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Circular building with raw earth: a qualitative assessment of two cases in Belgium

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Abstract. The built environment puts high pressure on our planet, and a great deal is related to resource extraction, material production and waste generation. In the context of circular construction, buildings must be designed and built in order to keep our natural resources in closed material loops for as long as possible. Raw earth has regained attention in the building industry as an abundant, low-impact and highly recyclable building material. However, little is known and experienced about the implementation of raw earth in circular building design. Therefore, this research offers a better understanding of the circularity of earth architecture by assessing two contemporary Belgian cases. Based on literature, semi-structured interviews and the analysis of technical documents, the circularity of the two cases is qualitatively assessed at different scales and levels. It appears that circularity is highest on the material scale and lowest on the building scale for both cases. It is also found that earth as a building material does not easily fit in existing circular assessment frameworks. This investigation represents a contribution towards the development of design support for circular building with raw earth.

1. Introduction

Globally, the built environment is responsible for the largest shares of final energy use, carbon emissions, resource depletion and waste generation [1–4]. To counteract these issues, demands to include circular economy principles in the construction sector are increasing [5,6]. Another tendency is the growing interest in vernacular building materials with various environmental benefits such as raw earth [7,8]. Raw, crude or unbaked earth is considered to be one of the oldest and most widely used building materials [7,9,10]. Although its use was almost abandoned in more industrialized countries, it has resurfaced as a low-impact, widely available and highly recyclable building material [7,11–13].

Raw earth used for construction is a mix of subsoil fractions of different particle sizes including silts, sands and possibly gravels within a clayey binding matrix providing cohesion [13,14]. The most common earthen construction techniques are wattle and daub (pressing earth onto a woven lattice of wooden strips in a timber load-bearing structure), cob (layering of an earth-straw mix to form masonry walls), rammed earth (compacting of consecutive earth layers in a formwork), adobe (masonry of moulded or extruded earth bricks) and compressed earth blocks (masonry of manually or mechanically pressurized earth blocks) [7,12,15,16].

Considering the global challenges the built environment is facing today, the interest for applications of raw earth in circular construction can grow. However, little is known about the circularity of earth architecture. Therefore, it is essential to have a clear understanding of the potential of this material in the context of a circular built environment. The circular economy and circular building are broad terms to grasp as they are a sustainability paradigm requiring a systemic worldview [17]. Therefore, the scope of this research is limited to the environmental and technological dimensions situated at the micro-scale (resources, materials and components) of circular building research [6]. This research aims to start filling this gap by assessing the circularity of two contemporary earth buildings in Belgium. Within a more extensive research project [18], it contributes towards the development of design support for circular building with raw earth.

2. Methodology

A qualitative assessment of the circularity of earthen constructions was performed on two cases (**Figure 2**) of which the selection criteria were as follows: located in Belgium, contemporary architecture (built after 2000), containing load-bearing or self-supporting earthen building elements, and two different earthen construction techniques. The Bio Class, designed by BC architects in 2015, is a centre for nature education which was built with compressed earth blocks (CEBs) inside a warehouse located on the Fort V-site in Edegem. The Bee Hall, designed by DAM architects in 2017, has a similar function in addition to housing beehives and was built with rammed earth as part of the educational garden The Helix in Geraardsbergen. Both projects were realized with the same (sub)contractor: Het Leemniscaat.

Figure 2. *Left*: Load-bearing CEB-walls with exterior hempcrete insulation in the Bio Class (©Thomas Noceto). *Right*: Naked load-bearing rammed earth walls in the Bee Hall (©Ken Dupont).

2.1. Research strategy

First, based on literature, a framework was developed to assess the circularity of the cases at different scales. Second, to assess the circularity of the two cases, three research methods were used: a literature review on earthen construction techniques in general, followed by case-specific semi-structured interviews and the analysis of technical documents. Literature was reviewed to assess the circular potential of earthen constructions. This was verified and complemented by data from the cases: semi-structured interviews with stakeholders and the analysis of technical documents. Data triangulation resulted in the verification of the circular potential of two earthen buildings.

2.2. Data collection and analysis

To develop a circular assessment matrix for this research (section **3.1**), literature was reviewed about circular building and existing circular assessment frameworks. In parallel, properties of earth as a building material and earthen constructions were inventoried through literature as well. Based on literature, a first general assessment of the circularity of earthen constructions was performed.

