Life cycle assessment data structure for building information modelling

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LIFE CYCLE ASSESSMENT DATA STRUCTURE FOR BUILDING INFORMATION MODELLING

Carmine Cavalliere [a,*], Guido Raffaele Dell'Osso [a], Alessandra Pierucci [a], Francesco Iannone [a]

[a] Polytechnic University of Bari, Department of Civil, Environmental, Land, Construction Engineering and Chemistry (DICATECh), Via Edoardo Orabona, 4, 70125 Bari, Italy

E-mail addresses: carmine.cavalliere@poliba.it (C. Cavalliere), guidoraffaele.dellosso@poliba.it (G.R. Dell'Osso), alessandra.pierucci@poliba.it (A. Pierucci), francesco.iannone@poliba.it (F. Iannone)

*Corresponding author

Abstract

The assessment of the environmental impacts related to the building lifecycle is a very complex issue because of the high number of variables involved. The aim of the research is to structure the information content into the Building Information Modelling (BIM) framework in order to conduct a Life Cycle Assessment (LCA). An information flows matrix is developed through the investigation of the parameters responsible for the environmental impacts of buildings. Such information content is tested on a case study after implementing the proposed parameters into a BIM. The purpose is to verify that the identified parameters, implemented in the BIM environment, are sufficient to conduct the LCA. The results show that the proposed parameters could potentially improve the data reliability and consistency in the process of sharing information from the digital model to the LCA software.

Keywords

Building Information Modelling (BIM)
Life Cycle Assessment (LCA)
Design process
Sustainability

1. Introduction

The achievement of sustainable projects involves the management of a large number of environmental variables throughout the stages of building's lifecycle. The construction industry consumes a large amount of natural resources (Yeheyis et al., 2013), contributing to their depletion and to the generation of significant

CO_2 emissions (Costa et al., 2013; Dimoudi and Tompa, 2008). Similarly, the transport of materials leads to the consumption of fossil fuels that increases the environmental impacts (Kellenberger and Althaus, 2009).

The growing interest in environmental issues has resulted in several Life Cycle Assessment (LCA) based studies (Agustí-Juan and Habert, 2017; Anand and Amor, 2017; Buyle et al., 2013; Geng et al., 2017). LCA can predict the environmental impacts of buildings during their lifecycle, so that sustainable decision making can be adopted (Russell-Smith et al., 2015). LCA is an objective methodology for assessing energy and environmental loads of activities and processes. This approach covers the whole lifecycle of buildings from raw materials extraction and processing to the use and end-of-life stage. The comparison of the environmental burdens among different studies can be developed considering the four phase of the LCA: Goal and Scope Definition, Life Cycle Inventory (LCI), Life Cycle Impact Assessment (LCIA) and Interpretation (ISO, 2006a, 2006b). However, the LCA of buildings must take into account the specificities of the construction sector. A building is a unique product made of many assembled parts each with its own life cycle (Means and Guggemos, 2015). Furthermore, the long lifespan of buildings requires several assumptions resulting from the lower predictability of some variables and parameters (Blom et al., 2011).

Designers must be able to reduce uncertainties linked to the nature of the buildings processes in order to adopt LCA as a decision-making tool. Building Information Modelling (BIM) could overcome these issues. BIM is not merely a type of software but a human activity that involves paradigmatic process changes in design, construction and facility management (Eastman et al., 2011). BIM is oriented to the modelling and to the communication of both graphical and non-graphical information, allowing the extraction of quantities, cost estimations and material properties for building, facility and infrastructures (Cheung et al., 2012). Interoperability is one of the key aspects related to BIM and relies to ICT issues, business process, and contractual issues among the interacting parties (Grilo and Jardim-Goncalves, 2010). The sharing of intelligent information contained in the BIM is made possible by the use of open standard models, such as the Industry Foundation Classes (IFC) (Grilo and Jardim-Goncalves, 2010).

Recent studies showed that BIM provides an effective way to investigate the options for the mitigation of emissions as regards to the materials processing, delivery, and construction methods (Giesekam et al., 2014; Yuan and Yuan, 2011). 3D BIM model represents a repository of information and data that could be used to conduct analysis on the model once extracted. BIM can manage the information flow by simplifying data input and implementing the environmental information into the digital model (Wong and Zhou, 2015). Furthermore, BIM can reduce the time-consuming nature of the LCA for collecting data as it allows for performing quick quantity take-off (Ajayi et al., 2015; Houlihan Wiberg et al., 2014).

1.1 Building Information Modelling and Life Cycle Assessment integration

The use of the BIM-based sustainable tools is increasing together with the studies focused on methods for the environmental impact assessment, based on digitized information models (Lee et al., 2015; Motawa and Carter, 2013). Several researches showed the interactions between BIM and sustainability aspects (Saieg et al., 2018) and the capabilities of BIM to take into account environmental analysis throughout the buildings lifecycle (Chong et al., 2017; Eleftheriadis et al., 2017; Soust-Verdaguer et al., 2017).

Several studies have been conducted to improve the dialogue between LCA and BIM for reaching sustainable construction projects (Kylili et al., 2015; Wong and Zhou, 2015): some of them, for example, promote the use of BIM increasing the knowledge of the model in order to facilitate the LCA (Grann, 2012). A different approach concerns the use of the embodied energy of construction products as a benchmark for assessing the sustainability level of the project (Shadram et al., 2016). The possibility of integrating this indicator in BIM comes from the opportunity of referring to available databases, such as the ICE database (Hammond and Jones, 2011), the Franklin and Andrews' Blackbook (Hutchins, 2011), and the Green Guide (Anderson et al., 2009). Different approaches suggested methods for reducing the environmental impacts using BIM, LCA, and energy simulation (Basbagill et al., 2013), alternatively through semantic web applications using BIM with EPD data sets (Schwartz et al., 2016). Recently, researches presented a BIM-based framework with Excel spreadsheet for managing the environmental impacts that could enable stakeholders to assist decision making throughout the building lifecycle (Russell-Smith and Lepech, 2012; Shin and Cho, 2015). Flager et al. (Flager et al., 2012) developed an automated optimization BIM-based method to analyse different design solutions assessing trade-offs between life cycle cost (LCC) and carbon footprint. Marzouk et al. (Marzouk et al., 2017) proposed a BIM-based model with Autodesk Revit in order to facilitate data retrieval from Microsoft Access and employed a windows application written in C#.net to calculate the overall emissions using Athena Impact Estimator. Jalaei & Jrade (Jalaei and Jrade, 2014) used a plug-in to assess the environmental impacts and the embodied energy of building components linking BIM, LCA, energy analysis, and lighting simulation tools with green building certification systems. Peng (Peng, 2016) developed the life cycle modelling of the building based on physical processes from cradle to grave and employed Autodesk Revit and Ecotect to simulate the building's performance. Najjar et al. (Najjar et al., 2017) proposed a case-study to evaluate the environmental impacts of materials over the entire life cycle of buildings. They used Autodesk Revit, Green Building Studio, and Tally to estimate the significance of impact on the elementary flows and to give recommendations.

Different approaches employed the parametric design as a tool for the automated generation of several design variants allowing the real-time optimization of the environmental parameters using mathematical formulas (Cellura et al., 2017; Hollberg and Ruth, 2016).

The reviewed papers show the potential of BIM to assist the LCA of buildings. They used BIM to store the data and facilitate the calculation of materials and components quantities. While there are different tools trying to facilitate the BIM-based LCA, there still is knowledge gap on how to match properties from the BIM with data needed to conduct the LCA. Cerezo et al. (Cerezo et al., 2014) pointed out the need of using the building properties (BP) templates through the design process stages for the buildings performance simulation workflows.

The present study aims at structuring the BIM parameters responsible for the environmental impacts of buildings, and not only those related to the geometrical aspects. The proposed parameters are tested on a case study to verify their consistency when conducting the LCA. Such information within a building model allow to perform the LCA by extracting all project data needed from the BIM. This could decrease the shortage of information that usually occurs in the environmental analysis and decision-making process.

2. Methodology

The buildings lifecycle oriented analysis consider the impacts related to the construction (from raw materials extraction to processing and products installation), use (consumption flows, maintenance, reconfiguration), and end of life stage (demolition or disassembly, transportation to the treatment site and end of life scenario) (Ramesh et al., 2010). In this context, it is possible to identify several variables competing on the final impact of the building processes. The study introduces a flow chart for mapping the design variables responsible for the environmental impacts. The proposed variables are composed by a number of parameters, which could characterize the Building Information Model. BIM tools provide the way to include additional data. Indeed, the parameters coming from the proposed flow chart are added to each object of the Autodesk Revit model and made available in their property browser. Consequently, the information needed to perform the LCA are made available and exportable from the model. The identified BIM parameters could be visualized in schedules and divided into categories. They could also be modified within the schedules or parametric objects, and each change iteratively affects the objects semantic contents. Finally, the BIM parameters could be exported in an external database for their manual or automatic management within further tools. The proposed methodology aims at identifying the BIM parameters needed to perform the LCA through structuring a workflow and testing it on a case study. Hence, the research intends to propose neither a tool for the automatic integration between BIM and LCA software nor a tool for a parametric LCA.

