Developing an integrated BIM/LCA framework to assess the sustainability of using earthen architecture

Citation for published version:
Estève, P, Beckett, CTS, Pedreschi, R, Bosché, F, Morel, JC, Charef, R & Habert, G 2022, Developing an integrated BIM/LCA framework to assess the sustainability of using earthen architecture. in *IOP Conference Series: Earth and Environmental Science: sbe22 Berlin D-A-CH conference: Built Environment within Planetary Boundaries (SBE Berlin) 20/09/2022 - 23/09/2022 Berlin.* vol. 1078, 012100, IOP Publishing, Sustainable Built Environment D-A-CH Conference Berlin 2022: , Berlin, Germany, 20/09/22. https://doi.org/10.1088/1755-1315/1078/1/012100

Digital Object Identifier (DOI):
10.1088/1755-1315/1078/1/012100

Published In:
IOP Conference Series: Earth and Environmental Science

Developing an integrated BIM/LCA framework to assess the sustainability of using earthen architecture

P Estève[1,] *, C Beckett[1], R Pedreschi[2], F Bosche[1], J C Morel[3], R Charef[4], G Habert[5]

[1] Institute for Infrastructure and Environment, School of Engineering, The University of Edinburgh, United Kingdom
[2] School of Architecture and Landscape Architecture, The University of Edinburgh, United Kingdom
[3] LTDS UMR CNRS 5513, ENTPE, Université de Lyon, France
[4] Independent Researcher, France
[5] Chair of Sustainable Construction, Institute of Construction and Infrastructure Management, Swiss Federal Institute of Technology (ETH Zurich), Switzerland
*: Corresponding author: pierre.esteve@ed.ac.uk

Abstract. The construction industry is responsible for one-quarter of the solid waste generated globally, much of which is excavated soil. Repurposing this soil for the use of earthen architecture (EA) will reduce a considerable amount of this waste. However, little research has been conducted on how to assess the use of EA within the architectural, engineering, environmental and economic context, and in comparison with other construction system solutions. This paper presents the development of an integrated building information modelling (BIM) and life cycle assessment (LCA) framework to explore what advantages EA may have, based on the client's needs and the building's requirements. The decision-making conditions and criteria for the use of EA are firstly identified in an extensive literature review supported by interviews with decision-makers. A workflow is secondly proposed to apply a LCA evaluating the decision criteria in a BIM tool at the early-design stages. This method allows for the evaluation and comparison of choice criteria as functional requirements of the building and objectives set by the decision-makers. The flexibility of setting input parameters in this tool increases the visibility of the potential benefits of EA over other construction systems. Along with this approach, upcoming applications on case studies will aim to be replicable by designers, based on their practices and design tools, to support clients in their choice of using EA.

Keywords: Earthen Architecture, Life Cycle Assessment, Building Information Modelling, Framework, Viability

1. Introduction

The building construction and operation sector is responsible for 38% of global CO_2 emissions, almost 50% of the resources extracted and removed from the ground [1] and more than 25% of the solid waste generated, mostly composed of excavated soil [2]. Reusing this soil as a primary construction material for earthen architecture (EA) will reduce both the extraction of virgin resources and the production of waste [3]. The development and wider adoption of EA has the potential to help the building construction and operation sector achieve the net-zero carbon targets by 2050 set by the IPCC [4]. This strategy fits, according to Bui et al. [5], in a circular economy logic defined by the European Green Pact [6] and is in line with the objectives of the New European Bauhaus [7] which assumes that creativity is sublimated in the search for attractive, accessible and inclusive solutions to climate challenges.

Life Cycle Assessment (LCA) is recognised as a method for assessing the impacts of buildings. It is also a standardised tool under the ISO 14040 standard [8], making its application possible globally, and is implemented for the construction sector with the EN 15978 standard [9]. The framework of the methodology is presented in 4 stages: definition of the goals and scope; development of the inventory of all the elements to be analysed; assessment of the impacts of the elements identified; and interpretation of the results (Figure 1). In particular, the first definition stage allows the building life cycle phases and the functional unit considered for the LCA study to be stated. This setup functions as a common basis for comparison between different systems.

The reliability of LCA studies is based on the quality and consistency of the data used that avoids comparative bias between two different construction systems. The Environmental Product Declaration (EPD), which includes the environmental impacts of transformed products such as the Global Warming Potential (GWP) or the Cumulative Energy Demand (CED), is defined by the European standard EN 15804 [10] and provides a framework for data reliability. Environmental information on construction products for LCA analysis is available both in databases using EPDs, either open-source such as INIES, Ökobaudat, or private such as Ecoinvent; or in databases using environmental data adapted to LCA analysis, such as provided by the UK Institution of Civil Engineers (ICE), the Swiss coordination conference of the responsible federal and cantonal clients and owners (KBOB), OpenDAP, or US-LCI [11]. Data found in the literature are also used for LCA analyses [12].

