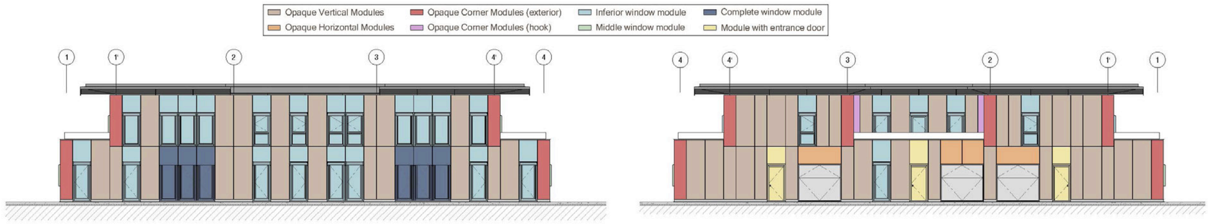

FIG. 8 *Schematic representation of the French demo building elevations showing the CMCWs developed in the Basajaun project. The two module types used in the validation depicted here are the ones named "Opaque Vertical Module" and "Inferior window module".*

According to the methodology logic, two databases were manually constructed, containing essential data for the analysis: one pertaining to design data and the other to environmental and circular data. No ETL systems were used during the validation phase of the framework. Instead, the users re-processed the information collected in the databases themselves.

The Project Database comprised six datasets:

A Three "A1 / A2" datasets corresponding to components within the selected CMCW for framework validation. These datasets included supplier information along with transportation details.
B An "A3" dataset detailing the assembly of modules in the manufacturing facility, including the average energy consumption in kWh per square meter of the assembled module (or Factory Energy Intensity).
C An "A4" dataset containing information related to module transportation to the construction site, including the transported weight and the distance.
D An "A5" dataset encompassing details of on-site operations necessary for module installation and related energy consumptions.

On the other hand, the Environmental and Circularity Database consisted of four datasets:

A An "A1" dataset containing Embodied Carbon Factors (ECF) or GWP Unit values related to the analysed module's possible components. In addition to these, information related to the circularity of products and processes was also collected. Where applicable, for example, an attempt was made to keep track of the presence or absence of product EPDs, percentages of recycled material, and description of the disassembly procedure recommended by suppliers. For products for which EPDs were available, data on other environmental impacts (e.g., water consumption) were also collected.
B An "A2 & A4" dataset containing the Transport Emission Factor (TEF) of the transportation mode used.
C An "A3" dataset and an "A5" dataset with respective Grid Carbon Factor (GCF) values for the module manufacturing facility and the construction site.

Due to their complexity, the three Basajaun CMCWs proved to be an ideal use case. Upon exporting the bill of materials for each module from the Enterprise Resource Planning (ERP) and Product Lifecycle Management (PLM) systems, the Opaque Vertical Module revealed 44 unique components, the Window Module 81 and the Glazed Vision Module 52. These components (and processes) consist mostly of frame profiles, insulation equipment, glass, and seal systems. It is worth noting that some of these components share the same characteristics but appear in different modules. Each component and process is linked to a database string associated with a unique @id. An ontology was developed to simplify the association of strings, and @type assignments were made for each data string in both databases. Additionally, Reference Measurement Units were defined in both datasets to facilitate the correlation of Functional Units.

The subsequent tables provide concise summaries of the @types defined for each lifecycle stage during the validation process and the mandatory Reference Measurement Units needed to calculate the GWP depending on the database. Lastly, it is critical to underscore that the quantity (Qi) at which a particular component or process is employed in the production of the façade module must be explicitly stated, even though it may be a straightforward notion.

4.5.1 A1 - Components supply and related processes

TABLE 2 Summary of the identified @product type(s) related to phase A1 of the life cycle