These findings were verified and complemented by a case study analysis of two earthen buildings. The respondents were selected based on their involvement in the design and construction of the cases: two architects and a contractor. The three semi-structured interviews took place at the office of the respondent, except for one which was conducted online due to COVID-19 measures. The recorded interviews were held in Dutch, took approximately 90 minutes, and were transcribed in their original language. The context of the interview was introduced with general open questions about their knowledge, opinion and experiences with earth construction and circular building. This was followed by case-specific questions, in which the cases were assessed on different scales. To stimulate the conversation and to avoid respondent's biases, a card-sorting method was used. For different scales and levels, a selection of circularity indicators (**Tables 3, 4** and **5**) was written on cards that were sorted by the respondents according to what extent it was applied in the case. By use of this method, the interviewees were encouraged to be critical about the circularity of their project. In the online interview, the card-sorting method was done with the *Miro* online visual collaboration platform. The transcribed interviews were coded and analyzed according to the circularity indicators and underlying principles.

Technical documents from the cases were obtained from the respondents and were analyzed using the circular assessment matrix. The most used documents were architectural and executive plans, construction details, visual media of the building process, and construction specifications.

3. Results

In the following paragraphs, a circular assessment matrix that will be used for this research is presented (section *3.1*) and the circularity of the two cases is assessed by means of this matrix on three different scales, i.e. the material scale, the element scale and the building scale (sections *3.2*, *3.3* and *3.4*).

3.1. Developing a circular assessment matrix

To assess the circularity of raw earth as a building material and earthen construction techniques from an environmental and technological perspective, the assessment must be done at different scales. Since the desired assessment scales for this research are seldom found together in one framework, a new circular assessment matrix was developed by combining existing frameworks found in literature.

First, the assessment is performed at three scales: the building material scale, corresponding to the resources or building products; the building element scale, corresponding to the parts of a building that fulfil a specific set of functions (e.g. an outer wall); and the building scale, corresponding to a composition of building elements offering space to people, activities and goods [19]. Second, each scale contains different levels at which the case can be assessed: the components level, the interfaces level, and the composition level. The scales and levels correspond to the rows and columns of the matrix in **Table 1,** respectively. The levels were adopted from the element and building scales of a qualitative assessment framework by OVAM [19] containing key principles of Design for Change, mainly inspired by Vandenbroucke [20]. To ensure coherence, the authors chose to maintain these levels at the material scale. At the material scale, the components refer to the extracted resources used for the building product, the interfaces refer to the bonds between the materials of the building product, and the composition refers to the assembly of different materials to manufacture the building product. At the element scale, the components refer to the design of the building products, the interfaces refer to the interaction of different components, and the composition considers the assembly of components in a building element. At the building scale, the components refer to the design of the building elements, the interfaces consider the interaction between different building elements, and the composition refers to the assembly of building elements [19,20].

Each field in the matrix of **Table 1** contains *circular principles* that will be assessed in the cases. At the element and building scale, these were adopted from [19]. At the material scale, these were selected from various sources. Sixteen 'circular design qualities' were summarized by Galle et al. [21], six of which apply to the material scale: reused, recycled, renewed, compostable, safe and healthy, and pure. The EMF [22] considers different 'material circularity indicators': recyclability, reuse, utility, scarcity, toxicity, and impact. A study to include 'circularity indicators' in BREEAM [23] indicates that material selection must be made keeping renewability, toxicity, scarcity and impact in mind. According to the WTCB [24], the integration of circular thinking in the selection of materials and products consists of choosing pure, non-toxic, renewable, reusable, recyclable, biodegradable or compostable, local materials with a low environmental impact. **Table 1** shows the resulting choice of circular principles.

At each assessment scale and level, the circular principles contain a set of indicators that were defined based on literature (**Tables 3, 4** and **5**). In the following sections, at all scale levels and for each indicator, the circular potential is assessed based on literature, and verified in the cases based on the interview and project data using the values described in **Table 2**.

Table 1. Circular assessment matrix with principles in each field (adapted from [19]).