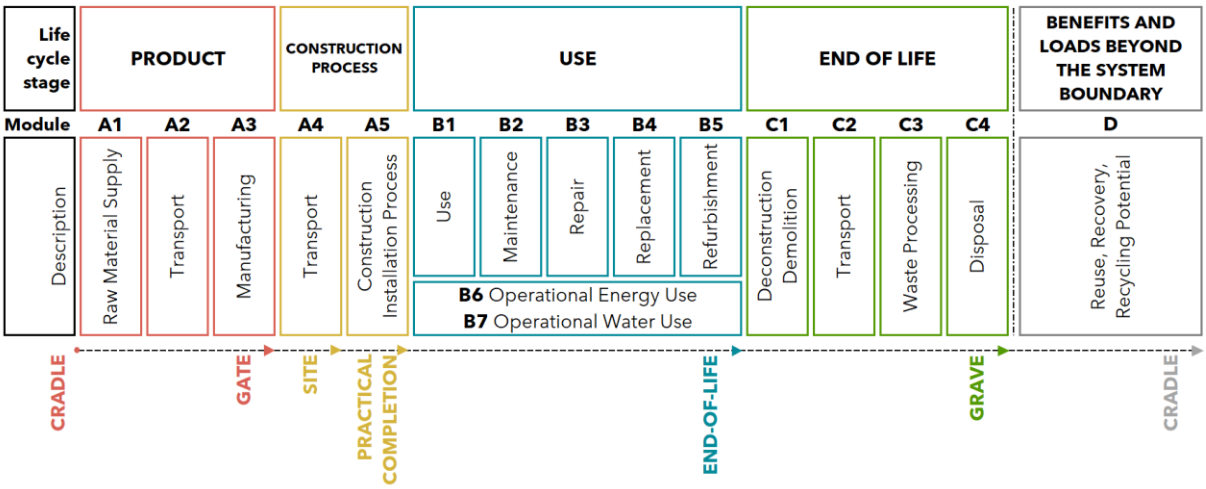

Figure 1. Life cycle stages and modules modified from EN 15978 [9].

In the same way that LCA is used to assess environmental impacts, Life Cycle Costs (LCC) are used to assess the economic impacts, within the standard framework of ISO 15686-5 [13]. Although LCC can be applied following the LCA methodological framework, the scope also takes into account the additional costs of feasibility studies or externalities in what is called the Whole Life Costs [13]. The data used for the LCC analyses come from price books or catalogues such as Spon's price books [14] or Batiprix [15] or from dedicated software such as RS Means [16]. Unlike LCA and LCC, there is no standardised framework for the assessment of social criteria but UNEP has built on the LCA framework to define guidelines for Social-LCA (S-LCA) [17].

The Building Information Modelling (BIM) strategy enables the federalisation, processing and analysis of data used and produced during the design, construction, operations, and maintenance phases. As such, it can facilitate the setting up of a circular economy [18], in the management of the quantity records of construction and demolition waste, including excavated earth. BIM methodology and structured data recording can benefit LCA analysis by assimilating, in the BIM model, the quantitative impacts resulting from the analyses that are related to the materials used in the building.

Despite its apparent environmental advantage and its integration in a circular economy strategy, EA still has to find a widely-recognised place among other construction systems [19]. To date, attention among academics and professionals has mostly been given to the mechanical and structural usability of EA. Economic, organisational and social barriers are also receiving increasing attention [20]. However, little research has been conducted on how to assess the use of EA in comparison with other construction system solutions [21]. This paper aims to establish how an objective assessment framework in early-design stage for the use of EA could be established. This assessment is based on the client's needs and the building's requirements to be designed as choice criteria assessed over the life cycle of the building with a LCA method. This proposed evaluation approach relies on the practices and tools of the designers, here the use of BIM, to integrate the LCA criteria into the model. Based on an inductive approach, constructing theories from collected empirical data [22], this paper addresses the following objectives:

- Determine which conditions and choice criteria should be considered, based on the client's needs and the building's requirements, to evaluate the use of EA with a LCA method.
- Identify how to integrate these LCA choice criteria into a BIM tool, in accordance with the practices of the designers, in the early-design phase.

2. Methodology

To meet the set objectives, the research design comprises two parts: data collection and analysis from the literature review; and the design of a decision-support tool.

In a first step, the literature review, supported by interviews with decision-makers, will allow the identification of the factors playing a role in the decision-making process of the use of EA by focusing on the actors, the timing, the criteria of choice, and the construction systems used as a reference for comparison. The results of this analysis will highlight the relevant criteria to consider in the LCA for evaluating the sustainability of the choice of EA.

In a second step, the decision-making tool will be elaborated, based on the problem-solving paradigm of Design Science Research (DSR) which encompasses the development and use of artefact, here a piece of software, to solve real problems [23]. A workflow will thus be proposed to create a scheme for implementing a LCA analysis in BIM software. This workflow will integrate, through parametric coding, an iterative process between the decision criteria and resulting impacts. The proposed approach will be meant to consider all the possible constructive systems (e.g., reinforced concrete, fired masonry etc.) to make an objective comparative assessment and thus offer the decision-maker the possibility to choose the preferred solution.

3. Conditions of the decision-making for a sustainable EA use in the early-design phase

The identification of the actors, timing and criteria for decision making provides a basis for the proposed decision support tool.