2.2 The Architecture of Variables

Data input for LCA is very time-consuming and BIM-LCA integration requires a significant amount of data. Nevertheless, it is recognized that LCA applications carried out with the aid of BIM can significantly reduce data input (Soust-Verdaguer et al., 2016).

The proposed flow chart, called *Architecture of Variables* (AoV), shows the design variables throughout the lifecycle stages of buildings (Fig. 1). The AoV is made by a Process Breakdown Structure that retraces the building lifecycle in accordance to the standard on the sustainable constructions (EN, 2011). The building processes lead to the production of physical objects that are called *deliverables* in the AoV. The method looks at the building production processes and does not cover all the possible tangent and ancillary processes (e.g. the impacts of the construction equipment, temporary works, etc.). Furthermore, the AoV introduces the concept of referral process whenever the information flow needs to be linked to another process or deliverable. Hence, the variables identified in the AoV are decomposed into parameters (Table 1). Two types of parameters could be identified: parameters with direct implication on the environmental impacts and those acting indirectly. The variation of the direct parameters leads to a direct change of the LCA results. The *Weight* parameter is taken as an example: the weight gain (e.g. resulting from the realization of several building components) directly leads to an increase of the environmental impact due to the increased request for resources. The indirect parameters must necessarily be made available in the BIM, although they do not seem to produce a change of the environmental impacts. The *Reference Service Life* (RSL) parameter, for example, does not directly lead to the environmental impact, but characterizes the maintenance/replacement of the building elements. Building components with a low RSL value require several replacements over the lifespan of the building system. This could lead to the increased request for resources, electricity, transport, with indirect implications on other parameters. It should be emphasised that a lower service life certainly drives to a more frequent maintenance increasing the environmental impacts, but these latter are related also to the technology employed, which could change during the lifespan of the building.

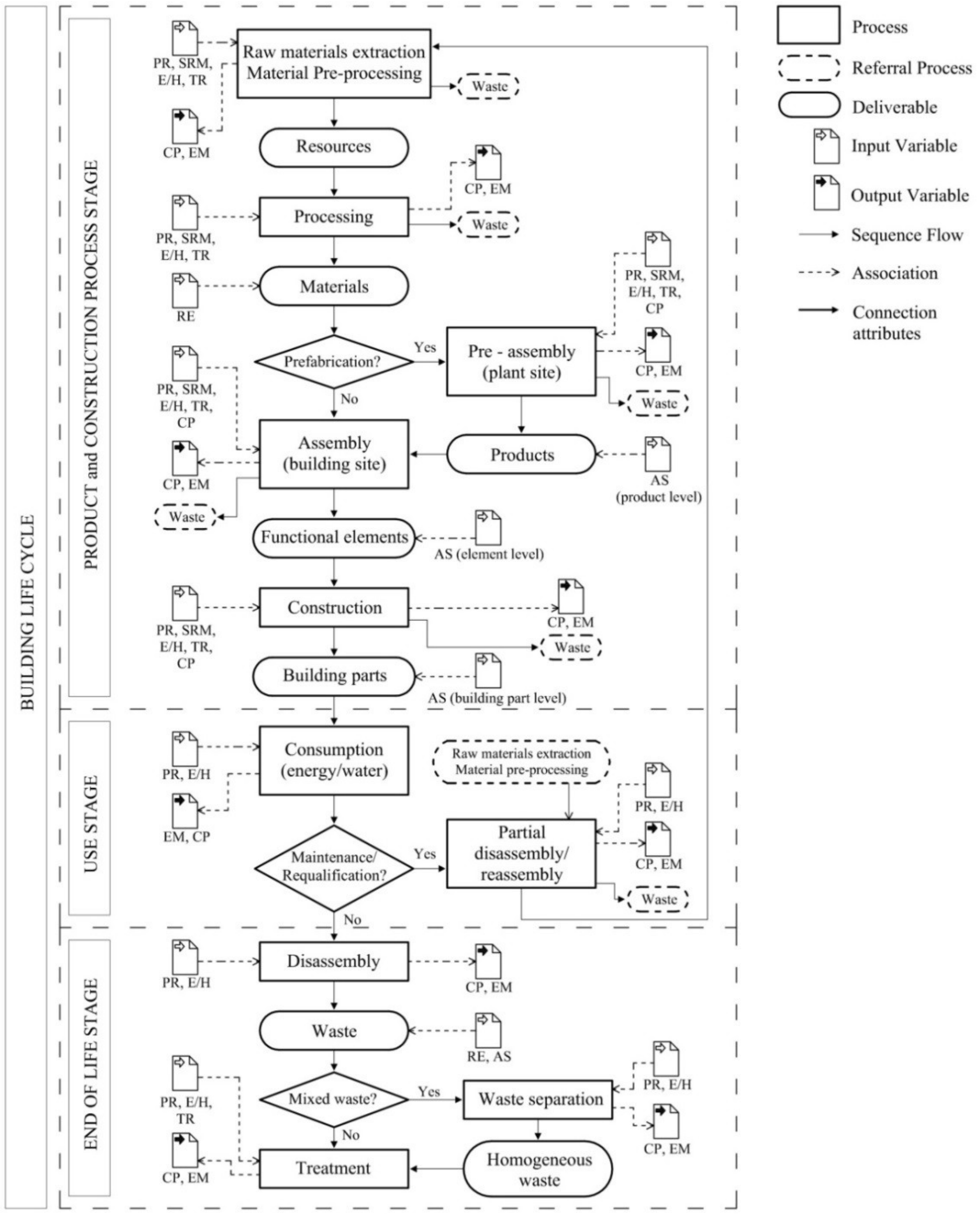

Fig. 1. The Architecture of Variables (AoV)

Abbreviations: PR, Primary Resources; **E/H**, Electricity/Heat, **TR**, Transport; **CP**, Co-Products; **SRM**, Secondary Raw Materials; **EM**, Emission; **RE**, Recyclability; **AS**, Assembly.

Table 1

Variables and related parameters

VARIABLES	DIRECT PARAMETERS	INDIRECT PARAMETERS
Primary Resources (PR)	Dimension (Volume, Area, Length), Weight, Nature of the Resource (allocable to recycle, reuse, incineration, landfill)	Reference Service Life

Electricity/Heat (E/H)	Source, Power, Time of Use, Georeference	
Transport (TR)	Type of transport (wheel, rail, ship, etc.), Weight of transported material (depending on the design specifications, the supply method or the site construction, etc.), Distance, Capacity, Class, Dimension (Volume, Area, Length)	
Co-Products (CP) or Secondary Raw Materials (SRM)	Dimension (Volume, Area, Length), Weight, Nature of Co-Products/Secondary Raw Materials, Time of Use	Residual Performance, Economic Residual Value
Emission (EM)	Nature of the Emission, Amount	
Recyclability (RE)	Nature of the Resource	Residual Performance, Georeference
Assembly (AS)		Connection type (Dry or Wet-assembly)

Tables 2-4 show the parameters belonging to each variable identified in the AoV. The parameters are coded for uniquely identifying the information into the BIM. However, many of them may have the same information. For example, consider the *Nature of the Resource* parameters concerning the various *Primary Resources* variables in the construction phase: the information linked to these parameters is the same used for the use and end-of-life (EoL) stage for characterizing the material/product to be maintained/disposed. According to this logic, many parameters are related to each other.