Scale ↓ / **Level →**	Components	Interfaces	Composition
Material	Resources	Bonds between materials	Assembly of materials
	Renewability *Scarcity* *Toxicity*	*Biodegradability*	*Purity* *Impact* *Recovery*
Element	Building products	Joints between components	Assembly of components
	Durability *Manageability* *Compatibility*	*Reversibility* *Simplicity* *Speed*	*Independence* *Pace-layering* *Prefabrication*
Building	Building elements	Joints between elements	Assembly of elements
	Demountability *Reusability* *Expandability*	*Accessibility*	*Versatility*

Table 2. Assessment values and corresponding meanings.

Symbol	Circular potential	Verification
+	High	Potential is applied in case
–	Low	Potential is not applied in case
?	Not found in literature	Not verifiable

3.2. Circular assessment at the material scale

Table 3 shows the circular assessment of raw earth at the material scale. The formation of raw earth is an ongoing chemical or physical weathering process of rocks that takes place constantly [15]. However, one may argue that it is a non-renewable resource as these processes largely exceed the human time scale and therefore, cannot be regarded as such [7]. Moreover, renewable resources are commonly referred to as biologically sourced or regrowable materials [21,22]. Then again, it can be argued that recyclable materials are considered renewable in the technical cycle of circularity [23]. Except for permafrost regions, naked bedrocks, and sand deserts, the availability of subsoil is pervasive [13]. However, the composition of the earth mix varies between construction techniques, and all components are not always locally available [25]. Earth is not considered to be a toxic material. On the contrary, multiple studies show that it improves indoor air quality [11], as it buffers relative humidity thanks to its hygroscopic behaviour [16]. The ability of raw earth to plasticize when water is added makes the recycling possibilities practically endless. By crushing, drying, and sieving, one can separate the earthen material and retrieve the virgin resources. However, the purity of the material affects its technical suitability when recycled as the presence of stabilizers or additives in the mix may significantly decrease the plasticizing properties [12]. Earthen building materials can be considered biodegradable since no chemical bonds hinder natural decomposition. However, if stabilizers or additives are used, rapid biodegradation of earthen materials is only possible in the case where these are organic [26]. Composting might be possible if organic additives can be separated from the earth, but no information was found in literature. Pure earthen construction wastes can be returned to the site without environmental hazards [7,12], but landscape transformation and changes in the soil composition are possible. Life Cycle Assessment (LCA) of CEB and rammed earth shows that the two processes with the largest impact are the transportation of soil and the use of stabilisers such as lime or cement [27]. Regarding material recovery, Schroeder [12] and Dethier [28] mention that the transformation of excavation soil into earthen building materials could result in lower demand for landfill space.

In the Bio Class, the earth mix contains 50% clay from a nearby quarry (~10 km) which was transported by truck, and 50% of two fractions of sand from a local distributor (~20 km) which was transported by boat from an unknown source and further transported by truck to the construction site. Wet clay lumps were mechanically crushed to dry on-site for four weeks with two ventilators naturally. Once dried out, the clay was mixed with the sand in an electric mixer, and the earth mix was compressed with a hydraulic press at 15 MPa into 19,000 blocks with a compressive strength of 3,3 MPa. Per hour, 200 CEBs were manufactured in a team of five to six volunteers during a three-week workshop. No additives nor stabilizers were used in the CEBs. However, the earth mortar was stabilized with 10% of cement, as it was designed in accordance with French earth building regulations for load-bearing CEB-walls. Recyclability, biodegradability and purity are therefore affected since, at the end-of-life phase of the building, the CEBs cannot easily be separated from the stabilized earth mortar.

In the Bee Hall, excavation soil – which is usually considered as waste – from the site was used in the rammed earth mix. However, a reformulation with additional clay, sand and gravel fractions from two distant quarries (~100 km) were needed to make the mix suitable for ramming. The exact proportions of the fractions are unknown. The mixing was done ex-situ and was transported in big-bags to the construction site by truck. No additives or stabilizers were used.

Table 3. Circular potential at the material scale of earth as a building material based on literature and verified in the Bio Class (BC) and in the Bee Hall (BH).