3.1. The stakeholders and the timing of the decision-making process

The decision-making of the construction system is done with actors belonging to several professions at the early-design stage, which corresponds to phases 0, 1, and 2 respectively of strategic definition, preparation and briefing and concept design, see Figure 2 [24], [25]. On the one hand, the project owner composed of clients and/or investors can make a difference by procuring sustainable projects [26]. On the other hand, the project delivery team, consisting of the architects and engineers accompanied by the builders in the case of EA, also has a role to play as, in the early-design stages, they influence environmental impacts, energy demand and costs [27].

These decision-makers traditionally intervene in different phases of the design process, preventing smooth cooperation between the actors. Bringing together clients, architects, engineers and builders at the early-design stages allows for a more relevant response to the needs and constraints of the building [28]. Thus, the project owner defines its objectives and the project delivery team, based on its knowledge of materials, orchestrates the design of different technical solutions to meet these objectives [29]. As the feasibility of an earthen project must be anticipated at an early-design stage, decision-makers need to have an informed view of the impacts of choosing this construction system.

	Early design			Detailed design				Management	
Design stages	0 Strategic definition	1 Preparation & briefing	2 Concept design	3 Spatial coordination	4 Technical design	5 Manufacturing & construction	6 Handover	7 Use	8 End-of-life
Core tasks	- Preparation and ratification of options for client requirements - Review of project risks and budget - Site appraisals	- Project brief and sustainability outcomes - Feasibility studies - Project programme and execution plan	- Architectural concept, strategic engineering and cost plan - Design reviews with stakeholders	- Design studies, engineering analysis and cost exercises to test architectural concept - Strategies update and cost plan	- Architectural and engineering technical design - Building system information development - Construction phase plan	- Manufacturing building systems and construction of building - Inspection of building quality	- Review of project performance - Commissioning of building - As-built documentation	- Facilities and asset management - Post occupancy evaluation - Improvement of building performances	- Deconstruction, reuse, and recycling

Figure 2. Project phases with corresponding objectives modified from RIBA's Plan of Work [30] and completed for stage 8 of end-of-life recovery from Charef [31] supporting circular activities.

3.2. The decision criteria for relevant use of EA

The level of sustainability of a building lies in its holistic assessment by environmental, economic, social, health or comfort criteria [32]. Stakeholders can set these criteria as objectives according to the requirements of the building to assess the relevance of EA and compare it to other construction systems in the early-design stage, see Figure 3.

For the environmental assessment of a building, among the large number of indicators used in the literature, the most recurrent are GWP (in $kgCO_2e$) and CED (in MJ) [12], [16]. Ben-Alon et al. [33] establish that the production of 1 m^2 of cob wall has lower impacts in terms of GWP and CED, than the equivalent concrete block or light-frame wood system from cradle-to-site (A1-4). Meek et al. [34] obtain similar results for the comparison of the production of stabilised walls, composed of recycled concrete and crushed brick materials, with walls employing cavity double brick and brick veneer construction systems. The distance of transported material (in tonne.km) must also be considered as this can quickly become an impacting factor in the case of EA. The transport of soil extracted off-site can multiply by 3 the environmental impact for the production of an earthen brick [35]. In this case, the location of the soil is crucial, the scale adopted is no longer that of a country but that of a region or a maximum radius.

Sustainability performance cannot be reduced to environmental impacts; it must also promote the benefits of choosing one construction system over another taking into account economic and social factors [36]. The economic viability of a building is based on the cost to the customer [16]. According to Floissac et al. [15], although a house made with local materials using a wood-earth-straw system is environmentally more efficient, it is 20% more expensive than a house made with standard materials for the cradle-to-practical completion phases (A1-5). In a European context, this is due to labour that is more expensive than the material, whereas, in a context where the cost ratio is reversed, earthen construction is economically more interesting [37]. Villain [38] recalls that despite a cost up to twice as expensive for a rammed earth wall, its social intensity, defined as the ratio of the cost of labour to the cost of manufacturing, is 5 to 6 times higher than for a concrete block wall.

Popovic et al. [39] consider that the evaluation of social criteria for a complex system is also done on health and comfort criteria. In a survey, Akom et al. [40] determine that occupant satisfaction is related to indoor air quality, and that frequently used health criteria are Volatile Organic Components (VOCs) and Particulate Matters (PM). Although there is little data available on thermal comfort for EA, some studies use coefficients such as Standard Effective Temperature (SET) to assess comfort based on temperature, relative humidity and air velocity [41]. The use of EA can improve both the thermal comfort and energy performance of a building; however, the impacts on the architecture must be considered. In a subtropical climate, based on modelling of a school, Yan et al. [42] achieve better thermal comfort performance by replacing concrete walls with rammed earth walls. However, these walls are respectively 230 and 430 mm thick (including 30 mm of insulation), resulting in a reduction in the usable habitable surface. Similarly, Paiva et al. [43] show experimentally that an earth-based bamboo coating achieves better energy performance than cementitious materials, but with the condition that the earth-based bamboo coating is replaced more frequently, increasing the need for maintenance.

