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ADVANCING CIRCULAR ECONOMY IN THE EXISTING BUILDING STOCK: A METHODOLOGY TO SUPPORT BUILDING CHARACTERISATION FOR SUSTAINABLE REFURBISHMENT DESIGN

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Abstract. The lack of standard practices and platforms for assessing refurbishment strategies towards Circular Economy (CE) and their impact in global warming constitutes a challenge for the decarbonization of existing building stock. Incorporating data and feedback from designers and practitioners since early design stages is important to feed a multi-criteria dynamic process with multiple dimensions, which must be assessed under a life cycle perspective. To tackle this issue, this paper introduces a new methodology to support the implementation of tailored refurbishment strategies for increased recovery, reuse and recycling of construction materials. The final objective is to build a methodological framework for sustainable refurbishment design in a BIM environment, which aims to facilitate standardized practices in the construction sector, regarding CE, with a positive impact in the mitigation of global warming and the decarbonization of the building stock. To test the development of this methodology, a case study building in Lisbon, corresponding to a 1919–1945 archetype is analysed, making use of its BIM model, where BIM standardization criteria and circularity indicators are discussed, in order to be implemented as a Plugin for Circularity.

Keywords: BIM-based platform; building archetype; building automated characterisation; CE; methodological framework; sustainable refurbishment design.

1. Introduction

Construction industry is responsible for over 30 % of the global extraction of natural resources and 25 % of solid waste generated [1], whereas only 20–30 % of construction and demolition waste is recovered [2]. Improving this situation is at the core of Circular Economy (CE), which is intended to reduce natural resource extraction, by minimizing waste, materials and energy consumption and extending and maximizing the use of materials and existing structures [3]. The CE Action Plan of the European Union manifests these efforts at the European level [4, 5].

A shared digital representation of buildings, the management of complex information in projects, and the improved collaboration and communication among stakeholders in all life cycle stages of the building are ideal processes for CE assessment in Architecture, Engineering and Construction (AEC) and can be provided by Building Information Modelling (BIM) tools. However, difficulties arise with the implementation of processes for measuring circularity in a BIM environment, from early design stages [6]. The characterisation of the existing buildings plays an important role in building refurbishment, since it constitutes the baseline scenario for circularity assessment, including deconstruction strategies and the definition of future design options, which are difficult to determine.

To overcome the described difficulties, this paper proposes a new methodology, Building Automated Characterisation (BAC), to support the implementation of tailored refurbishment strategies as a strategy for increased recovery, reuse and recycling of construction materials, and to provide quantitative information on buildings materials based on construction systems typification.

2. Background and major gaps

Developments for promoting CE in construction are still in their infancy. Typically, buildings are subject to demolition or renovation, with little or no parts that can be reused or recycled, because their different functions, systems, elements and materials are fixed in a closed structure that cannot be separated, for partial changes or disassembly, or simply because this information is not available. Moreover, there isn't yet a common methodology adopted for measuring circularity in the built environment, within its multiple dimensions [7]. The lack of standard practices for assessing refurbishment strategies towards energy efficiency and CE principles [1] constitutes a challenge for the decarbonisation of the existing building stock. Incorporating data and feedback from designers and practitioners starting from the early design stages is also crucial [3] to support a multi-criteria dynamic process with multiple dimensions, which have to be assessed under a life-cycle perspective.

The new methodology developed in this paper intends to fill these gaps and it assumes that the starting point of a refurbishment design consists in analysing existing buildings' architecture and construction systems and materials, on assessing their thermal performance, characterising its uses and their dynamic energy consumption [8]. It should allow the characterisation of existing building stock at a large scale, taking advantage of BIM, to create databases for circularity assessment adapted to existing building stock and implementing stock and flow analysis of resources and materials.