Table 2

Variables and related parameters of the Product and Construction Process stage

STAGE	PROCESSES/ DELIVERABLES	REFERRAL PROCESSES	VARIABLES	CODE	PARAMETERS
Product and Construction Process (C)	Raw material extraction (ME)	Waste	Primary Resources - (PR)	C.ME.PR	Dim, We, NoR, RSL
			Secondary Raw Materials - (SRM)	C.ME.SRM	RP, Dim, We, NSRM, TU, ERV
			Electricity/Heat - (E/H)	C.ME.E/H	So, Pw, TU, Geo
			Transport - (TR)	C.ME.TR	ToT, We, Dis, Cap, Class, Dim
			Co-Products - (CP)	C.ME.CP	RP, Dim, We, NCP, TU, ERV
			Emissions - (EM)	C.ME.EM	NoE, Am
	Processing (PG)	Waste	Primary Resources - (PR)	C.ME.PR	Dim, We, NoR, RSL
			Secondary Raw Materials - (SRM)	C.PG.SRM	RP, Dim, We, NSRM, TU, ERV
			Electricity/Heat - (E/H)	C.PG.E/H	So, Pw, TU, Geo
			Transport - (TR)	C.PG.TR	ToT, We, Dis, Cap, Class, Dim
			Co-Products - (CP)	C.PG.CP	RP, Dim, We, NCP, TU, ERV
			Emissions - (EM)	C.PG.EM	NoE, Am
	Materials (MT)	/	Recyclability - (RE)	C.MT.RE	NoR, RP, Geo
	Pre-Assembly (plant site) (PA)	Waste	Primary Resources - (PR)	C.PA.PR	Dim, We, NoR, RSL
			Secondary Raw Materials - (SRM)	C.PA.SRM	RP, Dim, We, NSRM, TU, ERV
			Electricity/Heat - (E/H)	C.PA.E/H	So, Pw, TU, Geo
			Transport - (TR)	C.PA.TR	ToT, We, Dis, Cap, Class, Dim
			Co-Products (inflow) - (CPi)	C.PA.CPi	RP, Dim, We, NCP, TU, ERV
			Co-Products (outflow) - (CPo)	C.PA.CPo	RP, Dim, We, NCP, TU, ERV
			Emissions - (EM)	C.PA.EM	NoE, Am
	Products (PRD)	/	Assembly - (AS)	C.PRD.AS	CT
	Assembly (building site) (AS)	Waste	Primary Resources - (PR)	C.AS.PR	Dim, We, NoR, RSL
			Secondary Raw Materials - (SRM)	C.AS.SRM	RP, Dim, We, NSRM, TU, ERV
			Electricity/Heat - (E/H)	C.AS.E/H	So, Pw, TU, Geo
			Transport - (TR)	C.AS.TR	ToT, We, Dis, Cap, Class, Dim

		Co-Products (inflow) - (CPi)	C.AS.CPi	RP, Dim, We, NCP, TU, ERV
		Co-Products (outflow) - (CPo)	C.AS.CPo	RP, Dim, We, NCP, TU, ERV
		Emissions - (EM)	C.AS.EM	NoE, Am
Functional Elements (FE)	/	Assembly - (AS)	C.FE.AS	CT
Construction (C)	Waste	Primary Resources - (PR)	C.C.PR	Dim, We, NoR, RSL
		Secondary Raw Materials - (SRM)	C.C.SRM	RP, Dim, We, NSRM, TU, ERV
		Electricity/Heat - (E/H)	C.C.E/H	So, Pw, TU, Geo
		Transport - (TR)	C.C.TR	ToT, We, Dis, Cap, Class, Dim
		Co-Products (inflow) - (CPi)	C.C.CPi	RP, Dim, We, NCP, TU, ERV
		Co-Products (outflow) - (CPo)	C.C.CPo	RP, Dim, We, NCP, TU, ERV
		Emissions - (EM)	C.C.EM	NoE, Am
Building Elements (BE)	/	Assembly - (AS)	C.BE.AS	CT

Abbreviations: Am, Amount; **Cap**, Capacity; **Class**, Class; **CT**, Connection type; **Dim**, Dimension; **Dis**, Distance; **ERV**, Economic Residual Value; **Geo**, Georeference; **NCP**, Nature of Co-Products; **NoE**, Nature of the Emission; **NoR**, Nature of the Resource; **NSRM**, Nature of Secondary Raw Materials; **Pw**, Power; **RP**, Residual Performance; **RSL**, Reference Service Life; **So**, Source; **ToT**, Type of transport; **TU**, Time of Use; **We**, Weight.

Table 3

Variables and related parameters of the Use stage

STAGE	PROCESSES/ DELIVERABLES	REFERRAL PROCESSES	VARIABLES	CODE	PARAMETERS
Use (U)	Consumption (CO)	/	Primary Resources - (PR)	U.CO.PR	Dim, We, NoR, RSL
			Electricity/Heat - (E/H)	U.CO.E/H	So, Pw, TU, Geo
			Emissions - (EM)	U.CO.EM	NoE, Am
			Coproducts - (CP)	U.CO.CP	RP, Dim, We, NCP, TU, ERV
	Partial disassembly (PD)	Raw materials extraction Waste	Primary Resources - (PR)	U.PD.PR	Dim, We, NoR, RSL
			Electricity/Heat - (E/H)	U.PD.E/H	So, Pw, TU, Geo
			Emissions - (EM)	U.PD.EM	NoE, Am
			Coproducts - (CP)	U.PD.CP	RP, Dim, We, NCP, TU, ERV

Abbreviations: Am, Amount; **Cap**, Capacity; **Class**, Class; **CT**, Connection type; **Dim**, Dimension; **Dis**, Distance; **ERV**, Economic Residual Value; **Geo**, Georeference; **NCP**, Nature of Co-Products; **NoE**, Nature of the Emission; **NoR**, Nature of the Resource; **Pw**, Power; **RP**, Residual Performance; **RSL**, Reference Service Life; **So**, Source; **ToT**, Type of transport; **TU**, Time of Use; **We**, Weight.

Table 4

Variables and related parameters of the End of Life stage

STAGE	PROCESSES/ DELIVERABLES	REFERRAL PROCESSES	VARIABLES	CODE	PARAMETERS
End of Life (EoL)	Disassembly (DI)	/	Primary Resources - (PR)	EoL.DI.PR	Dim, We, NoR, RSL
			Electricity/Heat - (E/H)	EoL.DI.E/H	So, Pw, TU, Geo
			Emissions - (EM)	EoL.DI.EM	NoE, Am
			Coproducts - (CP)	EoL.DI.CP	RP, Dim, We, NCP, TU, ERV
	Waste (WA)	/	Recyclability - (RE)	EoL.WA.RE	NoR, RP, Geo
			Assembly - (AS)	EoL.WA.AS	CT
	Waste separation (WS)	/	Primary Resources - (PR)	EoL.WS.PR	Dim, We, NoR, RSL
			Electricity/Heat - (E/H)	EoL.WS.E/H	So, Pw, TU, Geo
			Emissions - (EM)	EoL.WS.EM	NoE, Am
			Coproducts - (CP)	EoL.WS.CP	RP, Dim, We, NCP, TU, ERV
	Treatment	/	Primary Resources - (PR)	EoL.TT.PR	Dim, We, NoR, RSL

	Electricity/Heat - (E/H)	EoL.TT.E/H	So, Pw, TU, Geo
(TT)	Transport - (TR)	EoL.TT.TR	ToT, We, Dis, Cap, Class, Dim
	Emissions - (EM)	EoL.TT.EM	NoE, Am
	Coproducts - (CP)	EoL.TT.CP	RP, Dim, We, NCP, TU, ERV

Abbreviations: Am, Amount; **Cap**, Capacity; **Class**, Class; **CT**, Connection type; **Dim**, Dimension; **Dis**, Distance; **ERV**, Economic Residual Value; **Geo**, Georeference; **NCP**, Nature of Co-Products; **NoE**, Nature of the Emission; **NoR**, Nature of the Resource; **Pw**, Power; **RP**, Residual Performance; **RSL**, Reference Service Life; **So**, Source; **ToT**, Type of transport; **TU**, Time of Use; **We**, Weight.

3. Case study

3.1. LCA application to the case study

The proposed parameters are tested on the exterior wall of a new multi-dwelling building located in Bari, Italy, shown in Fig. 2. Table 5 shows the main features of the whole building.