Level	Principle	Indicator	Lit.	BC	BH
	Renewability	Rapid replenishment of virgin resource	–	?	?
		Regrowth at least as fast as functional service life	–	?	?
	Scarcity	Abundancy in the Earth's crust	+	?	?
		Local availability of resources	+	+	–
	Toxicity	No emittance of volatile organic compounds (VOC)	+	+	+
		No exposure to health risks of labourers in the life cycle	+	+	+
	Biodegra-dability	Ability to naturally decompose rapidly	+	–	+
		Ability to be used as mulch or compost	?	–	–
	Purity	No contamination in the life cycle of the material	+	?	?
		Selection of untreated/unfinished materials	+	+	+
		Limitation of different materials combined in a product	+	+	+
		Efficient separation of materials manually/mechanically	+	–	+
	Impact	Low environmental impact throughout the life cycle	+	+	+
		Low embodied energy throughout the life cycle	+	+	+
	Recovery	A proportion of residual waste stream in the product	+	–	+
		A proportion of recycled material in the product	+	–	–

3.3. Circular assessment at the element scale

Table 4 shows the circular assessment of the two cases at the element scale. Little research was found about the circularity of earthen constructions at this scale. By far, most of the literature is related to durability as it has become an increasingly popular topic over the last two decades [14] and draws the most attention from the general public [29]. Water is the most detrimental environmental agent to durability [14]. The key erosion mechanism is related to the kinetic energy from raindrops impacting the wall surface [29]. Moreover, more frequent maintenance is needed with earth constructions compared to concrete or fired bricks [13]. The addition of stabilizers such as lime or cement considerably improves durability [9], yet according to [13], this process merely upgrades earth into a low-quality concrete at a high environmental cost. Unstabilized earthen walls are durable – even in wet climates – provided that the architectural design principles of a “good hat” (roof) and “good boots” (foundation) are respected [13]. However, the ability to pass durability tests is one of the main reasons why stabilization is used in everyday practice. Then again, many of the durability tests designed for conventional building materials are not representative of earthen walls due to a large discrepancy between lab tests and natural conditions [9,13,14]. Improvements are being made to attain conformity, e.g. by selecting adequate tests for case-specific conditions [30]. However, quantitative observations within a large time scale in natural conditions turn out to be the most reliable way to assess the durability of earthen constructions [31]. Moreover, calculated erosion can be used to improve the durability of exposed rammed earth walls. The walls are built a few centimetres thicker than initially planned, and so-called erosion checks (horizontal layers of protruding fired clay or trass-lime mortar) decelerate the water flow down the wall causing the abrasion [32,33]. According to OVAM [34], manageability and pace-layering of vertical load-bearing structures are independent of the materiality. Regarding the manageability of vertical load-bearing structures, massive blocks are characterized by small dimensions and are, therefore, easy to handle [34]. However, the low speed of (dis)assembly relative to larger components is often considered an adverse effect [34]. Massive walls have large dimensions and therefore have low manageability, with the result that they are only reusable in a similar design. Adobes are considered to have compatible dimensions [34], and therefore, the compatibility potential for CEBs can be deemed similar. Prefabricated rammed earth is also regarded as compatible by OVAM [34]. Apart from a load-bearing function, massive structures mostly have a space-dividing function and therefore structural interventions are needed when one wishes to change the laout of the building. Therefore, pace-layering potential of adobes and rammed earth walls are considered low. Although this has not yet been tested, the reversibility of a CEB wall is likely to be dependent on the cohesive strength of the blocks and the mortar used. Unstabilized earth mortar is considered reversible according to Rauch [33]. Fired bricks layered with lime mortar can be reclaimed undamaged with simple tools [34]. However, this is a labor-intensive process that may be limited through prefabrication of larger modules. Blocks cannot be removed separately and are therefore not considered independent as stated by OVAM [34]. In the case of a monolithic rammed earth wall, independence can be considered valid since the wall is the component itself. Regarding prefabrication, a higher degree of quality and facilitation of the construction process can be obtained by off-site industrial production of rammed earth elements. Mechanical prefabrication machines, as developed by Lehm Ton Erde in Austria, can decrease the labor-intensity and accelerate the production process [33].

In the Bio Class, all CEB-walls are load-bearing and are either single- or double-layered using a conventional masonry technique (cross bond). The 5,5 kg weighing CEBs of 29×14×7 cm were dimensioned according to the hydraulic press standard and did not correspond to standards of conventional fired bricks. The blocks were carried from pallets with a brick clamp and layered with the cement-stabilized earth mortar by two labourers. Most walls contain an arch-shaped glass door opening with a diameter of 3,5 m and are separated from a concrete plinth by an impermeable layer to prevent the capillary rise. The CEB-walls support flat timber rafters with external hempcrete insulation covering the whole building. On the interior, the blocks are left apparent without finishing, and on the exterior, a wooden frame is attached to guide the loose-fill hempcrete formwork. The self-supporting hempcrete facade is fixed to the plinth by a steel profile connected to the foundation. Glazed bricks were used in the sanitary unit due to the CEB's vulnerability to water.