3. Methodological developments

Different existing approaches and various advancements are combined in the proposed methodology. It builds upon a method for the generation of archetypes developed by Monteiro et al. [9] for energy assessment at an urban scale and provides methodological advances to assess circularity and an information based system to provide information on materials and construction systems. The following sections detail the quantification of circularity from material to building scale and its impact on climate change, the conceptual workflow for circularity assessment in project design and BAC, and the characterisation of an existing building corresponding to an archetype.

3.1. Circularity Indicators

The adopted model for Circularity Indicators, at the core of this research, is based on Verberne [10] and Cottafava and Ritzen [11], which were developed from the Material Circularity Indicator (MCI) [12].

The MCI methodology was established by the Ellen McArthur Foundation in 2015 to measure the circularity potential at the product level, considering the mass of virgin raw material, the mass of unrecoverable waste and the utility factor. MCI assumes a score between 0 and 1, where 0 represents that the product is fully "linear" (only using virgin feedstock and its only future scenario is landfill) and where 1 refers to a fully "circular" product (containing neither waste nor virgin material).

Based on the existing literature, it is suggested to combine the MCI with a Disassembly Index [11, 13, 14], a weighting system that quantifies the connections between construction elements and their disassembly potential to obtain the Product Circularity Indicator (PCI). The PCI reflects the degree of circularity of a product in a particular system/building. Thereafter, the System Circularity Indicator (SCI) assesses the circularity of multiple products in a system based on their mass. It distinguishes between six system layers [15]. Each system consists of a collection of products and materials, including their characteristics and interrelated behaviour. Finally, the Building Circularity Indicator (BCI) assesses the various systems as a whole considering a factor that weighs the level of relative importance for each subsystem.

Embodied Energy (EE) and Life Cycle Global Warming Potential (GWP) [16] are calculated according to EN 15978:2011 [17], to assess the impact of the building on climate change.

An important feature of this methodology is that it was designed to be compatible with the EU Level(s) Framework [18].

3.2. Conceptual process map for BIM-based circularity assessment

A BIM model requires as a first step to "take a picture" of the existing situation by modelling it in the BIM software, with the minimum Level of Detail (LOD) 200 [19], as the geometry is already known. In this phase, an assembly code should be assigned for each construction element, to guarantee the necessary standardization for assessment and common outputs. Here, the Uniclass 2015 classification system is used.

Simultaneously, construction properties should also be assigned to BIM objects in LOD 200. A BAC (detailed in the next section) can be performed or, instead, specific information on the construction system and materials may be directly assigned to BIM objects, if known. In both scenarios, some predefined parameters need to be characterised for the Circularity Assessment. They are summarized in the Product Data Template [20], according to Figure 1.

Automated BIM-based circularity assessment for refurbishment design makes use of a BIM-based plugin, connected to external databases, namely the Classification System Database (Uniclass 2015), the Building Characterisation Database (containing information regarding archetypes and their construction systems and materials) and the Circularity Database (containing additional data for PDT indicators, per product). Its conceptual workflow (excluding interactions with other stakeholders) is represented in Figure 2, where the new features for BIM-based Circularity Assessment are in black and the BAC inside the red rectangle.

After introducing the minimum construction information, for LOD 200, analysing, discussing, and validating the existing situation with other stakeholders, the software platform will enable the designer to identify, in the BIM model, which elements will be maintained, demolished or created. The interconnections between new elements and elements to be demolished/disassembled (Figure 2), which constitute the Disassembly Index, will also be characterised at this stage, making use of predefined alternatives, through the BAC or inserted directly by the user.