@product type	Mandatory UoM (Project data)	Mandatory UoM (Environmental data)	Notes
PreassembledProduct or CommercialProduct	none	A1-A5 GWP [kgCO2eq /quantity] or, alternatively: ECF for the material [kgCO2eq /quantity]	As a Preassembled Product (or as a single commercial product), the unique factor is the quantity. During the finalisation, it will probably be necessary to consult technical drawings or product sheets to select adequate corresponding @types.
IGU	UoM Surface [m2]	A1-A5 GWP [kgCO2eq /m^2] or, alternatively: ECF for the material [kgCO2eq/m^2]	It will probably be necessary to consult technical drawings to determine the composition of the Insulated Glass Unit because it is not always specified in framework references (e.g., ERP).
Finishing or Machining	UoM Surface [m2]	A1-A5 GWP [kgCO2eq/m^2] or, alternatively: ECF for the material [kgCO2eq /m^2]	If the treatment is applied to a profile with a channel section, UoM thickness indicates the profile's thickness and length and width indicate its max dimensions.
Extruded&Pultruded	UoM Mass [kg], UoM Height [mm]	A1-A5 GWP [kgCO2eq /kg] or, alternatively: ECF for the material [kgCO2eq /kg]	
Panels&Materials	UoM length [mm], UoM width [mm], UoM thickness [mm]	A1-A5 GWP [kgCO2eq /m^3] or, alternatively: ECF for the material [kgCO2eq /m^3]	Mostly rectangular blocks made of singular or composed materials.
Tapes&Sealants	UoM width [mm], UoM Height [mm]	A1-A5 GWP [kgCO2eq /m^2] or, alternatively: ECF for the material [kgCO2eq/m^2]	This could also include sheets.

$$GWP_{A1} = \sum_{i} [Q_{i} \times {}_{component}UoM \times GWP_{A15i}] + \sum i \, [Qi \times {}_{component}UoM \times ECF_{A13i}] \quad (1)$$

Equation 1 calculates the total A1 GWP by summing the contributions of each @product type, considering the quantity, the specific reporting unit factor for that @product type, and the corresponding A1-A5 GWP or A1-3 ECF for each component.

4.5.2 A2 - Transport to factory

TABLE 3 Summary of the identified @shipping type related to phase A2 of the life cycle

@product type	Mandatory UoM (Project data)	Mandatory UoM (Environmental data)	Notes
Components_Lorry_avg	Transport Distance (TD) [km]	Average km TEF [kgCO2eq /km] (Transport Emissions Factors = TEF)	No specific data about the type of large goods vehicle (lorry) used for the components' supply have been collected for the validation assessment. A standard lorry has been assumed for all the components.

$$GWP_{A2} = \sum_i [Q_i \times TD \times TEF] \quad (2)$$

Equation 2 calculates the total A2 GWP associated with transporting components to the façade manufacturing plant using an average large goods vehicle. It considers the quantity of each component, the transport distance, and the Total Emission Factor associated with the average large goods vehicle used for transportation.

4.5.3 A3 - Manufactory (fabrication and assembly)

TABLE 4 Summary of the identified @production type related to phase A3 of the life cycle

@product type	Mandatory UoM (Project data)	Mandatory UoM (Environmental data)
Production_line_2021	UoM Surface (S) [m2], Average Consumption per m^2 [kWh/m2]	Generated electricity carbon factor (GECF) [kgCO2eq/kWh], Off-site waste emissions [%]

$$GWP_{A3} = (Q_i \times S \times Average\_Consumption\_per\_m^2 \times GECF) + Off\text{-}site\_waste\_emissions \quad (3)$$

Equation 3 assesses the environmental impact of the assembly and production process of the CMCW by considering the energy consumption per square meter, carbon factor associated with electricity generation, and off-site waste emissions.

4.5.4 A4 - Transport to site

TABLE 5 Summary of the identified @shipping type related to phase A4 of the life cycle

@product type	Mandatory UoM (Project data)	Mandatory UoM (Environmental data)
Lorry_Euro_5_avg	Transport Distance [km], UoM Mass [kg]	TEF (km•Kg) kgCO2eq /km•kg] (Transport Emissions Factors = TEF)

$$GWP_{A4} = \sum_i [Q_i \times TD \times mUoM \times TEF] \quad (4)$$

Equation 4 calculates the total GWP associated with the transportation process using an average Euro 5 large goods vehicle. It considers the quantity, transport distance, mass of shipped items, and the emission factor specific to the type of lorry and the mass of items transported.

4.5.5 A5 – Construction

TABLE 6 Summary of the identified @working activity type related to phase A5 of the life cycle

@product type	Mandatory RMU (Project data)	Mandatory RMU (Environmental data)
Pallet_truck_use	Machine or plant usage time (MT) [hours], Ren. Energy cons. [kW], Non-Ren. Energy cons. [kW], Fuel consumption (uFC) [litre]	Generated electricity carbon factor (GECF) [kgCO2eq /kWh], or, alternatively: Grid carbon factor (GCF) [kgCO2eq /kWh] site waste emissions [%]
Pick&Carry_Crane,2t	Machine or plant usage time (MT) [hours], Ren. Energy cons. [kW], Non-Ren. Energy cons. [kW], Fuel consumption (uFC) [litre]	Generated electricity carbon factor (GECF) [kgCO2eq /kWh], or, alternatively: Grid carbon factor (GCF) [kgCO2eq /kWh] site waste emissions [%]
Boom_lifter_use	Machine or plant usage time (MT) [hours], Ren. Energy cons. [kW], Non-Ren. Energy cons. [kW], Fuel consumption (uFC) [litre]	Generated electricity carbon factor (GECF) [kgCO2eq /kWh], or, alternatively: Grid carbon factor (GCF) [kgCO2eq /kWh] site waste emissions [%]

$$GWP_{A5} = \sum_i [Q_i \times m_{Average\_Consumption} \times GECF] + site\_waste\_emissions \quad (5)$$