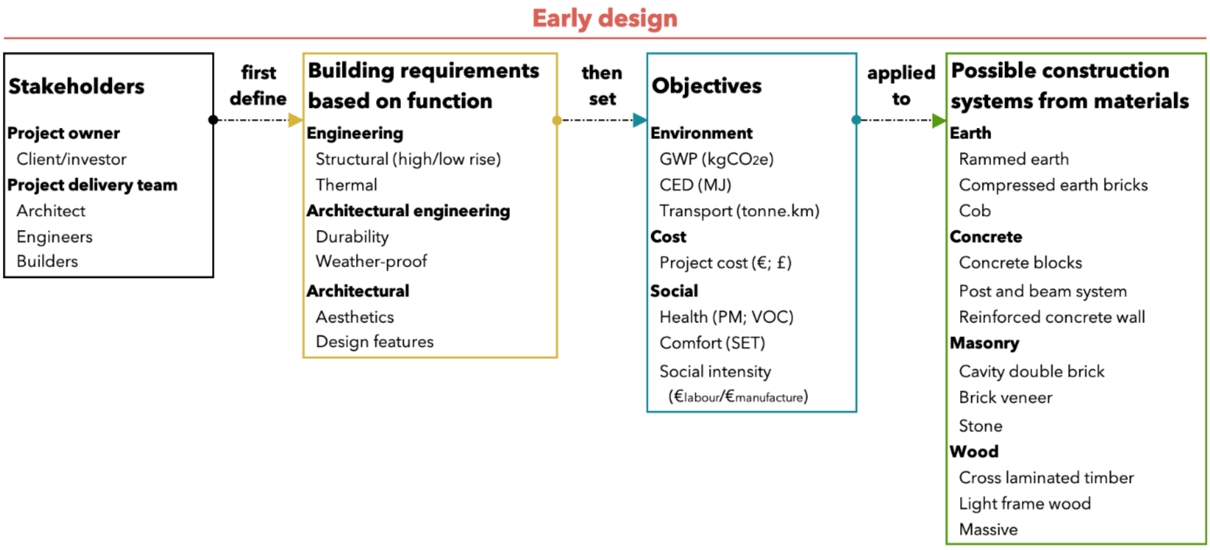

Figure 3. Conditions for assessing the sustainability of the EA use.

4. Implementation of a decision-support tool using a BIM/LCA strategy

This procedure is intended to be replicable by architects and engineers using the RIBA stages and the BIM design tool. Such a tool allows the evaluation of the use of EA by integrating data related to LCA choice criteria into a model. This strategy will provide better visibility to architects and engineers on the results of the LCA and therefore enhance communication with clients.

4.1. The use of a BIM strategy as a collaborative tool

The development and usage of BIM methodology and tools has been assisting in complex decision-making by connecting stakeholders across the design, construction, operations, and maintenance phases and supporting more automated data analysis. The use of BIM for the deconstruction phases has an increasing interest among researchers and is used in several projects [44]. The simulation of using BIM allows the focus to be on the design with an insight into the effects of a design or material choice [45]. According to Morel et al. [20], a better understanding of the impact criteria that the building will have would allow more cohesion for the whole decision chain, necessary for the smooth running of an earthen project. The stakeholders will work cooperatively and create a federated model in a cloud environment. The client checks the feasibility of a project; the architect manages the creation of the BIM model; the structural and thermal engineers include the physical-thermal and environmental properties in the model; and the quantity surveyor uses the model information for LCC [46]. The choice is made in this study to present an approach based on the Rhinoceros3D modelling software, and its graphical coding interface Grasshopper, as it is a common and affordable design tool used by designers [47].

4.2. An approach for evaluating the sustainability of EA using a BIM/LCA strategy

The standardised LCA framework [8] allows for the systematic comparison of different construction systems based on quantitative environmental, economic, and social data. This approach is in line with the Sustainable Development Goals set by the United Nations [48] and is therefore defined as Life Cycle Sustainable Assessment [36]. In the early-design stages, the choice of EA is usually perceived by the clients as a more onerous initial investment, with more risks and with less visibility on its whole life cycle than for other materials [20]. These choice phases also offer little visibility on more qualitative criteria such as the user comfort or the environmental impact of the building. The use of the LCA method coupled with BIM tools allows the implementation of a design scenario to analyse, control and visualise impacts to optimise the design and thus orient it towards a more resource-efficient building [46]. Such implementation of LCA data in a model developed in Grasshopper can be done through open-source plugins such as Cardinal LCA (linked to LCA databases) [49] or Ladybug for energy analyses [50].