With this information recorded in the information system associated to the BIM model, a Circularity Assessment is performed making use of a BIM-based plugin, and a score for BCI is quantified. Afterwards,

Product Data Template (Standard)
Template Category
Description
Classification
Lifespan
Building Layer
Mass
Normalised total material

LEVEL(S) Macro Objective	Parameter Name/ Indicator	Parameter Name/ Indicator - Tier 1	Parameter Name/ Indicator - Tier 2
1.1 Use stage energy performance	Delivered energy needs assessment	From fuel or energy carrier - Heating	
	Energy performance assessment results	Regulated total primary energy	
1.2 Life cycle Global Warming Potential	Global Warming Potential	Global Warming Potential - total	
		Global Warming Potential - fossil fuels	
		Global Warming Potential - biogenic	
		Global Warming Potential - land use and land use change	
	Embodied Energy		
2.2 Construction & demolition waste and materials	Reuse of materials		
	Recycling of Demolition Waste		
	Material recovery (backfill)		
	Energy recovery		
	Inert		
	Non-hazardous		
	Hazardous		
	Amount of virgin material	Recycled material	
		Reused material	
		Biological material from sustained production	
	Amount of unrecoverable waste	Waste from the linear flow	Fraction of mass of a product being collected to go into a recycling process
			Fraction of mass of a product going into component reuse
			Fraction of mass of a product being collected for energy recovery where the material satisfies the requirements for inclusion
		Waste to produce any recycled content used as feedstock in the recycling process	Efficiency of the recycling process used to produce recycled feedstock for a product
			Fraction of mass of a product's feedstock from recycled sources
		Waste generated in the recycling process	Efficiency of the recycling process used for the portion of a product collected for recycling
			Fraction of mass of a product being collected to go into a recycling process
	Product Utility	Product lifespan	
		Average lifespan of similar products on the market	
		Intensity of use	
		Intensity of use - market average	
2.4 Design for deconstruction, reuse and recycling	Connection Type	Dry Connection	
		Connection with added elements	
		Direct integral connection	
		Soft chemical compound	
		Hard chemical connection	
	Connection acessibility	Freely Accessible	
		Accessibility with additional actions that do not cause damage	
		Accessibility with additional actions with reparable damage	
		Not accessible irreparable damage to objects	
	Crossings	Modular zoning of objects	
		Crossings between one or more objects	
		Full integration of objects	
	Form Containment	Open, no inclusions	
		Overlaps on one side	
		Closed on one side	
		Closed on several sides	

Figure 1. Product Data Template for circularity assessment.

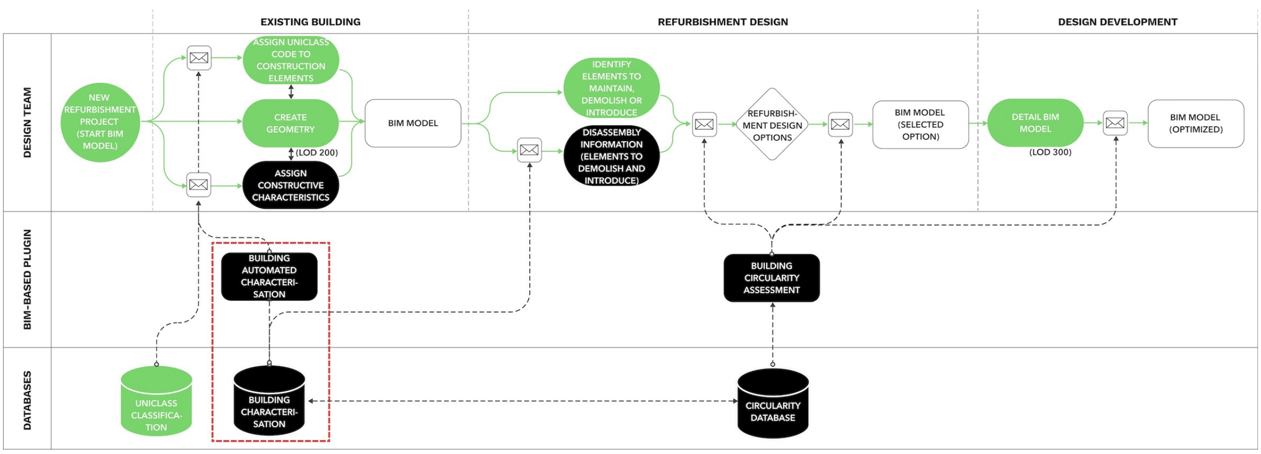


Figure 2. BIM-based circularity assessment conceptual workflow for refurbishment design.