Equation 5 comprehensively assesses the environmental impact of different working activities, considering both energy consumption and on-site waste emissions. The summation of different working activities allows for a holistic evaluation of the overall contribution to global warming potential associated with the specified activities. It is possible to calculate the GWPA15 result by summing the GWPs obtained from applying all five equations.

The simplification of the company's practice has had a significant impact on the analysis, especially in the life cycle stage A1. Previously, 177 unique objects with individual article numbers, as translated by @id, were identified in the first dataset. However, the process has now been streamlined to six categories with unique rules (i.e., @product types), which include components and processes. Meanwhile, on-site installation activities have been reduced from four @id to one @ working activity type. As this was the first time the framework was defined for the manufacturing company, data had to be manually searched for within the company software. The tables in annexes' Tables A1-A4 provided the typical data reference for each data type. However, with the systematization of the framework, this data transposition can now be automated with an ETL system, further increasing the time saved during assessments. Additionally, organising data in this manner makes it easier for non-technical personnel to access information related to environmental impacts and circularity.

5 DISCUSSIONS

Measuring a product's environmental impact through primary data has been confirmed as a best practice (Silva et al., 2020). However, retrieving project data has been found to require less effort than environmental data. This is because project data is readily available in the company's software systems, whereas environmental data may be more demanding to obtain due to various factors such as data availability, reliability, and accessibility. Integrating project data and primary data declared directly by suppliers can significantly enhance the environmental assessment process and make it more cost-effective compared to relying solely on tools available in online databases

(Morganti et al., 2023). While suppliers may have access to data that can contribute to a more holistic assessment, these are typically limited and require additional verification and integration; they often lack comprehensive LCA data on several impact factor indicators besides global warming potential. An ecological approach can be easily implemented during various stages of the product's life cycle. By considering environmental factors from the early design phase to manufacturing, distribution, and end-of-life (EoL) management, companies can identify opportunities for reducing environmental impacts and promoting sustainability. Moreover, one of the challenges lies in including information about costs associated with each stage of the product's life cycle (Amon et al., 2021). Without sellers involved in the data collection, economic data related to the supply chain would be typically retrieved from Enterprise Resource Planning Software, which tends to be focused on past purchases and may not accurately reflect current market variations. This can lead to misleading cost analyses and hinder the integration of cost considerations into environmental and circularity assessments.

Improving strategies for the EoL management of construction products is crucial for promoting their circularity and increasing value creation after dismantling (Giovanardi et al., 2023b). Actors who play a vital role in Digital Product Passports (DPPs) should be identified and assigned responsibilities. By involving stakeholders throughout the product's life cycle, such as designers, manufacturers, and managers, companies can ensure comprehensive data collection and utilisation for circular industrialised construction products, such as CMCW. For instance, the Material Passport Ontology provides a structure that offers guidance to industrialised construction firms on how to design, produce, and manage circular products effectively (Kedir et al., 2021). An outcome DPP should include specific data for its components and materials and instructions for repairing and disassembly. This comprehensive information can incentivise the creation of closed life cycles for product components, increasing the overall circularity of the entire module. Additionally, a digital building logbook can be utilised to document relevant information about buildings, their components, and maintenance activities, supporting ongoing sustainability efforts. The type of data selected and represented in annexe Tables A3 and A4, related to the design data according to a precise ontology within the proposed Semantic Data-driven Framework (SDF), would facilitate all these developments of the DPP and draft its semi-automatic realisation for both façade models and their components. Furthermore, the development of qualitative or quantitative circularity Key Performance Indicators (KPIs) can be linked to the circularity information values captured in the product passport. This will allow companies to track and measure their progress towards circularity goals, providing insights into the effectiveness of their sustainability initiatives.