	Simplified component-based approach			Detailed material-based approach		
Design stages	**0 Strategic definition**	**1 Preparation & briefing**	**2 Concept design**	**3 Spatial coordination**	**4 Technical design**	**5 Manufacturing & construction**
LOD stage	**Pre-LOD** Masses disposition	**LOD 100** Conceptual design	**LOD 200** Approximate design	**LOD 300** Precise design	**LOD 400** Fabrication	**LOD 500** As built
LOG	2.5D surfaces	3D generic representation	Approximate quantity, size, shape, location	Accurate quantity, size, shape, location	Detailing and installation information	Representation of field components
LOI	None	None	Non-graphic information	Non-graphic information	Non-graphic information	Non-graphic information
BIM Structure	Main group	Element	Component material	Component material	Material as planned for fabrication	Material as built
Building element	C - Building C02 - Wall	C02.01 - External wall	C02.01 00x - Cob C02.01 00x - Straw C02.01 00x - Earth plaster	00x - Cob 00x - Straw 00x - Earth plaster 00x - Masonry base 00x - Lintel wood	00x - Cob 00x - Straw 00x - Earth plaster 00x - Masonry base 00x - Lintel wood	00x - Cob 00x - Straw 00x - Earth plaster 00x - Masonry base 00x - Lintel wood
Visual aspect						

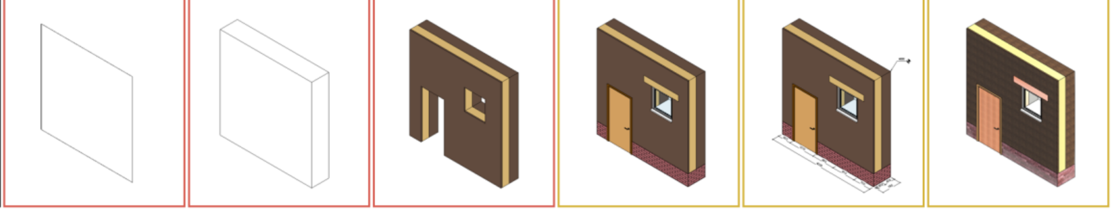

Figure 4. The relationship between the building phases, LOD and BIM management modified from [51] using SN 506511 building elements classification [52].

One of the main challenges in comparing EA with common construction systems lies in the necessary architectural rethinking involved in the choice of earth materials. Indeed, depending on its structural role, it may be impossible to change a concrete, wood, fired clay (or other) wall for an earthen wall of the same thickness or span, meaning that the whole design must be adapted. This challenge requires reconsidering the comparison method between construction systems that cannot be based only on architectural elements, such as 1 m^2 of wall or floor, but using equivalent architectural systems. A possible common denominator of the comparison is that the functional needs and constraints of the building must be the same for the use of concrete, wood, fired clay, or other, than for an earthen construction system. Some authors already make comparisons on a larger scale than the wall, based on the whole building. Meek et al. [34] base their comparison on the wall scale for the cradle-to-gate phases (A1-3) and the whole building for the gate to practical completion phases (A4-5). Likewise, Floissac et al. [15] support their comparison of construction systems on a whole house for the cradle-to-practical completion phases (A1-5). Gong et al. [53] base the functional unit of their comparison on a building providing the same living space with the same thermal comfort. The use of this comparison involves adapting the design to the material for the manufacturing, construction, operation, and disposal phases (A1-3,5; B6-7; C3-4). Ventura et al. [35] warn, however, that comparisons at the level of the whole building are generally unfavourable to raw earth for high-rise buildings. A three-storey earthen building has a 19% higher GWP and CED impact than a one storey earthen building due to the need to thicken the walls to increase their resistance.

Integrating LCA data into the BIM model involves matching the information to the components. It means the BIM elements and the LCA database must be adapted to ensure a bijective link between them [54]. A reference such as SN 506511 [52] of names of building elements allows setting a classification system for the attribution of LCA data. In a BIM model, the Level Of Development (LOD), comprising both the level of geometry (LOG) and level of information (LOI), is standardized by the EN 17412 [55] allowing to link the project phase to the design level. The strategic phase corresponds to a Pre-LOD, the preparation and briefing phase to LOD 100 and the concept design phase to LOD 200, see Figure 4 [16], [51]. Although there is no referencing of LCA data for the different LOD [16], a LOD 200 is recommended for using a simplified component-based approach that takes materials into account, in both LCA [51] and LCC [16] analyses integrated into a BIM strategy. To conduct a LCA at the early-design stages and at the building level, the EeBGuide [56] recommends including external walls, windows, roofs, ceilings, floors, internal walls, columns, foundations, coatings and services. Other data is accounted for with default values [24].

For the life cycle phases, according to the EeBGuide, an early-design stages' LCA needs to take into account phases A1-3, B4, B6-7, C3-4 and possibly D (see Figure 1), which account for 70 to 90% of the environmental impact of a residential building [24], [56]. Gervásio et al. [57] propose to adapt the A4 and C2 transport phases to the context while the Institution of Structural Engineers (UK) [27] indicates that phases B1-5 can be neglected for structural studies. In addition, the LCC may include programming and design costs [58] in the project costs, for the considered building life cycle phases.

4.3. Application of a systematic routine for implementing a decision support tool

In the early-design stages, architectural design leads to large variations in geometry. The process of automating the selection criteria meets the iterative needs imposed by this design process. The form of visualisation taken by these results must be clear and concise to ensure that the non-expert decision-makers can instinctively understand the meaning of the results. A graphical coding interface, such as Grasshopper, allows creating an iterative routine using scripts for task automation [59], linking the variation of an input parameter to the consequent output result in instant feedback.