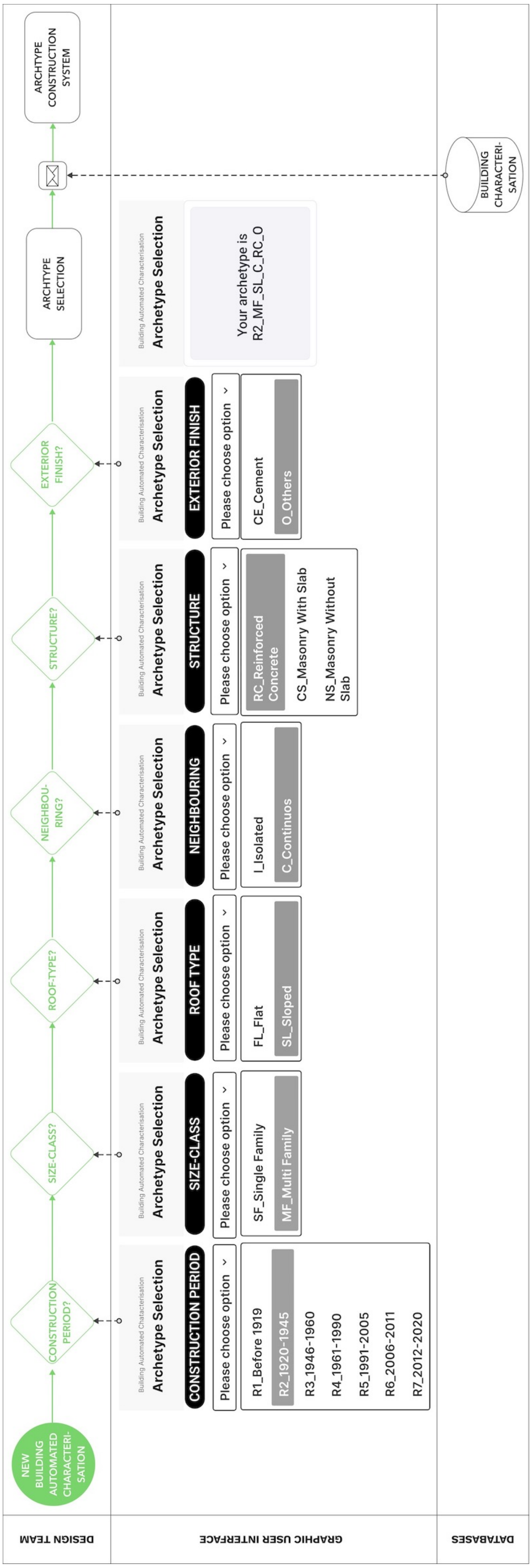


Figure 3. Building Automated Characterisation workflow.

new refurbishment options can be simulated, resulting in new Circularity Assessments, which can be compared with previous ones or an optimized design can be suggested by the plugin. As an example, finding the design optimization to improve insulation of a wall considers the trade-off between the impact of operational energy, embodied energy and embodied carbon, as increasing thickness of conventional insulation material reduces operational energy but increases embodied impact. The use of bio-based materials can also be considered as a possible solution for this dilemma.

After choosing the optimized design, which should be validated by all stakeholders, the BIM model can be detailed for construction (LOD 300) and a new circularity assessment can be performed afterwards, if necessary.