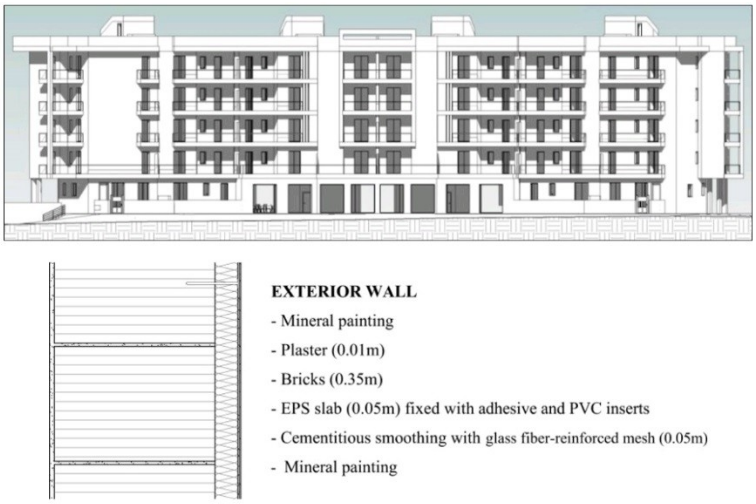

Fig. 2. Top, 3D model of the reference building; bottom, section of the exterior wall as case study for LCA

Table 5

Main features of the reference building

FEATURES	REFERENCE BUILDING
Type	Multi-dwelling building
No. of stairwells	4
No. of floors	4 + high floor
Apartments per floor	2 (per each stairwells)
Elevation per floor	2.74 m
Structure	Reinforced concrete
External wall	Bricks with thermal insulation in Expanded Polystyrene Sintered (EPS) slabs (5 cm), fixed to the wall with adhesive and PVC inserts
Base slab	Insulation of the first floor with EPS slabs (10 cm), placed at the bottom of screed plants system (7cm) and parquet or tile flooring, fixed with adhesive/mortar
Intermediate slab	Stratification of the intermediate floor with a screed plants system (7 cm), PE sound-absorbing layer (0.8 cm), screed for the partition of loads (5 cm) and flooring (same types above mentioned)
Roof	Flat roof with a PE vapour barrier, XPS slabs layer (8 cm), PE sheets, screed slope (7 cm) and bitumen sheet
Windows	Double glazing (4-16-4 mm), cavity of argon air and PVC frame

The LCA performed allows for verifying if the inventory requirements are covered by the parameters shown in Tables 2-4. This would make it possible to verify the completeness of the LCA information stored into the building model, providing the basis for the BIM-LCA integration. Firstly, the LCA is conducted with reference to the case study. Secondly, it is verified that all the data required for the LCA are identified among the proposed parameters. Therefore, the study does not consider to start extracting data directly from the Building Information Model and then using them for the analysis: in that case, the methodology would be implicitly verified.

3.2. Goal and scope definition

3.2.1. Goal

The analysis intends to assess the environmental impact of the external walls of the building depicted in Table 5 throughout its entire life cycle. The lifetime of the building is assumed to be 50 years according to the most of the published studies (Mastrucci et al., 2017; Moschetti et al., 2015; Sartori and Hestnes, 2007). The environmental impact is assessed with IMPACT 2002+ method by SimaPro 8.0.4.30 software. LCA results are normalized using midpoint impacts indicators.

3.2.2. Functional unit and system boundaries

The functional unit is a quantified performance of a system used as reference unit (ISO, 2006a). For the case study, the functional unit is the whole external wall, equal to 2484.20 m^2, with a U-value of 0.213 W/m^2K. As shown in Fig. 2, the wall is made up of bricks (thickness 0.35 m) placed with cement mortar of 1800 Kg/m^3 density and thickness of 0.007 m. A thermal insulation in expanded polystyrene sintered (EPS) slab (thickness 0.05 m) is installed with the adhesive and PVC inserts. A cementitious smoothing with a drowned glass fiber-reinforced mesh is applied on the insulating slab. The external finishing completes the technological solution.

Regarding the system boundaries, the LCA is performed for the product and construction, use, and EoL stages in 50 years. The extraction of raw materials, the production of building materials, the on-site assembly processes of building components, and transports, are considered in the product and construction process stage. The assessment of the impacts due to the use phase is referred to the maintenance issues (the demolition and disposal of elements to be replaced and the production and assembly of new products), neglecting the operational energy use and the operational water use. According to the RSL of the building materials and components (Tables 6-9), the replacement of the external finishing is planned every 10 years. Therefore, four maintenance actions occur during the lifetime of the building. The EPS slabs, cement mortar for gluing and skimming, PVC inserts, and plaster, are replaced twice over the lifespan of the building, since their RSL is 20 years. In order to replace the EPS slab, the glass fiber-reinforced mesh needs to be replaced although its RSL is 50 years. The end-of-life phase involves the processes required for the demolition and disposal of the external walls as their transportation to the landfill site or recycling sorting plant. Technical equipment embedded in the walls are left out of the analysis.

3.3. Inventory analysis

The management of the inventory flows has been conducted with the use of the database Ecoinvent v3 and its system model allocation at the point of substitution. The Italian electricity mix given in Ecoinvent is used with regard to the energy flows for the installation of materials, their assembly, and their removal or dismantling at EoL phase. The inventory of the construction phase covers the materials and energy flows with reference to the construction of the external walls. The transports and electricity supplies for powering the machinery for the assembly and installation of the materials are taken into account. Transports are modelled with reference to the total volume of the materials needed for the production of 2484.20 m^2 of external wall. The choice of the type of transport and the number of trips are related both to the volume and weight of the materials involved. The distance from the bricks factory is 100 km and an average distance of 5 km from the factories of others materials is assumed. The use of 5 km as average data is used to simplify the calculation since it does not affect the validity of the parameters to be tested.

The flows linked to the use of the building are not modelled (e.g. energy for heating, cooling, and hot water production). The inventory of this stage considers the new materials for the replacement and the energy flows linked to the use of the construction machinery. The transports of the new materials (from the factory to the construction site) and the disposed ones (from the construction site to the disposal site or recycling sorting plant) are taken into account.

During the end-of-life scenarios, two different options are considered: disposal without recycling and recycling. Bricks, plaster, and mortar, are recycled to be reused as inert materials. The other materials are sent to the disposal site. As in the previous phases, the transports required to convey the demolished material to the treatment plant are modelled. The insulating materials are conveyed to a specialized disposal plant that is 80 km away from the construction site. The other materials are conveyed to a disposal plant 15 km far.

4. Results

The analysis show the environmental impacts of the external walls during the construction, maintenance, and end-of-life phase (Figs. 3-5). Figs. 3-5 show the LCA results with reference to the processes involved using the logarithmic scale. The processes modelled in SimaPro are identified by the related variables and parameters according to the AoV (Fig. 1) and Table 2. As depicted in Table 6, all the processes involved in the construction phase can be represented by the variables identified within the AoV and characterized by the related parameters. This means that the proposed parameters define the information flows required to perform the LCA. Hence, each model element can be characterized by the information identified in Table 6. It should be emphasised that in Table 6 some variables do not refer to any process as they rely on the deliverables, according to the AoV (Fig. 1).

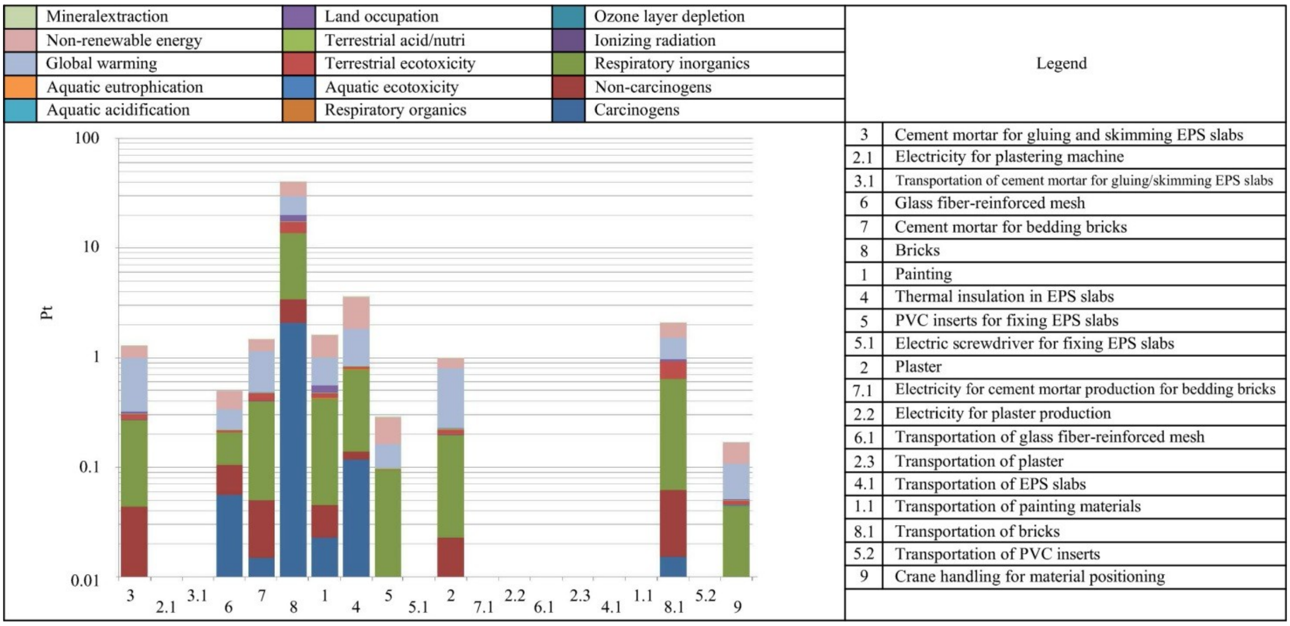

Fig. 3. LCA of the Product and Construction Process stage

Table 6

Processes, Variables, and related parameters of the Product and Construction Process stage