From the workflows of Meek et al. [24], Otovic et al. [59], and Ogunkah and Yang [60] who define the stages necessary to automate a decision support tool, seven steps are identified to define a systematic routine, see Figure 5. The choice of one construction system over another is made in relation to the functional requirements and constraints of the building, the objectification of which allows a common basis for comparison to be established. The decision-makers then set environmental, economic and social objectives to gain visibility on the consequences of choosing EA [25], [60].

The sustainable impact being not necessarily reduced by a change of materials but potentially by optimising the design [61], an optimisation step can be added to the automation. It allows to propose alternative solutions in the automated exploration of the design parameter space and to save time in the design by identifying relevant design parameters, such as the orientation of the building or the size of the openings [47]. In this optimisation process, the use of a Pareto optimal front allows the user to choose the combination of factors that suits them best [62].

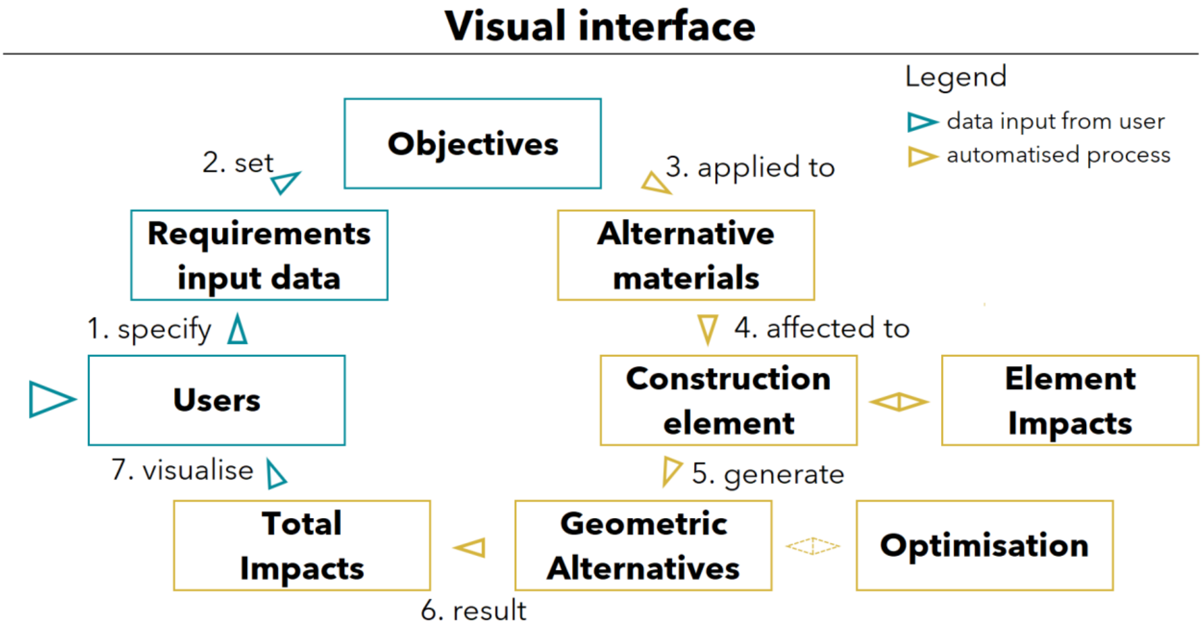

Figure 5. Systematic iterative routine for the implementation of the decision support tool, based on Figure 3 (in blue), using an iterative BIM/LCA strategy (in yellow).

5. Discussion

This paper outlines the conditions and criteria for the choice of EA by clients, designers, and builders. A procedure is therefore proposed for the development of a workflow to evaluate in early-design stage the sustainability of EA use from the perspective of the above decision-makers.

The approach proposed in this paper is based on the client's needs and the functional requirements of the building, considering the design specificities of EA. These parameters can be defined at the early-design stage, when the decision on the construction system to adopt is made, and can include engineering, architectural, environmental, economic, or social criteria. They allow the identification of objectives that can be evaluated over the entire life cycle of the building by assigning impacts to the different construction systems and evaluating them with a LCA method. The real importance of these impacts as criteria for the choice of EA is being consolidated by interviews with decision makers. However, LCA data variability remains a major issue for assessing EA at the early-design stage, the strong contextual dependence of the earth construction properties and the weak definition of the project at the early-design stages raise a dual challenge regarding the management of the data. The variability of this data could be controlled with an uncertainty analysis. Such an analysis provides a probability distribution of results rather than a single value, making the estimated value of the impacts from LCA more reliable and secure [63].

The development of the framework relies on the designers' tools by using a BIM software, such as Rhinoceros3D, to assemble the LCA data and visualise the results to help them make decisions. This is done in an early-design stage using a simplified component-based approach allowing the analysis of data with a basic architectural model for the most significant parts of the building life cycle. The link between the architectural elements and the LCA data is made directly in the BIM tool using plugins. Rhinoceros3D and Grasshopper also offer a wide range of plugins to evaluate most of the criteria for choosing EA to complement the LCA, such as stresses or user comfort. The flexibility induced by the parameterisation of LCA criteria in the BIM tool thus increases the visibility of the potential benefits of EA over other construction systems. Despite its growing interest, the numerical BIM/LCA tools are still little used in early-design stages due to the high time consumption or conflicting requirements [47]. The automation of tasks for the development of an iterative routine allowing direct observation of the input/output link is made possible by the development of scripts that can be executed in parametric tools. Thus, the approach presented in this paper is in line with the ambition to develop and widely disseminate such decision support tools for using EA missing from the literature to date.