3.3. Methodology for the characterisation of existing building stock (BAC)

An archetype-based methodology is proposed to overcome the lack of information to characterise the existing building's construction systems [9]. The characterisation of the building stock through building archetypes is illustrated with a case study from Lisbon, Portugal. The TABULA Project (Typology Approach for Building Stock Energy Assessment) methodological approach is adopted. Archetypes are defined according to the buildings' physical characteristics [9], making use of a top down approach. The detailed characterisation of building stock will be the first level for the analysis and tool development. Different parameters are taken into consideration, such as the main use (residential or non-residential), construction period, size-class, roof type and neighbouring conditions, in a total estimate of 56 residential building archetypes and 28 non-residential building archetypes.

An existing building representing one archetype was modelled in a BIM software, considering its construction elements and the following shearing layers: skin, structure, service and space plan [15]. The BIM model includes the exterior envelope, foundations, bearing structural frame, interior walls, partitions and doors, floors, etc.; fittings and fixed furnishings (sanitary fittings, cupboards, wardrobes, etc.) and services (energy, ventilation, sanitary, lifts, etc.). Shared parameters for assembly code and disassembly information are to be created for BIM objects [21, 22], to assess circularity and impact on global warming, and also to evaluate the elements' potential of reversibility, derivation points, critical points that can be changed without demolition of other construction elements, etc.

To operationalize the BAC, the user answers consecutively to a set of questions (the former criteria used for categorizing archetypes), in a Graphic User Interface (GUI) (Figure 3) which leads to archetype identification. Once the archetype is identified, the plugin

Figure 4. Site map (Google Maps).

Figure 5. Main façade (Google Maps).

returns the standard corresponding composition (materials and construction systems) for Skin (exterior envelope: walls, roofs, doors and windows); Structure (foundations, bearing elements, stairs) and Space Plan (interior walls, partitions, doors, ceilings, floors, sanitary fittings and kitchens). The Service layer is not considered, because, it varies from one building to another.

The information stored in the Building Characterisation Database is obtained by statistical information combined with on-site inspections, building permits and literature review.

4. Testing BAC with a case study

The selected archetype corresponds to a residential building (R), built between 1919 and 1945 (period 2), multi family ("MF"), with sloped roof ("SL"), continuous ("C"), with masonry with slab structure ("CS") and non-cement exterior finish ("O"). A building, located at Rua Capitão Leitão, 80-82, in Marvila, Lisbon (Figures 4 and 5), provides a real case study corresponding to this archetype.

Metric information was obtained, in this case, in building's construction permit (Figure 6).

After modelling the building in BIM and running BAC, the results obtained are presented in Figure 7.

The connections between construction elements (disassembly information) have already been characterised in background, so that they can be added to the model when designing refurbishment options. Figure 8 shows the results of disassembly information.

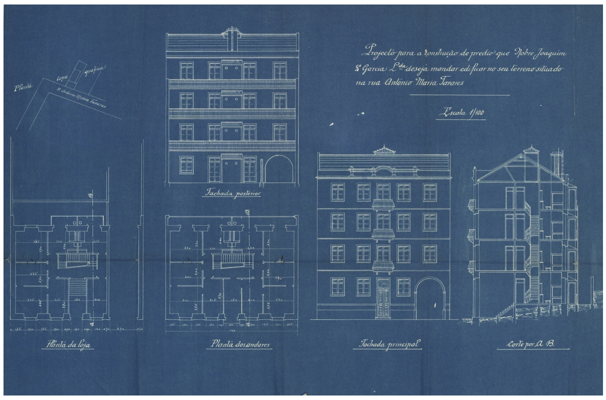


Figure 6. Original project (Lisbon Municipal Archive).