PROCESSES	VARIABLES	BIM PARAMETERS
3	C.ME.PR	**Dim**: 2484.20 m^2; **We**: 34778.80 kg; **NoR**: Cement mortar; **RSL**: 20 years
2.1	C.C.E/H	**So**: Electricity; **Pw**: 1.3 kW; **Tu**: 41.24 h; **Geo**: IT
3.1	C.AS.TR	**ToT**: Transport on wheel; **We**: 34778.80 kg; **Dis**: 5 km; **Cap**: > 32 metric ton; **Class**: EURO 4; **Dim**: 2484.20 m^2
6	C.ME.PR	**Dim**: 2484.20 m^2; **We**: 437.22 kg; **NoR**: Glass fiber; **RSL**: 50 years
7	C.ME.PR	**Dim**: 2484.20 m^2; **We**: 31300.92 kg; **NoR**: Cement mortar; **RSL**: 50 years
8	C.ME.PR	**Dim**: 2484.20 m^2; **We**: 630365.75 kg; **NoR**: Light clay brick; **RSL**: 50 years
1	C.ME.PR	**Dim**: 4968.40 m^2; **We**: 1738.94 kg; **NoR**: Alkyd paint; **RSL**: 10 years
4	C.ME.PR	**Dim**: 2484.20 m^2; **We**: 2484.20 kg; **NoR**: Polystyrene; **RSL**: 20 years
5	C.ME.PR	**Dim**: 19874 p; **We**: 320.37 kg; **NoR**: Polyvinylchloride; **RSL**: 20 years
5.1	C.C.E/H	**So**: Electricity; **Pw**: 0.71 kW; **Tu**: 11.04 h; **Geo**: IT
2	C.ME.PR	**Dim**: 2484.20 m^2; **We**: 32294.60 kg; **NoR**: Lime, Sand, Cement; **RSL**: 20 years
7.1	C.C.E/H	**So**: Electricity; **Pw**: 1.4 kW; **Tu**: 31.30 h; **Geo**: IT
2.2	C.C.E/H	**So**: Electricity; **Pw**: 1.3 kW; **Tu**: 41.40 h; **Geo**: IT
6.1	C.AS.TR	**ToT**: Transport on wheel; **We**: 437.22 kg; **Dis**: 5 km; **Cap**: 7.5-16 metric ton; **Class**: EURO 4; **Dim**: 2484.20 m^2
2.3	C.AS.TR	**ToT**: Transport on wheel; **We**: 32294.60 kg; **Dis**: 5 km; **Cap**: > 32 metric ton; **Class**: EURO 4; **Dim**: 2484.20 m^2
4.1	C.AS.TR	**ToT**: Transport on wheel; **We**: 2484.20 kg; **Dis**: 5 km; **Cap**: 7.5-16 metric ton; **Class**: EURO 4; **Dim**: 2484.20 m^2
1.1	C.AS.TR	**ToT**: Transport on wheel; **We**: 1738.94 kg; **Dis**: 5 km; **Cap**: 7.5-16 metric ton; **Class**: EURO 4; **Dim**: 4968.40 m^2
8.1	C.AS.TR	**ToT**: Transport on wheel; **We**: 630365.75 kg; **Dis**:100 km; **Cap**: >32 metric ton; **Class**: EURO 4; **Dim**: 2484.20 m^2
5.2	C.AS.TR	**ToT**: Transport on wheel; **We**: 320.37 kg; **Dis**: 5 km; **Cap**: 7.5-16 metric ton; **Class**: EURO 4; **Dim**: 19874 p
9	C.C.E/H	**So**: Electricity; **Pw**: 16.16 kW; **Tu**: 57.14 h; **Geo**: IT
	C.MT.RE	**NoR**: (see PR); **RP**: Yes; **Geo**: IT
	C.PRD.AS	**CT**: Wet-assembly
	C.FE.AS	**CT**: Wet-assembly
	C.BE.AS	**CT**: Wet-assembly
Total parameters		**100**

The variables and the related parameters are defined in an inclusive way to fully detail the information throughout the entire building process. However, data can be considerably streamlined. According to the

Table 6, it can be seen how much information deriving from the different parameters are correlated. The Dim parameter of the C.ME.PR variables belonging to the different processes is always the same, since it refers to the geometrical dimension of the walls. The We parameter of the C.ME.PR variables is exactly equal to the We parameter of C.AS.TR variables, since the material used for the external walls is equal to the material to be transported (with the exception of the packaging that is left out of the assessment). Another parameter that is linked to others is the Geo parameter of the C.C.E/H variables: once the type of energy supply for the construction site is fixed, it is going to be the same. In the specific case study considered, the materials are transported on wheels with a EURO 4. Therefore, for the ToT and Class parameters it is possible to make the same simplifications as the parameters previously discussed.

With these simplifications, it is possible to streamline the amount of information. Hence, in order to describe the construction phase of the external walls and to carry out the analysis in SimaPro, the parameters shown in Table 7 would be sufficient. Fig. 4 and Table 8 show the parameters related to the use stage while Fig. 5 and Table 9 those linked to the EoL.

Table 7

Processes, Variables, and related parameters of the Product and Construction Process stage with simplifications

PROCESSES	VARIABLES	BIM PARAMETERS
3	C.ME.PR	**Dim**: 2484.20 m^2; **We**: 34778.80 kg; **NoR**: Cement mortar; **RSL**: 20 years
2.1	C.C.E/H	**So**: Electricity; **Pw**: 1.3 kW; **Tu**: 41.24 h; **Geo**: IT
3.1	C.AS.TR	**ToT**: Transport on wheel; **Dis**: 5 km; **Cap**: > 32 metric ton; **Class**: EURO 4
6	C.ME.PR	**We**: 437.22 kg; **NoR**: Glass fiber; **RSL**: 50 years
7	C.ME.PR	**We**: 31300.92 kg; **NoR**: Cement mortar; **RSL**: 50 years
8	C.ME.PR	**We**: 630365.75 kg; **NoR**: Light clay brick; **RSL**: 50 years
1	C.ME.PR	**We**: 1738.94 kg; **NoR**: Alkyd paint; **RSL**: 10 years
4	C.ME.PR	**We**: 2484.20 kg; **NoR**: Polystyrene; **RSL**: 20 years
5	C.ME.PR	**Dim**: 19874 p; **We**: 320.37 kg; **NoR**: Polyvinylchloride; **RSL**: 20 years
5.1	C.C.E/H	**So**: Electricity; **Pw**: 0.71 kW; **Tu**: 11.04 h
2	C.ME.PR	**We**: 32294.60 kg; **NoR**: Lime, Sand, Cement; **RSL**: 20 years
7.1	C.C.E/H	**So**: Electricity; **Pw**: 1.4 kW; **Tu**: 31.30 h
2.2	C.C.E/H	**So**: Electricity; **Pw**: 1.3 kW; **Tu**: 41.40 h
6.1	C.AS.TR	**Dis**: 5 km; **Cap**: 7.5-16 metric ton
2.3	C.AS.TR	**Dis**: 5 km; **Cap**: > 32 metric ton
4.1	C.AS.TR	**Dis**: 5 km; **Cap**: 7.5-16 metric ton
1.1	C.AS.TR	**Dis**: 5 km; **Cap**: 7.5-16 metric ton
8.1	C.AS.TR	**Dis**: 100 km; **Cap**: >32 metric ton
5.2	C.AS.TR	**Dis**: 5 km; **Cap**: 7.5-16 metric ton
9	C.C.E/H	**So**: Electricity; **Pw**: 16.16 kW; **Tu**: 57.14 h
	C.MT.RE	**NoR**: (see PR); **RP**: Yes; **Geo**: IT
	C.PRD.AS	**CT**: Wet-assembly
	C.FE.AS	**CT**: Wet-assembly
	C.BE.AS	**CT**: Wet-assembly
Total parameters		**64**