6. Conclusion and future research

This paper presents the development of a decision-making framework, using project delivery practices, to provide a way to have greater visibility on the benefits of using EA, by assessing its sustainability and in perspective with another system. It is based on a LCA methodology integrated with BIM software to assist decision-makers in choosing a suitable construction system for new and refurbished buildings. This research, therefore, may provide a more holistic approach to assessing the most appropriate construction system to choose at the early-design stages leading to the use of a more environmentally, economically, and socially sustainable construction material.

Assumptions are made about the conditions for deciding which construction system to use. It is supposed that the actors in the decision-making process are the clients, architects, engineers, and builders and that the decision is made at the early-design stages from strategic definition to concept design. Furthermore, some criteria are identified as relevant to the assessment of the sustainability of the use of EA such as GWP, CED, transport, costs, or user comfort. It is further suggested that the most relevant comparison between EA and other construction systems should be made based on the functional requirements of the building. These assumptions need to be validated, reinforced, and complemented in further research with the clients and the expertise of design and construction professionals of raw earth, defined by von Hippel [64] as 'lead-users' capable of improving the commercial attractiveness of the material.

References

[1] United Nations Environment Programme 2020 *Global Status Report for Buildings and Construction* (Nairobi: UNEP).

[2] Benachio G L F, Freitas M do C D and Tavares S F 2020 *J. Clean. Prod.* **260** 121046.

[3] Klinge A, Eike R-K, Radeljic L, Bojic D and Neumann E 2020 *8th Int. Conf. on Build. Earth* (Weimar: Dachverband Lehm e.V.).

[4] Intergovernmental Panel on Climate Change 2021 *Climate Change 2021: The Physical Science Basis - Summary for Policymakers* (Switzerland: IPCC).

[5] Bui Q B and Morel J C 2015 *Materials* **8** 1–15.

[6] European Commission 2019 *A European Green Deal*.

[7] European Commission 2021 *New European Bauhaus*.

[8] British Standards Institution 2020 *BS EN ISO 14040-2006+A1-2020 - Environmental management — Life cycle assessment — Principles and framework.*
[9] British Standards Institution 2012 *BS EN 15978:2011 - Sustainability of Construction Works: Assessment of Environmental Performance of Buildings: Calculation method.*
[10] British Standards Institution 2019 *BS EN 15804:2012+A2:2019 - Sustainability of construction works - Environmental product declarations.*
[11] Pagnon F, Mathern A and Ek K 2020 *IOP Conf. Ser.: Earth Environ. Sci.* **588** 042051.
[12] Cabeza L F, Boquera L, Chàfer M and Vérez D 2021 *Energy Build.* **231** 110612.
[13] British Standards Institution 2017 *BS ISO 15686-5:2008 Buildings and constructed assets - Service life planning - Part 5: Life-cycle costing.*
[14] AECOM 2020 *SPON'S Architects' and builders' price book* (Oxon: CRC Press).
[15] Floissac L, Marcom A, Colas A S, Bui Q B and Morel J C 2009 *5th Urb. Res. Symp.* (Marseille: IISD).
[16] Lu K, Jiang X, Yu J, Tam V W Y and Skitmore M 2021 *J. Clean. Prod.* **285** 125438.
[17] Norris C *et al.* 2020 *Guidelines for Social Life Cycle Assessment of Products* (UNEP).
[18] Charef R and Emmitt S 2021 *J. Clean. Prod.* **285** 124854.
[19] Zami M S 2021 *Archit. Eng. Des. Manag.* **17** 1–18.
[20] Morel J-C, Charef R, Hamard E, Fabbri A, Beckett C and Bui B 2021 *Phil. Trans. R. Soc. B* **376** 20200182.
[21] Ben-Alon L 2019 *Natural Buildings: Integrating Earthen Building Materials and Methods Into Mainstream Construction*, (Pittsburgh: Carnegie Mellon University).
[22] Creswell J W 2017 *Research design: qualitative, quantitative, and mixed methods approaches*, 5th ed. (Los Angeles: SAGE Publications, Inc.).
[23] Olawumi T O and Chan D W M 2022 *Expert Syst. Appl.* **188** 116020.
[24] Meex E, Hollberg A, Knapen E, Hildebrand L and Verbeeck G 2018 *Build. Environ.* **133** 228–236.
[25] Hollberg A, Kiss B, Röck M, Soust-Verdaguer B, Wiberg A H, Lasvaux S, Galimshina A and Habert G 2021 *Build. Environ.* **190** 107530.
[26] Habert G *et al.* 2020 *Build. Cities* **1** 429–452.
[27] Institution of Structural Engineers UK 2020 *How to calculate embodied carbon* (London: ISE).
[28] Hollberg A, Götz M, Lichtenheld T, Hollberg P, Galimshina A and Habert G 2019 *Proc. Build. Sim.* (Rome: International Building Performance Simulation Association) 2627–33.
[29] Hay T J, Lee D and Larsen O P 2012 *Int. Conf. Des. Creativity* (Glasgow: The Design Society).
[30] Royal Institute of British Architects 2020 *Plan of Work 2020 - Overview* (London: RIBA).
[31] Charef R 2022 *Cleaner Engineering and Technology* **8** 100454.
[32] Thanu H, Rajasekaran C and Deepak M 2020 *Smart Sustain. Built Environ.* **ahead-of-print**.
[33] Ben-Alon L, Loftness V, Harries K A, DiPietro G and Hameen E C 2019 *Build. Environ.* **160** 106150.
[34] Meek A H, Elchalakani M, Beckett C T S and Grant T 2021 *Constr. Build. Mater.* **267** 120997.
[35] Ventura A *et al.* 2022 in *Environmental Potential of Earth-Based Building Materials: Key Facts and Issues from a Life Cycle Assessment Perspective*, **35** (Cham: Springer) 261–296.
[36] Fauzi R T, Lavoie P, Sorelli L, Heidari M D and Amor B 2019 *Sustain.* **11** 636.
[37] Adegun O B and Adedeji Y M D 2017 *Front. Arch. Res.* **6** 519–528.
[38] Villain V 2020 *Sociologie du champ de la construction en terre crue en France (1970-2020)*, (Lyon: Université de Lyon).
[39] Popovic T and Kraslawski A 2015 in *Social Sustainability of Complex Systems*, **36** 605–614.
[40] Akom J B, Sadick A-M, Issa M H, Rashwan S and Duhoux M 2018 *J. Green Build.* **13** 98–120.
[41] Beckett C T S, Cardell-Oliver R, Ciancio D and Huebner C 2017 *J. Build. Eng.* **13** 146–158.
[42] Yan Y K and Song Y F 2021 *J. Phys. Conf. Ser.* (Kiev: IOP Publishing Ltd).
[43] Paiva R de L M, Caldas L R, Martins A P de S, de Sousa P B, de Oliveira G F and Toledo Filho R D 2021 *Sustain.* **13** 10429.