Regarding the components (CEBs), the respondent from BC architects appointed the highest score of circularity in the card-sorting exercise to the ease of maintenance and repair (durability) along with architectural possibilities (compatibility). Lowest scores were given to the requirement for maintenance and damage associated with transportation (durability). To extend the service life of components, the architect highlights the importance of a good design to protect the earth from humidity and to prevent cracking due to point loads. During construction, the wet hempcrete humidified the clayey CEBs in its drying process and caused the arches to sag 1 or 2 cm due to a decrease in stiffness. Damage due to transportation is more common with CEBs than with other building materials. Maintenance has not occurred since the project was finished recently, except for final treatment with a sponge float of the interior wall surface to make the transition of the block edges and the mortar less sensitive. Regarding the interfaces (earth mortar joints and other connections), visible and accessible joints (speed) scored highest along with disassembly without damage (reversibility). Lowest scores of circularity were given to the number of joints (speed) and the use of standard joints and tools (reversibility). Although standard joints and tools are used, the architect mentions a somewhat higher technical complexity than fired brick masonry or concrete walls due to the CEB's limited strength. Regarding the composition (assembly of CEBs with other materials in the wall), the independence of components scored highest and the added value of prefabrication degree lowest. The hempcrete skin and CEB structure are separated, but the services are embedded in the skin and perforate the structure. The architect acknowledges the possibility of separating the services as well but states this was a design choice. To the question how the Bio Class could be disassembled and reassembled on another location, the architect suggested comparing the cost and time efficiency of two methods: the disassembly of CEBs in one wall and the demolition and remanufacturing of CEBs in another. In the first case, the time (and therefore cost) invested in recovering all blocks could be too high as a percentage of loss is inevitable due to disassembly and transportation. In the second case, there would be no loss, and the demolition would be faster, but the cost to remanufacture could be higher.

In the Bee Hall, the two zig-zag rammed earth walls are load-bearing and 35 cm thick. One wall is interrupted by a steel pivoting door and is perforated by a hexagon-shaped opening of about 60 cm in diameter. The two walls are connected on the interior by a window and a timber-framed partitioning wall. As in the Bio Class, the walls stand on a concrete plinth separated by an impermeable layer. The walls support a flat timber green roof with an overhang around the perimeter of the building to protect the rammed earth from precipitation. During two two-day workshops with four volunteers and one labourer, the rammed earth mix was manually shovelled from big-bags into the standardized concrete formwork. The earth was rammed layer by layer with a manual and a pneumatic rammer.

Regarding the components (in this case the rammed earth walls), the respondent from DAM architects appointed the highest score to cards with durability indicators except for the damage associated with transportation. Other lowest scores were given to manageability and standard dimensions (although the latter was a design choice). The architect believes maintenance is not needed as long as vandalism does not occur, since the roof design protects the rammed earth from incident rainfall. Regarding the interfaces (connections of the wall with other materials), the architect gave the highest score to speed and the lowest to reversibility. Reinforcement bars run 40 cm through the walls every meter, at the bottom through the concrete plinth and at the top through the timber divider beam. The latter is connected to the wall by an earth mortar without stabilizer. At the level of the windows, a timber column was rammed within the walls to connect the window frames to the supporting structure. The architect argues disassembly of the walls cannot be done without damaging the rammed earth unless performed with extreme care and therefore neither cost nor time-efficient. Regarding the composition (assembly of the wall), the architect appoints the highest score to independence and the lowest to prefabrication. The architect also argues the added value of prefabrication and the associated transportation damage.

Table 4. Circular potential at the element scale of compressed earth blocks (CEB) and rammed earth (RE), based on literature and verified in the Bio Class (BC) and in the Bee Hall (BH).