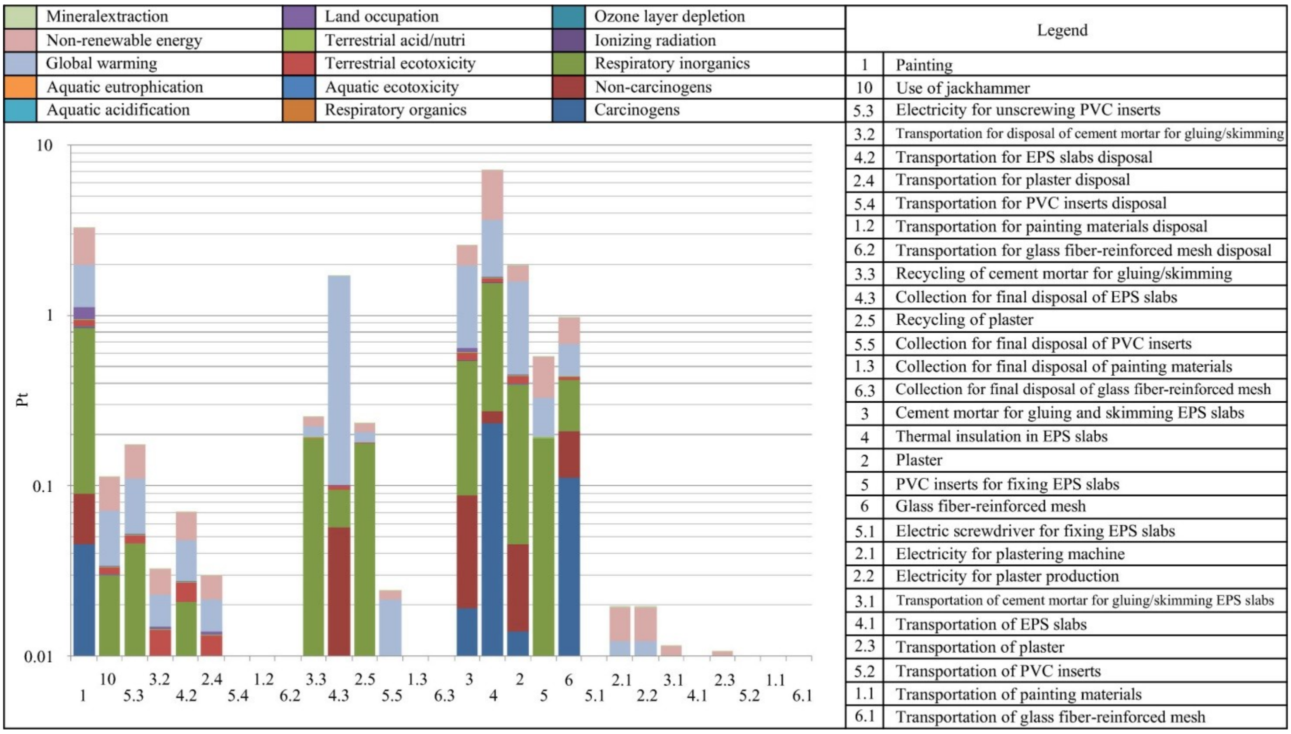

Fig. 4. LCA of the Use stage

Table 8

Processes, Variables, and related parameters of the Use stage

PROCESSES	VARIABLES	REFERENCE	BIM PARAMETERS
1		C.ME.PR	**Dim**: 4968.40 m^2; **We**: 1738.94 kg; **NoR**: Alkyd paint; **RSL**: 10 years
10	U.PD.E/H	EoL.DI.E/H	**So**: Electricity; **Pw**: 1.24 kW; **Tu**: 248 h; **Geo**: IT
5.3	U.PD.E/H	EoL.DI.E/H	**So**: Electricity; **Pw**: 0.7 W; **Tu**: 675 h; **Geo**: IT
3.2		EoL.TT.TR	**ToT**: Transport on wheel; **We**: 34778.80 kg; **Dis**: 15 km; **Cap**: > 32 metric ton; **Class**: EURO 4; **Dim**: 2484.20 m^2
4.2		EoL.TT.TR	**ToT**: Transport on wheel; **We**: 2484.20 kg; **Dis**: 80 km; **Cap**: 7.5-16 metric ton; **Class**: EURO 4; **Dim**: 2484.20 m^2
2.4		EoL.TT.TR	**ToT**: Transport on wheel; **We**: 32294.60 kg; **Dis**: 15 km; **Cap**: > 32 metric ton; **Class**: EURO 4; **Dim**: 2484.20 m^2
5.4		EoL.TT.TR	**ToT**: Transport on wheel; **We**: 320.37 kg; **Dis**: 15 km; **Cap**: 7.5-16 metric ton; **Class**: EURO 4; **Dim**: 19874 p
1.2		EoL.TT.TR	**ToT**: Transport on wheel; **We**: 1738.94 kg; **Dis**: 15 km; **Cap**: 7.5-16 metric ton; **Class**: EURO 4; **Dim**: 4968.40 m^2
6.2		EoL.TT.TR	**ToT**: Transport on wheel; **We**: 437.22 kg; **Dis**: 15 km; **Cap**: 7.5-16 metric ton; **Class**: EURO 4; **Dim**: 2484.20 m^2
3.3		EoL.TT.PR	**Dim**: 2484.20 m^2; **We**: 34778.80 kg; **NoR**: Cement mortar; **RSL**: 20 years
4.3		EoL.TT.PR	**Dim**: 2484.20 m^2; **We**: 2484.20 kg; **NoR**: Polystyrene; **RSL**: 20 years
2.5		EoL.TT.PR	**Dim**: 2484.20 m^2; **We**: 32294.60 kg; **NoR**: Lime, Sand, Cement; **RSL**: 20 years
5.5		EoL.TT.PR	**Dim**: 19874 p; **We**: 320.37 kg; **NoR**: Polyvinylchloride; **RSL**: 20 years
1.3		EoL.TT.PR	**Dim**: 4968.40 m^2; **We**: 1738.94 kg; **NoR**: Alkyd paint; **RSL**: 10 years
6.3		EoL.TT.PR	**Dim**: 2484.20 m^2; **We**: 437.22 kg; **NoR**: Glass fiber; **RSL**: 50 years
3		C.ME.PR	**Dim**: 2484.20 m^2; **We**: 34778.80 kg; **NoR**: Cement mortar; **RSL**: 20 years
4		C.ME.PR	**Dim**: 2484.20 m^2; **We**: 2484.20 kg; **NoR**: Polystyrene; **RSL**: 20 years
2		C.ME.PR	**Dim**: 2484.20 m^2; **We**: 32294.60 kg; **NoR**: Lime, Sand, Cement; **RSL**: 20 years
5		C.ME.PR	**Dim**: 19874 p; **We**: 320.37 kg; **NoR**: Polyvinylchloride; **RSL**: 20 years
6		C.ME.PR	**Dim**: 2484.20 m^2; **We**: 437.22 kg; **NoR**: Glass fiber; **RSL**: 50 years
5.1	U.PD.E/H	C.C.E/H	**So**: Electricity; **Pw**: 0.71 kW; **Tu**: 11.04 h; **Geo**: IT
2.1	U.PD.E/H	C.C.E/H	**So**: Electricity; **Pw**: 1.3 kW; **Tu**: 41.24 h; **Geo**: IT
2.2	U.PD.E/H	C.C.E/H	**So**: Electricity; **Pw**: 1.3 kW; **Tu**: 41.40 h; **Geo**: IT
3.1		C.AS.TR	**ToT**: Transport on wheel; **We**: 34778.80 kg; **Dis**: 5 km; **Cap**: > 32 metric ton; **Class**: EURO 4; **Dim**: 2484.20 m^2
4.1		C.AS.TR	**ToT**: Transport on wheel; **We**: 2484.20 kg; **Dis**: 5 km; **Cap**: 7.5-16 metric ton; **Class**: EURO 4; **Dim**: 2484.20 m^2

2.3	C.AS.TR	**ToT**: Transport on wheel; **We**: 32294.60 kg; **Dis**: 5 km; **Cap**: > 32 metric ton; **Class**: EURO 4; **Dim**: 2484.20 m^2
5.2	C.AS.TR	**ToT**: Transport on wheel; **We**: 320.37 kg; **Dis**: 5 km; **Cap**: 7.5-16 metric ton; **Class**: EURO 4; **Dim**: 19874 p
1.1	C.AS.TR	**ToT**: Transport on wheel; **We**: 1738.94 kg; **Dis**: 5 km; **Cap**: 7.5-16 metric ton; **Class**: EURO 4; **Dim**: 4968.40 m^2
6.1	C.AS.TR	**ToT**: Transport on wheel; **We**: 437.22 kg; **Dis**: 5 km; **Cap**: 7.5-16 metric ton; **Class**: EURO 4; **Dim**: 2484.20 m^2
Total parameters		**140**