Regarding data portability, further research is needed to establish common technical standards that facilitate seamless data transfer from one data controller to another. This can include the ability to export data into user-accessible local files, promoting interoperability between different systems, and enabling searchability through sophisticated tools. By addressing data portability challenges, companies can enhance the accessibility and usability of environmental data, fostering collaboration and knowledge sharing within the industry. As mentioned, in Industry 4.0, the connectivity between systems is crucial for moving towards automation. Open Platform Communications Unified Architecture (OPC UA) has developed companion information models to bring the industry together and establish a scalable framework that allows for seamless integration. Implementing such standardised languages can accelerate the processes of environmental data evaluation and dissemination.

The primary limitations that need to be addressed for its successful implementation are mainly technical. One of the primary technical limitations is the need of the involved companies to acquire computational-aided technologies aimed at managing the commission job and its specific aspects if the company does not already have it. This requirement can pose a challenge for small enterprise organisations that do not already possess the necessary software infrastructure or have insufficient financial resources. Additionally, developing the implementation framework requires interdisciplinary skills from the technicians or team responsible for its design and ontology development. These skills include a deep understanding of the business organisation, environmental impact assessment, circular economy approach, and some expertise in the software involved. Furthermore, the approach necessitates the involvement of IT engineers responsible for managing the data workflow, organising and structuring the data, and establishing relationships between different data elements following the Life Cycle Inventory needs. The success of this process relies on extensive collaboration among all roles and departments within the company. Effective communication and cooperation are essential to ensure a cohesive and integrated approach. This could also be extended to the supply chain actors besides the company's internal departments. It is important to acknowledge the initial commitment of time and resources required to set up the design software system. This includes incorporating both standard and eco-design tools to enable the reading, completion, storage, and collaboration of the life cycle standard data model. The company needs to allocate sufficient resources to implement and maintain this system effectively.

Although the proposed approach offers significant benefits in framing environmental impact reduction options in the life cycle of façade modules, it is currently hardly applicable on an entire building scale. The complexity and uncertainties associated with large-scale building projects make it challenging to implement this approach effectively. Because it would require the retrieval of detailed data from the entire supply chain of all contractors involved in the construction, it would be a compelling development for the future. However, it can be already highly valuable for early eco-design assessments, where there is a higher degree of control over the supply chain. During the initial stages of the design process, the approach can provide helpful insights and inform decision-making regarding sustainability concerns.

Considerations of temporal aspects play a significant role during the commissioning process, influencing the dynamic modelling of systems and impacts (Beloin-Saint-Pierre et al., 2020). This includes understanding the differences and establishing links between preliminary studies, ongoing flowcharts, and practical completion flowcharts. As the project develops, the source of data may change, and it is crucial to account for these potential variations. Flexibility in the approach is necessary to accommodate evolving data sources and ensure the accuracy and relevance of the analysis throughout the project lifecycle.

Another critical factor to consider in the field of industrial innovations is the marketability of software implemented using the SDF. Currently, it is difficult to envision a readily available digital product tool in the market that can undertake the comprehensive analysis required for sustainable design with omni-comprehensive data. The complexity arises from the need to integrate and analyse data from various databases, which could be public, owned by individual production companies, or subject to licensing agreements. In the absence of a standardised approach or shared database, it is more likely that each company involved in complex custom-building products will develop its own databases to meet its specific requirements. Therefore, they are not set up for the automatic and semi-automatic data exchange as proposed here. However, if environmental database owners were to share their data more openly, it would facilitate the establishment of more precise benchmarks for sustainable future development. Collaboration and data sharing among stakeholders could lead to a more comprehensive understanding of the environmental impact of building materials and processes, fostering a collective effort towards sustainable practices.

6 CONCLUSIONS

This study has presented a comprehensive methodology for developing and implementing a semantic data-driven and LCA-based framework (SDF) to develop low-carbon and circular Custom prefabricated Modules for Curtain Walls (CMCW). This framework can be considered a fundamental part of developing digital eco-design tools to support design. The findings highlight the importance of a primary data recovery framework and collection through integration with the project and environmental data stored in the manufactory company's computer-aided technology software—in addition to adopting an ecological approach throughout the product's life cycle. By obtaining primary data directly from their IT management systems and suppliers, companies can enhance the assessment process and obtain more reliable and detailed information about the environmental impacts and circular End-of-Life options of CMCWs. This approach allows for a more comprehensive and precise evaluation of impact factors such as Global Warming Potential (GWP), water consumption, waste generation, construction time, and productivity. At the same time, it would gather data that can be automatically organised into a Digital Product Passport (DPP) for the custom façade module and its components and materials. In the future, disassembly and reverse logistics will be simplified with this kind of approach. Additionally, it will aid the development of a Digital Building logbook to keep track of buildings.