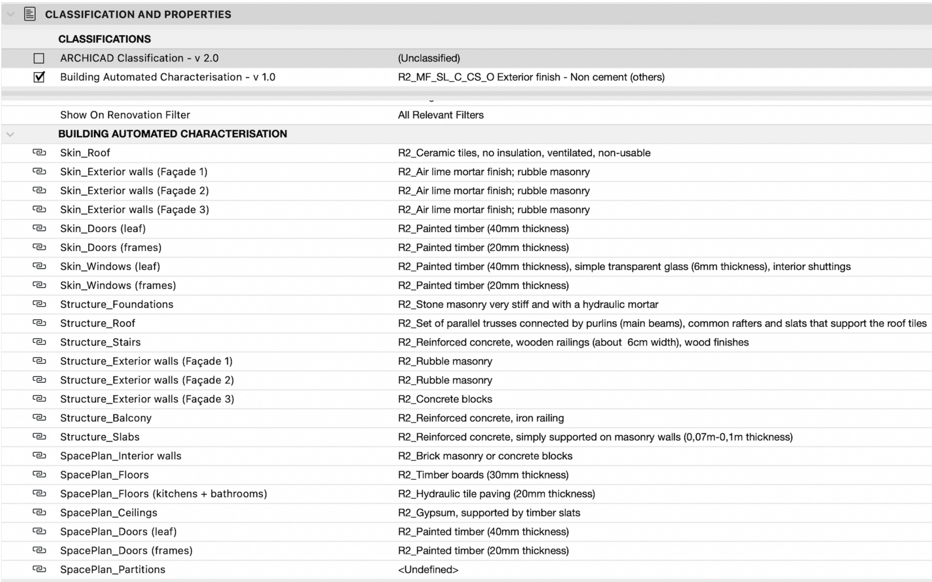
BAC returns qualitative results (materials / composition of materials and their thickness) for the characterisation of construction elements, corresponding to BIM objects, after determining the corresponding archetype for the existing building. This allows the user to introduce construction information when modelling the existing building in BIM.

To perform the circularity assessment and evaluate the building's impact on global warming, the designer needs to add further information to BIM objects to be demolished and created: disassembly information (adjacent elements, connection type, connection accessibility, crossing and form containment), if there is any existing reused or recycled content (BAC assumes, by default, that there isn't) and the end of life strategy (to be repaired, reused, refurbished, remanufactured, recycled, not modified or not recoverable), which are also results provided by this method.

With this qualitative data together with the quantitative data on all the construction elements composition, and the corresponding circularity and environmental data stored in the external database, all indicators from the Product Data Template can be calculated and BCI can be determined.