[44] Interreg North-West Europe 2022 *Digital Deconstruction*.
[45] Röck M, Hollberg A, Habert G and Passer A 2018 *Procedia CIRP* **69** 218–223.
[46] BIM World 2016 *Manifeste BIM* (Paris: BIM World).
[47] Østergård T, Jensen R L and Maagaard S E 2016 *Renew. Sustain. Energy Rev.* **61** 187–201.
[48] United Nations 2015 *THE 17 GOALS - Sustainable Development*.
[49] Chen J, Kharbanda K and Loganathan H 2021 *Cardinal LCA v0.0.1*.
[50] Sadeghipour Roudsari M and Michelle P 2013 *13th Int. IBPSA Conf.* (Chambery: IBPSA).
[51] Naneva A, Bonanomi M, Hollberg A, Habert G and Hall D 2020 *Sustain.* **12** 3748.
[52] CRB Zurich 2020 *SN 506511:2020 - eBKP-H - Elementbasierter Baukostenplan Hochbau*
[53] Gong X, Nie Z, Wang Z, Cui S, Gao F and Zuo T 2012 *J. Ind. Ecol.* **16** 576–587.
[54] Abu-Ghaida H and Kamari A 2021 *Proc. 38th Int. Conf. CIB W78* (Luxembourg: Luxembourg Institute of Science and Technology) 782–792.
[55] British Standards Institution 2020 *BS EN 17412-1:2020 - Building Information Modelling. Level of Information Need. Concepts and Principles.*
[56] European Commission 2012 *EeBGuide Guidance Document - Part B: Buildings - Operational guidance for life cycle assessment studies of the Energy-Efficient Building Initiative*.
[57] Gervásio H, Santos P, Martins R and Simões da Silva L 2014 *Build. Environ.* **73** 256–270.
[58] Lee J, Yang H, Lim J, Hong T, Kim J and Jeong K 2020 *J. Asian Archit. Build. Eng.* **19** 384–399.
[59] Otovic A, Negendahl K and Jensen L 2016 *ASHRAE Annu. Conf.* (St. Louis: ASHRAE).
[60] Ogunkah I and Yang J 2012 *Build.* **2** 1–32.
[61] Hart J, D'Amico B and Pomponi F 2021 *J. Ind. Ecol.* **25** 403–418.
[62] Apellániz D, Pasanen P and Gengnagel C 2021 *12th Annu. Symp. Simul. Archi. Urban Des.* (San Diego: Society for Computer Simulation International).
[63] Belizario-Silva F, Galimshina A, Reis D C, Quattrone M, Gomes B, Marin M C, Moustapha M, John V and Habert G 2021 *J. Build. Eng.* **44** 102979.
[64] von Hippel E 2005 *JfB* **55** 63–78.