Integrating semantic web technology standards and ontologies offers significant potential for facilitating collaboration, automating processes, and improving sustainability implications in operations and supply chains. The use of ontologies and semantic models enables the effective management and exchange of data between different systems and actors involved in the assessment process. However, it is important to acknowledge the technical limitations and challenges associated with implementing such a system, ensuring data portability, and establishing common technical standards. Moreover, at this research stage, the SDF is designed to assess and support Façade Design for production and construction management and innovation. Implementing it on a building scale presents challenges due to the complexity and uncertainties associated with large-scale projects. Further research and adaptation of the methodology are needed to address these challenges and enable the assessment of sustainability implications at a broader scale. Additionally, the proposed methodology and framework rely on the availability and reliability of data from various sources. Obtaining comprehensive and up-to-date data can be challenging, and data collection processes may require significant effort and resources. Furthermore, the marketability and widespread adoption depend on the willingness of companies to share data and collaborate transparently. Overcoming these data-related challenges and fostering a culture of data sharing and collaboration within the construction industry is crucial for realising the full potential of data-based ecological approaches, such as the one presented.

In conclusion, this study contributes to the field of sustainable design and assessment of CMCW by providing a development methodology for an eco-design framework aimed at evaluating environmental and circular aspects. The integration of primary data, project data, and an ecological approach enables a comprehensive analysis of the environmental impacts of CMCWs throughout their life cycle. Despite the acknowledged limitations, this research provides a foundation for future developments in data-driven sustainability assessments and circularity in construction façade technologies, with the potential to drive positive environmental and economic outcomes in the industry.

Credit author statement

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Data Availability Statement

The datasets collected during the validation of the framework and openly available have been published in the Zenodo repository under the title: "Project Database and Environmental and Circularity Database containing information on Basajaun Façade System Modules" (DOI: https://doi.org/10.5281/zenodo.10557349).

Furthermore, the results of the validation step concerning Global Warming Potential measurement of modules' life cycle stages from cradle to practical completion (A1–A5) and their related circularity insights have been published in a paper titled: "A1–A5 Embodied Carbon Assessment to Evaluate Bio-Based Components in Façade System Modules" (DOI: https://doi.org/10.3390/su16031190).

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ANNEXES

TABLE ANNEX. A1 Summary of the required CMCW project data

CMCW PROJECT DATA				
Information required	**Information Description**	**Physical Dimension**	**Typical data reference**	**Ref.**
A1 - COMPONENTS SUPPLY				
Curtain wall framing (Qty)	Transom, Mullion, Intermediate transom, Cover caps, Trims, Beads, Thermal breaks, Gaskets, Others.	Qty, m, kg, ...	Company's PLM and ERP, Technical drawings, BIM model	1, 2, 3
Glass (Qty)	Glazing (inner laminate), Glazing (outer laminate), Spacer, Others.	Qty, m^2, m, kg, ...	Company's PLM and ERP, Technical drawings, BIM model	1, 2, 3
Mechanical joints (Qty)	Sealant, Glue, Gaskets, Others.	Qty, kg, ...	Company's PLM and ERP, Product's Datasheet, Technical drawings, BIM model	1, 2, 3
Spandrel (Qty)	Insulation, Aluminium panel, Steel back panel, Acoustic board, Fixings, Trims, Beads, Others.	Qty, m^2, m, kg, ...	Company's PLM and ERP, Technical drawings, BIM model	1, 2, 3
Architectural features (Qty)	Petal fins, Horizontal fins, Vertical fins, Support brackets, Spigots, Trims, Caps, Others.	Qty, m^2, m, kg, ...	Company's PLM and ERP, Product's Datasheet, Technical drawings, BIM model	1, 2, 3
Others used on site (Qty)	Fire floor-stop, Support bracket (plate, cast-in channels, anchors, bolts), Fixings, Membranes, Sealing tape, Coping, Weather protection, Others.	Qty, m^2, m, kg, ...	Company's PLM and ERP	1, 2
A2 - TRANSPORT TO FACTORY				
Component / Material transportation distances	Distances covered by components and materials to reach the factory. Different kinds of assessment are required for trains, roads and boats.	km	Company's PLM and ERP, DDT, Departments worksheets	1, 2, 3
A3 - MANUFACTORY (FABRICATION + ASSEMBLY)				
Factory energy intensity per assembled module (mFEI)	Energy consumed during production and assembling of the module.	kWh/module, kWh/m2	Electricity bill kWh data divided by the number of modules or m^2 produced	1, 2, 3
A4 - TRANSPORT TO SITE				
Module transport distance	Distances covered by the modules to the construction site Different kinds of assessment are required for train, land and ship.	km	Company's PLM and ERP, DDT, Departments worksheets	1, 2, 3
A5 - CONSTRUCTION / INSTALLATION (SITE EMISSIONS)				
Machine or plant usage time per module installed (MT)	Assumed and real construction site hours. Considering machinery rental and construction site's Gant chart.	h	Production and construction company	1, 2, 3
Fuel consumption per module installed (mFC)	Litres or kWh of consumption over the entire duration of activity. Considering vehicle rental and construction site's Gant chart.	kWh, litre	Production and construction company	1, 2, 3
B2 - MAINTENANCE				
Cleaning rate (CR)	Number of times the module will be cleaned in the future (e.g. glass) each year	Qty/years	Production company, use and maintenance regulations	1, 2, 3
Maintenance rate (MR)	Number of times the module is the object of maintenance operations each year	Qty/years	Production company, use and maintenance regulations	1, 2
Reference study period (RSP)	Representative of typically required service lives of the different building types	years	Production company, use and maintenance regulations	1, 2, 3
C2 - WASTE / DECONSTRUCTION TRANSPORT				
Materials and components (Qi)	Same list of the A1 - components supply	Qty, m^2, m, kg, ...	Company's PLM and ERP, Technical drawings, BIM model	1, 2, 3
C4 - DISPOSAL OF NON-RECYCLABLE / REUSABLE MATERIALS				
Materials and components (Qi)	Same list of the A1 - components supply	Qty, m^2, m, kg, ...	Company's PLM and ERP, Technical drawings, BIM model	1, 2, 3