Level	Principle	Indicator	CEB		RE	
			Lit.	BC	Lit.	BH
	Durability	Long expected service life	+	+	+	+
		Little maintenance required	–	–	–	–
		Easy to repair or remanufacture	+	+	+	+
		Little damage associated with transportation	?	–	+	–
	Compatibility	Standard shapes and sizes of components	+	+	+	–
		Exchange of components with other buildings	+	+	+	–
		Capability to form new configurations	+	+	+	–
	Manageability	Small-sized components	+	+	–	–
		Lightweight components	+	+	–	–
		Ergonomically stackable components	+	+	–	–
	Reversibility	Disassembly of components without damage	+	?	?	–
		Reusability of the joints	+	–	+	+
	Simplicity	Standard joints and tools	+	+	+	+
		No need for specialized training	+	+	+	+
		A small number of different components	+	+	+	+
	Speed	A small number of joints	–	–	+	+
		A small number of different types of joints	+	+	+	+
		Visible and reachable joints	+	+	+	+
	Pace-layering	Layering of components according to lifespan	–	–	–	–
		Layers with shorter lifespan closer to surface	–	–	–	–
	Independence	Geometry allows individual removal	–	–	+	+
		Disassembly from multiple directions	–	–	+	+
	Prefabrication	Off-site preassembly into larger modules	?	–	+	–

3.4. *Circular assessment at the building scale*

Table 5 shows the circular assessment of the two cases at the building scale. It is important to note that in this case, the component level tackles the building elements in their entirety, i.e. the CEB walls with hempcrete insulation in the case of BC and the rammed earth walls in the case of BH. The interfaces level deals with the connections between these walls, and the composition addresses the assembly of these walls in the building volume. No literature was found directly related to the circular principles on this scale, except for the low accessibility of the joints in cross-bonding brickwork [34].

The Bio Class is a rectangular single-storey volume positioned in oblique inside a rectangular warehouse. The building (surface area ~350 m^2) is subdivided into six square volumes of about 25 m^2. Except for one wall delimiting the bathroom area, all internal walls have the same arch-shaped openings as most external walls and some spaces are separated by glass doors. The architect appointed the highest score to the demountability of the infill and the ease of reinforcing supporting elements. The lowest score was given to movable building elements. The supporting elements cannot be disassembled as a whole, but the infill elements such as the glazed-brick partitioning walls can possibly be disassembled from the supporting structure. Reuse of the supporting elements as a whole is excluded, and reusability of the infill elements in other buildings depends on their compatibility. Although the CEBs are slightly over-dimensioned due to higher safety factors as chosen by the structural engineer, this was not a design choice with the prospect of expandability. The cross-bonding brickwork hinders the accessibility of supporting elements as one element cannot be separated from the other. The layout can be considered multipurpose thanks to the identical shapes and sizes of the spaces, but it is not transformable since the elements are not movable or demountable.

The Bee Hall (surface area ~50 m^2) is a single-storey volume comprising a hexagonal space in between two hexagon halves, open at one end and closed by a glass pane at the other. Three spaces are divided by a timber partitioning wall and a window. The architect appointed the highest score to the demountability and reusability of the infill and gave the lowest scores to the over-dimensioning of technical elements and the transformable lay-out. The supporting elements cannot be disassembled as a whole, but the infill elements such as the timber partitioning wall can be disassembled from the supporting structure. As in the Bio Class, reuse of the supporting elements as a whole is excluded, and reusability of the infill elements in other buildings depends on their compatibility. Like the Bio Class, the safety factors were taken higher by the structural engineer, but the design was not intended for expansion. For the same reason, technical elements were not over-dimensioned. Reinforcement of supporting elements seems a difficult option as the synergy between the existing and the added wall must be ensured. Accessibility of the supporting elements is complicated because of the reinforcement bars at the bottom and at the top, as well as the wooden columns inside the rammed earth walls connected to the window frames. Given the size and shape of the building, the layout is not considered multipurpose. As in the Bio Class, the immobile and undemountable supporting elements do not allow the layout to be transformed.

Table 5. Circular potential at the building scale of the Bio Class (BC) and the Bee Hall (BH), based on the interviews and the analysis of technical documents.