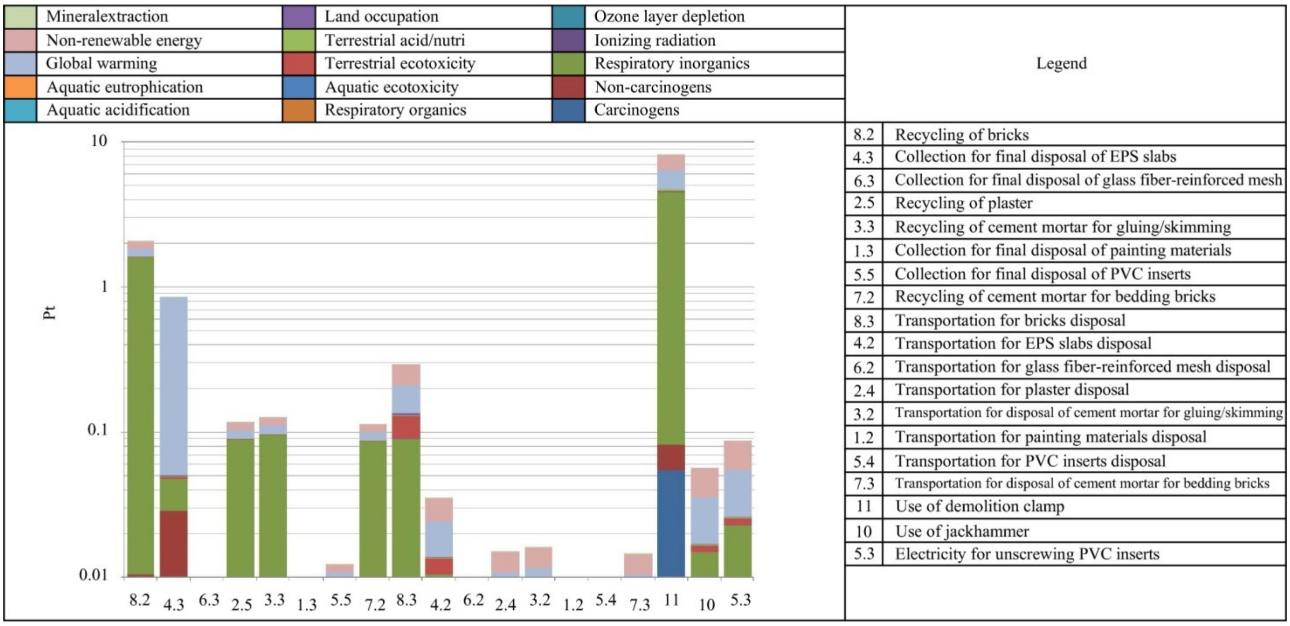

Fig. 5. LCA of the End of Life stage

Table 9

Processes, Variables, and related parameters of the End of Life stage

PROCESSES	VARIABLES	REFERENCE	BIM PARAMETERS
8.2	EoL.TT.PR	C.ME.PR	**Dim**: 2484.20 m^2; **We**: 630365.75 kg; **NoR**: Light clay brick; **RSL**: 50 years
4.3	EoL.TT.PR	C.ME.PR	**Dim**: 2484.20 m^2; **We**: 2484.20 kg; **NoR**: Polystyrene; **RSL**: 20 years
6.3	EoL.TT.PR	C.ME.PR	**Dim**: 2484.20 m^2; **We**: 437.22 kg; **NoR**: Glass fiber; **RSL**: 50 years
2.5	EoL.TT.PR	C.ME.PR	**Dim**: 2484.20 m^2; **We**: 32294.60 kg; **NoR**: Lime, Sand, Cement; **RSL**: 20 years
3.3	EoL.TT.PR	C.ME.PR	**Dim**: 2484.20 m^2; **We**: 34778.80 kg; **NoR**: Cement mortar; **RSL**: 20 years
1.3	EoL.TT.PR	C.ME.PR	**Dim**: 4968.40 m^2; **We**: 1738.94 kg; **NoR**: Alkyd paint; **RSL**: 10 years
5.5	EoL.TT.PR	C.ME.PR	**Dim**: 19874 p; **We**: 320.37 kg; **NoR**: Polyvinylchloride; **RSL**: 20 years
7.2	EoL.TT.PR	C.ME.PR	**Dim**: 2484.20 m^2; **We**: 31300.92 kg; **NoR**: Cement mortar; **RSL**: 50 years
8.3	EoL.TT.TR	C.AS.TR	**ToT**: Transport on wheel; **We**: 630365.75 kg; **Dis**:15 km; **Cap**: >32 metric ton; **Class**: EURO 4; **Dim**: 2484.20 m^2
4.2	EoL.TT.TR	C.AS.TR	**ToT**: Transport on wheel; **We**: 2484.20 kg; **Dis**: 80 km; **Cap**: 7.5-16 metric ton; **Class**: EURO 4; **Dim**: 2484.20 m^2
6.2	EoL.TT.TR	C.AS.TR	**ToT**: Transport on wheel; **We**: 437.22 kg; **Dis**: 15 km; **Cap**: 7.5-16 metric ton; **Class**: EURO 4; **Dim**: 2484.20 m^2
2.4	EoL.TT.TR	C.AS.TR	**ToT**: Transport on wheel; **We**: 32294.60 kg; **Dis**: 15 km; **Cap**: > 32 metric ton; **Class**: EURO 4; **Dim**: 2484.20 m^2
3.2	EoL.TT.TR	C.AS.TR	**ToT**: Transport on wheel; **We**: 34778.80 kg; **Dis**: 15 km; **Cap**: > 32 metric ton; **Class**: EURO 4; **Dim**: 2484.20 m^2
1.2	EoL.TT.TR	C.AS.TR	**ToT**: Transport on wheel; **We**: 1738.94 kg; **Dis**: 15 km; **Cap**: 7.5-16 metric ton; **Class**: EURO 4; **Dim**: 4968.40 m^2
5.4	EoL.TT.TR	C.AS.TR	**ToT**: Transport on wheel; **We**: 320.37 kg; **Dis**: 15 km; **Cap**: 7.5-16 metric ton; **Class**: EURO 4; **Dim**: 19874 p
7.3	EoL.TT.TR		**ToT**: Transport on wheel; **We**: 31300.92 kg; **Dis**: 15 km; **Cap**: > 32 metric ton; **Class**: EURO 4; **Dim**: 2484.20 m^2

11	EoL.DI.E/H	**So**: Electricity; **Pw**: 200 kW; **Tu**: 248 h; **Geo**: IT
10	EoL.DI.E/H	**So**: Electricity; **Pw**: 1.24 kW; **Tu**: 248 h; **Geo**: IT
5.3	EoL.DI.E/H	**So**: Electricity; **Pw**: 0.7 W; **Tu**: 675 h; **Geo**: IT
	EoL.WA.RE	**NoR**: (see PR); **RP**: None; **Geo**: IT
	EoL.WA.AS	**CT**: Wet-assembly
Total parameters		**96**

As can be seen in Tables 8 and 9, 236 parameters are needed to model the use and the EoL phase of the case study. However, as shown for the construction phase, the parameters have some correlations. The correlations among the parameters are made possible assuming that the maintenance activities are based on the same technology and materials involved in the construction phase. The use and EoL phases necessarily refer to the materials flow required for the construction phase, and the related information are already defined. In these phases, the additional parameters that can be modelled in BIM are related to the transport and disassembly/demolition activities. As proof of this, the columns called "reference" in the Tables 8 and 9 show the reference variables from which information was derived for modelling the parameters. As an example, consider the process 8.2 in Table 9: according to the AoV, the parameters related to the EoL.TT.PR variable are the same parameters modelled for the C.ME.PR variable of the process 8 of the construction phase. Hence, these parameters have already been modelled and, for this reason, are redundant.

It should be noted that most of the processes refer only to the “reference" column for defining the variable in Table 8. This is due to the fact that, as depicted in the AoV (Fig. 1), in the use phase there are referral processes when the information refer to different life cycle phases than the one under consideration. For example, consider the process 1 in Table 8: the parameters for modelling the paint that is to be restored are the same as those of C.ME.PR variable of the construction phase. Therefore, according to the "reference" columns in Tables 8 and 9, it is possible to clear the redundant information.

The parameters of the use phase, as shown in Table 8, are all related to the variables of the construction and EoL phase (see the "reference" column, Table 8). This means that the information linked to these parameters are correlated and therefore can be removed in the BIM. In the case study shown, with reference to the use phase, no additional parameters are required to perform the LCA.