TABLE ANNEX. A2 Summary of the required CMCW environmental data.

CMCW ENVIRONMENTAL DATA (e.g. data related to GWP)				
Information required	**Information Description**	**Physical Dimension**	**Typical data reference**	**Ref.**
A1 - COMPONENTS SUPPLY				
Global Warming Potential from EPDs (GWPA13,i)	Module A1-3 Global Warming Potential (GWP) of the materials (This is more reliable than ECFA13,i).	kgCO2eq/Qty, kgCO2eq/m2, kgCO2eq/kg	Supplier Components' EPD	1, 2
Embodied carbon factor for the material (ECFA13,i)	Module A1-3 Embodied Carbon Factor (ECF) of the materials.	kgCO2eq/Qty, kgCO2eq/m2, kgCO2eq/kg	Internal information or external databases (e.g. ecoinvent, ICE, CWCT)	1, 2, 3
A2 - TRANSPORT TO FACTORY				
Trasport emission factor (TEFmode)	Transport emission factor of the transportation used. Trains, roads and boats, but also if it is electric, by gas or by other fuels.	kgCO2eq/km	Internal information or external databases (e.g. ecoinvent, ICE, CWCT)	1, 2, 3
A3 - MANUFACTORY (FABRICATION + ASSEMBLY)				
Generated electricity carbon factor (GECF)	Measured as mass of CO2 equivalent emitted for each kWh of electricity generated by a local energy source or by the manufacturing plant.	kgCO2eq/kWh	Electricity production sensors (e.g. linked to photovoltaic panels)	1, 2
Grid carbon factor (GCF)	Measured as mass of CO2 equivalent emitted for each kWh of electricity generated on the National Grid.	kgCO2eq/kWh	Internal information or external databases (e.g. ecoinvent, or defra)	1, 2, 3
A4 - TRANSPORT TO SITE				
Trasport emission factor (TEFmode)	Distances covered by the modules to the construction site. Different kinds of assessment are required for trains, roads and boats.	kgCO2eq/km	Internal information or external databases (e.g. ecoinvent, ICE, CWCT)	1, 2, 3
A5 - CONSTRUCTION / INSTALLATION (SITE EMISSIONS)				
Fuel carbon factor for fuel source (FCFs)	Measured as mass of CO2 equivalent emitted for each kWh or litre of fuel per machinery activity.	kgCO2eq/kWh kgCO2eq/litre	Internal information or external databases (e.g. ecoinvent, GaBi)	1, 2, 3
Fuel consumption per module installed (mFC)	Litres or kWh of consumption over the entire duration of activity. Considering vehicle rental and construction site's Gant chart.	kWh, litre	Production and construction company	1, 2, 3
B2 - MAINTENANCE				
Cleaning emissions factor (CEF)	Measured as mass of CO2 equivalent emitted for each cleaning activity.	kgCO2eq/Qty	Internal information or external databases (e.g. ecoinvent, GaBi)	1, 2, 3
Maintenance emissions factor (MEF)	Measured as mass of CO2 equivalent emitted for each maintenance activity.	kgCO2eq/Qty	Internal information or external databases (e.g. ecoinvent, GaBi)	1, 2
C2 - WASTE / DECONSTRUCTION TRANSPORT				
Global Warming Potential from EPDs (GWPC2,i)	Module C2 Global Warming Potential (GWP) of the materials (This is more reliable than ECF).	kgCO2eq/Qty, kgCO2eq/m2, kgCO2eq/kg	Supplier Components' EPD	1, 2
Embodied carbon factor for the material (ECFC2,i)	Module C2 Embodied Carbon Factor (ECF) of the materials.	kgCO2eq/Qty, kgCO2eq/m2, kgCO2eq/kg	Internal information or external databases (e.g. ecoinvent, ICE, CWCT)	1, 2, 3
C4 - DISPOSAL OF NON-RECYCLABLE / REUSABLE MATERIALS				
Global Warming Potential from EPDs (GWPC4,i)	Module C2 Global Warming Potential (GWP) of the materials (This is more reliable than ECF).	kgCO2eq/Qty, kgCO2eq/m2, kgCO2eq/kg	Supplier Components' EPD	1, 2
Embodied carbon factor for the material (ECFC4,i)	Module C2 Embodied Carbon Factor (ECF) of the materials.	kgCO2eq/Qty, kgCO2eq/m2, kgCO2eq/kg	Internal information or external databases (e.g. ecoinvent, ICE, CWCT)	1, 2, 3