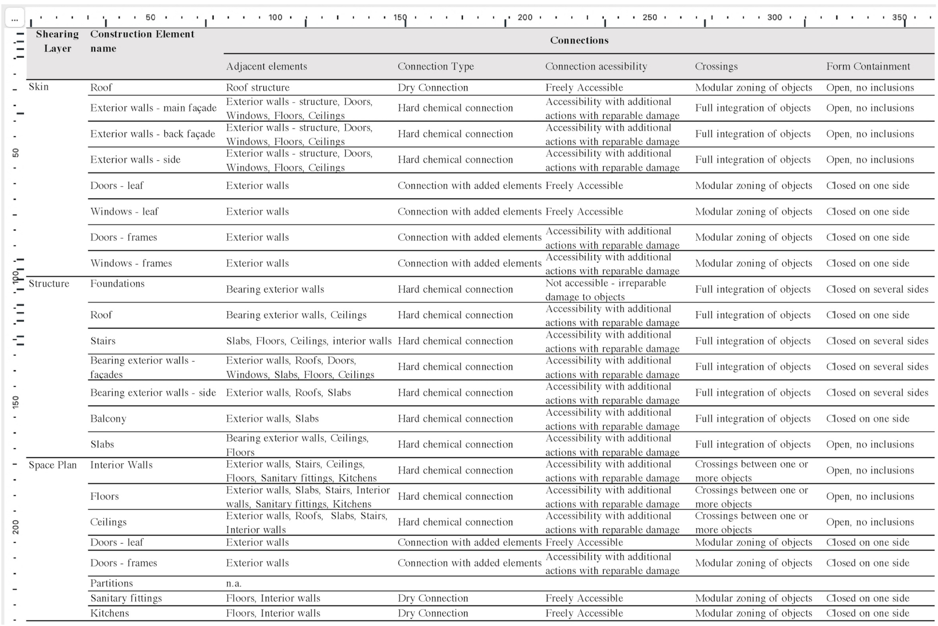
5. Discussion and Conclusions

This paper contributes with a new methodology that supports the characterisation of existing buildings for the implementation of tailored refurbishment strategies for increased recovery, reuse and recycling of construction materials. This BAC methodology is tested in a case study building from Lisbon, corresponding to a 1919–1945 archetype, making use of its BIM model. Regarding its results, BAC proves to be a useful tool for architects, engineers and other practitioners in AEC industry, by providing a reliable basis for data collection and standardization in the early stages of refurbishment projects, which is essential for the circularity assessment of existing building stock. With the automated BIM plugin, designers can obtain immediately circularity indicators per square meter,



CLASSIFICATION AND PROPERTIES	
CLASSIFICATIONS	
ARCHICAD Classification - v 2.0	(Unclassified)
Building Automated Characterisation - v 1.0	R2_MF_SL_C_CS_O Exterior finish - Non cement (others)
Show On Renovation Filter	All Relevant Filters
BUILDING AUTOMATED CHARACTERISATION	
Skin_Roof	R2_Ceramic tiles, no insulation, ventilated, non-usable
Skin_Exterior walls (Façade 1)	R2_Air lime mortar finish; rubble masonry
Skin_Exterior walls (Façade 2)	R2_Air lime mortar finish; rubble masonry
Skin_Exterior walls (Façade 3)	R2_Air lime mortar finish; rubble masonry
Skin_Doors (leaf)	R2_Painted timber (40mm thickness)
Skin_Doors (frames)	R2_Painted timber (20mm thickness)
Skin_Windows (leaf)	R2_Painted timber (40mm thickness), simple transparent glass (6mm thickness), interior shuttings
Skin_Windows (frames)	R2_Painted timber (20mm thickness)
Structure_Foundations	R2_Stone masonry very stiff and with a hydraulic mortar
Structure_Roof	R2_Set of parallel trusses connected by purlins (main beams), common rafters and slats that support the roof tiles
Structure_Stairs	R2_Reinforced concrete, wooden railings (about 6cm width), wood finishes
Structure_Exterior walls (Façade 1)	R2_Rubble masonry
Structure_Exterior walls (Façade 2)	R2_Rubble masonry
Structure_Exterior walls (Façade 3)	R2_Concrete blocks
Structure_Balcony	R2_Reinforced concrete, iron railing
Structure_Slabs	R2_Reinforced concrete, simply supported on masonry walls (0,07m-0,1m thickness)
SpacePlan_Interior walls	R2_Brick masonry or concrete blocks
SpacePlan_Floors	R2_Timber boards (30mm thickness)
SpacePlan_Floors (kitchens + bathrooms)	R2_Hydraulic tile paving (20mm thickness)
SpacePlan_Ceilings	R2_Gypsum, supported by timber slats
SpacePlan_Doors (leaf)	R2_Painted timber (40mm thickness)
SpacePlan_Doors (frames)	R2_Painted timber (20mm thickness)
SpacePlan_Partitions	<Undefined>

Figure 7. BAC – construction system characterisation.