With respect to the EoL phase, some correlations are identified. The parameters not related to any reference variable, however, are not redundant. Furthermore, the parameters belonging to the EoL.TT.TR variables in Table 9, referring to the C.AS.TR variables, are not all redundant. The data related to the ToT, We, Cap, Class, and Dim parameter, is the same used to characterize the parameters in the construction phase. Conversely, the Dis parameter is different in the EoL phase: in the construction phase, it refers to the distance between the construction site and the materials production site, while in the EoL phase it is related to the distance between the construction site and the final treatment site. In addition, with regard to the parameters of the EoL.TT.TR variable of process 7.3, the cement mortar is not moved from the production site but produced directly on-site. For this reason, the only redundancies affect the We and Dim parameters. Table 10 shows the parameters of the EoL phase without correlations.

Table 10

Processes, Variables, and related parameters of the End of Life stage with simplifications

PROCESSES	VARIABLES	REFERENCE	BIM PARAMETERS
8.3	EoL.TT.TR	C.AS.TR	**Dis**:15 km
4.2	EoL.TT.TR	C.AS.TR	**Dis**: 80 km
6.2	EoL.TT.TR	C.AS.TR	**Dis**: 15 km
2.4	EoL.TT.TR	C.AS.TR	**Dis**: 15 km
3.2	EoL.TT.TR	C.AS.TR	**Dis**: 15 km
1.2	EoL.TT.TR	C.AS.TR	**Dis**: 15 km
5.4	EoL.TT.TR	C.AS.TR	**Dis**: 15 km
7.3	EoL.TT.TR	C.ME.PR	**ToT**: Transport on wheel; **Dis**: 15 km; **Cap**: > 32 metric ton; **Class**: EURO 4
11	EoL.DI.E/H		**So**: Electricity; **Pw**: 200 kW; **Tu**: 248 h; **Geo**: IT
10	EoL.DI.E/H		**So**: Electricity; **Pw**: 1.24 kW; **Tu**: 248 h; **Geo**: IT
5.3	EoL.DI.E/H		**So**: Electricity; **Pw**: 0.7 W; **Tu**: 675 h; **Geo**: IT
	EoL.WA.RE		**NoR**: (see PR); **RP**: None; **Geo**: IT
	EoL.WA.AS		**CT**: Wet-assembly
Total parameters			**27**

5. Discussion

The proposed framework identifies the relevant BIM parameters needed for performing the LCA. The case study shows that the proposed parameters are sufficient for conducting the LCA of the external wall. The analysis show that it is possible to provide the BIM with a non-too high number of parameters, since most of them are correlated. The implementation of these parameters into the BIM allows for performing the LCA in an effective way. The storage of this information during the design process make it possible to have LCA data when needed.

Table 11 highlights, based on the case study shown, how many parameters are needed to characterize the BIM from the LCA logics, clearing the interconnections found.

Table 11

BIM-LCA parameters

Lifecycle stages	Complete parameters	Parameters with simplifications
Product and Construction Process	100	64
Use	140	0
End of Life	96	27
Total parameters	**336**	**91**

With reference to the modelling, Table 12 shows the parameters required to characterize each material of the case study as well as the means and tools necessary for its construction. Each row of the table is therefore representative of an instance modelled within the BIM and it is related to the single layer/material of the external wall, as well as the equipment for its implementation. Each material is linked to one or more processes that have a number of parameters.

Table 12

BIM parameters related to each BIM element, with simplification

BIM ELEMENT	PROCESSES	BIM PARAMETERS	TOTAL PARAMETERS
Painting	1; 1.1; 1.2	C.ME.PR.**We**/**NoR**/**RSL**; C.AS.TR.**Dis**/**Cap**; EoL.TT.TR.**Dis**	6
Plaster	2; 2.1; 2.2; 2.3; 2.4	C.ME.PR.**We**/**NoR**/**RSL**; C.C.E/H.**So**/**Pw**/**Tu**/**Geo**; C.C.E/H.**So**/**Pw**/**Tu**; C.AS.TR.**Dis**/**Cap**; EoL.TT.TR.**Dis**	13
Cement mortar for gluing/skimming	3; 3.1; 3.2	C.ME.PR.**Dim**/**We**/**NoR**/**RSL**; C.AS.TR.**ToT**/**Dis**/**Cap**/**Class**; EoL.TT.TR.**Dis**	9
EPS slab	4; 4.1; 4.2	C.ME.PR.**We**/**NoR**/**RSL**; C.AS.TR.**Dis**/**Cap**; EoL.TT.TR.**Dis**	6
PVC inserts	5; 5.1; 5.2; 5.3; 5.4	C.ME.PR.**Dim**/**We**/**NoR**/**RSL**; C.C.E/H.**So**/**Pw**/**Tu**; C.AS.TR.**Dis**/**Cap**; EoL.DI.E/H.**So**/**Pw**/**Tu**/**Geo**; EoL.TT.TR.**Dis**	14
Glass fiber-reinforced mesh	6; 6.1; 6.2	C.ME.PR.**We**/**NoR**/**RSL**; C.AS.TR.**Dis**/**Cap**; EoL.TT.TR.**Dis**	6
Cement mortar for bedding bricks	7; 7.1; 7.3	C.ME.PR.**We**/**NoR**/**RSL**; C.C.E/H.**So**/**Pw**/**Tu**; EoL.TT.TR.**ToT**/**Dis**/**Cap**/**Class**	10
Bricks	8; 8.1; 8.3	C.ME.PR.**We**/**NoR**/**RSL**; C.AS.TR.**Dis**/**Cap**; EoL.TT.TR.**Dis**	6
Crane	9	C.C.E/H.**So**/**Pw**/**Tu**	3
Jackhammer	10	EoL.DI.E/H.**So**/**Pw**/**Tu**/**Geo**	4
Demolition clamp	11	EoL.DI.E/H.**So**/**Pw**/**Tu**/**Geo**	4

Table 12 does not include the parameters of the deliverables shown by AoV (Fig.1) as they do not refer to any process and, therefore, to no BIM element. The information related to the parameters of the deliverables is not part of the information flow of a specific BIM element, but it is included among the information of the model or a group of BIM elements.

Table 12 shows that each BIM element is characterized by few parameters, which are sufficient to conduct the LCA of the case study. However, the LCA carried out does not comply with the operational impact and it covers only the process referring to the exterior walls construction. The parameters defined could be tested at the whole building level in the future, also covering the operational impacts. Currently, structuring such parameters is feasible in all BIM software used, but when it comes to interoperability it is a challenging task. Parameters have to be exported/imported in the right place to be useful, and a common model is required. Manufacturers have to be aware of it, and need to provide their BIM objects with the right level of information, duly localised. Moreover, breaking BIM components as they are built in real life with real materials is another challenge, more complex when it comes to associating parameters. These topics are treated in the BIM research community and product modelling activities. Nowadays, researchers tackle the issues of how to link BIM to external databases and include BIM objects in the models. Also norms and standards are being elaborated by ISO and CEN in this direction (i.e. CEN/TC 442/WG 4).

The environmental impact of the case study is assessed with IMPACT 2002+ method. The choice of the impact assessment method does not affect the proposed framework. Moreover, the comparison of different impact methods does not add any benefit in testing the validity of the parameters. Furthermore, LCA is conducted with the use of SimaPro to generalize the method. Generic LCA tools, such as SimaPro and Gabi, have been developed for the LCA of products and processes. These tools are not practical for the designers since they require extensive background knowledge (Hollberg and Ruth, 2016). Nevertheless, to meet the goal of the present study, a generic tool is suitable to test the proposed BIM parameters in a comprehensive manner. However, future research may expand the framework by using different impact assessment methods and different types of LCA tools such as spreadsheet-based tools, component catalogues, and BIM-based tools. This recommendation for future work could help to test the usability of the proposed parameters against the use of different impact methods and tools.

6. Conclusion

Usually, building information models lack of data for a whole LCA. To counter this lack, many other activities need to be considered to have detailed information when the BIM is finished. This paper identifies and encodes the relevant parameters to perform the LCA of buildings, which can be implemented in the BIM environment. A case study is presented in a way to test the effectiveness of the proposed parameters for performing the LCA. The proposed methodology allows for structuring the information in a coded and non-redundant way. This approach makes it possible to perform the LCA based on the available data into the BIM and would allow for extracting information directly from the template in a consistent manner, reducing the risk of errors, approximations, and omissions due to inconsistent or missing data. Hence, the LCA can be performed as soon as the building information model is ready for the analysis. The proposed framework fills the information gap between the extracted BIM parameters and the LCA data requirements. This results in the reduction of time-consuming activities and assumptions made.

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