ANNEXES PROJECT AND ENVIRONMENTAL DATA REFERENCES LEGEND
References
[1] EN 15978:2011
[2] EN 15804:2012+A2:2019
[3] CWCT, et al., 2022

TABLE ANNEX. A3 Summary of the required CMCW circularity data

CMCW CIRCULARITY PASSPORT DATA				
Information required	**Type of data**	**Information description**	**Typical data reference**	**Ref.**
GENERAL INFORMATION				
Module name	Short Text, Alphanumeric data	Name of the façade module (e.g. a short description).	Production Company	3
Supplier Company	Short Text, Alphanumeric data	Name of the façade module manufacturer.	Production Company	1, 3, 5
Company contacts and production site	Long Text (Memo), Large amounts of alphanumeric data	Information that should help future stakeholders to contact the manufacturer eventually.	Production Company	3
Production date	DateTime, Date	Date in which the façade module has been produced.	Company's PLM and ERP	1, 8
Certifications	Hyperlink, Link address to the certifications of the object	Link to the environmental certification related to the module (e.g. ISO:14001, BES:6001, EPD).	Quality and Sustainability Department	1, 6, 8
Data portability	Hyperlink, Link address	Information to ensure that module data are transferable from one software system to another.	e.g., blockchain, centralised databases, centralised ledgers, OPC UA	2, 8
PHYSICAL DATA				
Dimensions and weight	Number, Numeric data	Physical dimensions useful to describe the façade module (i.e. dimensions and weight).	Company's PLM and ERP, Technical drawings, BIM model	1, 8
Bill of components/ materials	Hyperlink, Link address to the list of the objects	Detailed list of the components and materials part of the façade module. Those should be linked to their own DPP data sheets.	Company's PLM and ERP	1, 4, 5, 7
Technical drawings and 3D model	Hyperlink, Link address to the technical drawings of the object	Any kind of drawing or 3D model that can be useful in the life cycle stages of the module after the installation at the construction site.	Company's PLM and ERP	1, 7, 8
U-value of the module	Number, Numeric data	Factory thermal transmittance of the façade module (i.e. IGU, spandrel, etc.)	Production Company	8
INFORMATION ABOUT CIRCULARITY				
Disassembly methods, specialised knowledge	Long Text (Memo), Large amounts of alphanumeric data or Hyperlink	Description of the connection systems to building. Construction practices that prioritise the ability to disassemble and remove components.	Quality and Sustainability department, Technical drawings, BIM model	1, 2, 3, 4, 5, 7
Maintenance/Warranty	Number, Numeric data	Asset reference period (e.g. Every how many years maintenance is required).	Production Company, manuals of use and maintenance	4, 5
Reuse potential and recyclability	Long Text (Memo), Large amounts of alphanumeric data	Description of the second life options foreseeable during the design stage.	Production company, Quality and Sustainability depart.	1, 3, 4, 5, 7
Life span period	Datetime, Date	Date beyond which façade module becomes obsolete or unusable.	Production Company, manuals of use and maintenance	1, 4, 8
OTHER				
Products exposure history	Hyperlink, Link address to the technical drawings of the object	Information to enable real-time data (if needed), and report and documentation for prediction.	Facade Digital-Twin, sensors, owner, leasing service.	1, 2, 6, 7
Financial concepts for multiple life cycles	Long Text (Memo), Large amounts of alphanumeric data	Information about incentives or budget allocation for companies or end users to extend module lifespans through services or take-back agreements.	Production company, owner, leasing service.	4, 5, 6