Shearing Layer	Construction Element name	Connections				
		Adjacent elements	Connection Type	Connection acessibility	Crossings	Form Containment
Skin	Roof	Roof structure	Dry Connection	Freely Accessible	Modular zoning of objects	Open, no inclusions
	Exterior walls - main façade	Exterior walls - structure, Doors, Windows, Floors, Ceilings	Hard chemical connection	Accessibility with additional actions with reparable damage	Full integration of objects	Open, no inclusions
	Exterior walls - back façade	Exterior walls - structure, Doors, Windows, Floors, Ceilings	Hard chemical connection	Accessibility with additional actions with reparable damage	Full integration of objects	Open, no inclusions
	Exterior walls - side	Exterior walls - structure, Doors, Windows, Floors, Ceilings	Hard chemical connection	Accessibility with additional actions with reparable damage	Full integration of objects	Open, no inclusions
	Doors - leaf	Exterior walls	Connection with added elements	Freely Accessible	Modular zoning of objects	Closed on one side
	Windows - leaf	Exterior walls	Connection with added elements	Freely Accessible	Modular zoning of objects	Closed on one side
	Doors - frames	Exterior walls	Connection with added elements	Accessibility with additional actions with reparable damage	Modular zoning of objects	Closed on one side
	Windows - frames	Exterior walls	Connection with added elements	Accessibility with additional actions with reparable damage	Modular zoning of objects	Closed on one side
Structure	Foundations	Bearing exterior walls	Hard chemical connection	Not accessible - irreparable damage to objects	Full integration of objects	Closed on several sides
	Roof	Bearing exterior walls, Ceilings	Hard chemical connection	Accessibility with additional actions with reparable damage	Full integration of objects	Closed on one side
	Stairs	Slabs, Floors, Ceilings, interior walls	Hard chemical connection	Accessibility with additional actions with reparable damage	Full integration of objects	Closed on several sides
	Bearing exterior walls - façades	Exterior walls, Roofs, Doors, Windows, Slabs, Floors, Ceilings	Hard chemical connection	Accessibility with additional actions with reparable damage	Full integration of objects	Closed on several sides
	Bearing exterior walls - side	Exterior walls, Roofs, Slabs	Hard chemical connection	Accessibility with additional actions with reparable damage	Full integration of objects	Closed on several sides
	Balcony	Exterior walls, Slabs	Hard chemical connection	Accessibility with additional actions with reparable damage	Full integration of objects	Closed on one side
	Slabs	Bearing exterior walls, Ceilings, Floors	Hard chemical connection	Accessibility with additional actions with reparable damage	Full integration of objects	Open, no inclusions
Space Plan	Interior Walls	Exterior walls, Stairs, Ceilings, Floors, Sanitary fittings, Kitchens	Hard chemical connection	Accessibility with additional actions with reparable damage	Crossings between one or more objects	Open, no inclusions
	Floors	Exterior walls, Slabs, Stairs, Interior walls, Sanitary fittings, Kitchens	Hard chemical connection	Accessibility with additional actions with reparable damage	Crossings between one or more objects	Open, no inclusions
	Ceilings	Exterior walls, Roofs, Slabs, Stairs, Interior walls	Hard chemical connection	Accessibility with additional actions with reparable damage	Crossings between one or more objects	Open, no inclusions
	Doors - leaf	Exterior walls	Connection with added elements	Freely Accessible	Modular zoning of objects	Closed on one side
	Doors - frames	Exterior walls	Connection with added elements	Accessibility with additional actions with reparable damage	Modular zoning of objects	Closed on one side
	Partitions	n.a.				
	Sanitary fittings	Floors, Interior walls	Dry Connection	Freely Accessible	Modular zoning of objects	Closed on one side
	Kitchens	Floors, Interior walls	Dry Connection	Freely Accessible	Modular zoning of objects	Closed on one side

Figure 8. BAC – disassembly information.

which can work as reference values for future design refurbishment options.

BAC provides standard information for clusters of buildings, but does not replace inspection on site, which should be the primary source for building characterisation. On the other hand, BAC provides the characterisation of the construction system "as built", without later modifications.

Further steps will be made by the authors to improve data collection and organization for circularity assessment in a BIM environment, defining the optimal detail level of information for each construction element and its impact on the circularity assessment. The goal is to develop an automatic tool that integrates circularity within a BIM software and defines which further information can be added to national legislation, taking advantage of the use of BIM, to create building passports regarding circularity.

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