TABLE ANNEX. A4 Summary of the required CMCW's components and materials circularity data.

CMCW'S COMPONENTS AND MATERIALS CIRCULARITY PASSPORT DATA				
Information required	**Type of data**	**Information description**	**Typical data reference**	**Ref.**
GENERAL INFORMATION				
Product name	Short Text, Alphanumeric data	Name of the component (e.g. a short description or a commercial name).	Component supplier's company	3, 7
Supplier Company	Short Text, Alphanumeric data	Name of the component supplier.	Component supplier's company	1, 3, 7
Source mill	Geographic data, location or area data	Geographic data about where the component materials come from.	Component supplier's company	1, 3, 4, 8
Certifications	Hyperlink, Link address to the technical drawings of the object	Link to the environmental certification related to the module (e.g. ISO:14001, BES:6001, FSC®/PEFC®, EPD, CRADLE TO CRADLE, VOC)	Component supplier's company	1, 7, 8
Data portability	Hyperlink, Link address to the technical drawings of the object	Information aimed to ensure that component data are transferable from one software system to another.	E.g., blockchain, centralised databases, centralised ledgers	2, 7, 8
PHYSICAL DATA				
Material and product composition	Long Text (Memo), Large amounts of alphanumeric data	Description of the product's material (e.g. mono-lytical material, chemical substance, potentially harmful substances, health risks)	Component supplier's company	1, 3, 4, 5, 6, 7, 8
Applied coatings or furniture	Short Text, Alphanumeric data	Description of the product's coatings or furniture (e.g. varnishing, etc.)	Company's PLM and ERP, Technical drawings, BIM model	1, 7
Relevant Physical properties	Number, Numeric data	Physical dimensions useful to describe the type of the component (e.g. weight, length, volume, surface, etc.)	Company's PLM and ERP, Technical drawings, BIM model	1, 7, 8
Technical drawings and 3D models	Hyperlink, Link address to the technical drawings of the object	Any kind of drawing or 3D model that can be useful in the life cycle stages of the component.	Company's PLM and ERP	1, 8
Pre-consumer recycled content	Percentage, Numeric data	Percentage of the pre-consumer content in the component.	Component supplier's company	3, 4, 6, 7
Post-consumer recycled content	Percentage, Numeric data	Percentage of the post-consumer content in the component.	Component supplier's company	3, 4, 6, 7
Bio-composite quantity	Percentage, Numeric data	Percentage of the bio-composite content in the material.	Component supplier's company	
INFORMATION ABOUT CIRCULARITY				
Expected material reverse stream / Waste category	Long Text (Memo), Large amounts of alphanumeric data	Description of a feasible reverse logistic foreseeable during the design stage.	Component supplier's company	5, 6, 7, 8
Reuse potential and recyclability	Long Text (Memo), Large amounts of alphanumeric data	Description of the second life options foreseeable during the design stage.	Component supplier's company	1, 3, 4, 5, 6, 7
Compostability	Yes/No or True/False	Information about the quick and complete breakdowns in a composting environment, leaving no harmful residues or by-products.	Component supplier's company	4
Life span period	Datetime, Date	Information about incentives for companies or end users to extend component lifespans through services or take-back agreements.	Component supplier's company	1, 4, 8

ANNEXES CIRCULARITY PASSPORT DATA REFERENCES LEGEND

References	Papers about tools, frameworks, or models					
	Generic Product Analysis	Specific analysis for Buildings	Circular Assessment	Sustainability Assessment	Referred to DPP	Referred to LCA
[1] Heinrich & Lang, 2019		x	x		x	
[2] Jansen et al., 2023	x		x		x	
[3] Mulhall et al., 2022	x		x		x	
[4] Zabek et al., 2023		x	x	x		x
[5] Klein et al., 2022		x	x	x		x
[6] Oluleye et al., 2023		x	x			
[7] Morganti et al., 2023		x	x	x		x
[8] European Commission et al., 2020		x	x		x	x