Level	Principle	Indicator	BC	BH
	Demountability	Selective disassembly of the support	–	–
		Selective disassembly of the infill	+	+
	Reusability	Reusable elements in the same building	–	–
		Reusable elements in other buildings	–	–
	Expandability	Over-dimensioning of supporting elements	–	–
		Over-dimensioning of technical elements	–	–
		Ease of reinforcing supporting elements	+	–
	Accessibility	Visible and reachable joints	–	–
		Reversible joints between elements	–	–
	Versatility	Multipurpose building layout	+	–
		Transformable building layout	–	–
		Movable building elements	–	–

4. Discussion

In the following paragraphs, the results of the assessment are discussed on three scales by comparing theory and practice on the one hand and by comparing the two earthen construction techniques on the other. Additionally, improvement potential for the cases and particular potential compared to more conventional building materials are discussed. Furthermore, critical reflections are made for the methodology, the framework and the assessment; and recommendations are given for future research.

4.1. Interpretations and implications

At the material scale, the results indicate that, based on findings in literature, the circular potential of earth as a building material is high for the majority of principles. The results also show that the circular potential that was identified based on literature, highly corresponds with the verification in the two cases. However, it must be said that some principles are independent of the studied cases, i.e. the replenishment of earth as a virgin resource by weathering of rocks and the abundance of these resources in the Earth's crust. Possible improvements in the Bio Class are the elimination of cement stabilizer in the earth mortar increasing the purity, biodegradability and reducing the impact; more local resourcing of the sand fraction reducing the impact and using a proportion of excavation soil or recycled earthen material. Improvement potential in the Bee Hall lies in the more local resourcing of the clay, sand and gravel fractions needed to reformulate the excavated soil to make it suitable for ramming. Particular potential lies in the low impact, low toxicity and low scarcity, and in the high purity and high biodegradability. Moreover, the use of excavation soil in the earth mix seems particularly promising in terms of circularity.

At the element scale, the results demonstrate that the circular potential is relatively high and mainly corresponds with the verification in the cases. By comparing the techniques, the overall manageability is high for CEB and low for RE, whereas the overall independence is low for CEB and high for RE. In addition, the speed of disassembly would be lower with CEB than with RE because of the many joints compared to none in a RE wall. Although pace-layering is ruled out for massive vertical load-bearing structures, the structure and skin are separated in the Bio Class, and the structure and skin are one and the same in the Bee Hall. Additionally, it must be noted that some principles are less related to the earthen material than others. For instance, manageability depends more on the component's geometry than on the materiality. Likewise, pace-layering depends more on the chosen structure design than on the materiality (columns and beams versus massive walls), although this is an indirect consequence of the material's properties. Possible improvements in the Bio Class lie again in the elimination of cement stabilizer in the earth mortar, potentially increasing the reversibility. In the Bee Hall, prefabrication of the rammed earth elements may increase the reversibility due to less damage with disassembly. Particular potential on this scale lies in the simplicity and the reversibility. The latter is due to the fact that unstabilized earth is able to plasticize when water is added. Moreover, the low adhesive strength of earth allows it to be easily separated from other materials. Furthermore, the remnants of earth on the other material can easily be washed away with water. It seems therefore fair to say that, in terms of reversibility, water may be seen as a friend rather than a foe, other than in terms of durability.

At the building scale, the results show a relatively low circular potential. Given the fact that the two studied cases were not intentionally designed to maximize circularity is a plausible reason for their low potential on this scale. For instance, versatility and expandability rely much on design choices and the prospect of future adaptation of the building. Thus, improvement and particular potential are out of place here. To the question how they would tackle a disassembly and reassembly of the discussed case, the interviewees had similar responses: they would choose between disassembly and reuse; demolition, recycling and reproducing; or demolition, disposal and reproducing by balancing cost, time and environmental impact. Transportation of the earthen material and the associated impact was one of the primary factors of consideration. Hence, some questions from a circular perspective may arise: When is it interesting for earthen building elements and components to be demountable and reusable? And when is it more interesting to demolish and dispose or to recycle and reproduce, given the fact that there are fewer negative externalities linked to these processes than with conventional building materials? In fact, disassembly and reuse of earthen building components or elements have possibly not yet been tested in practice. Therefore, the next step in research may be to physically test the reuse potential of earthen construction samples to give more insights from a technical perspective. From an environmental perspective, a comparative life cycle analysis of reuse versus recycling or disposal of earthen building components and elements may support decision-making processes.

4.2. *Limitations and recommendations*

Raw earth is an atypical building material in the context of circularity since it hovers in between the biological and the technical cycle of resource flows. Therefore, it does not fit well in existing circularity frameworks, and circular checklists are more challenging to use due to ambiguities of terms and definitions. Moreover, "reuse" is often confused with "recycle" in earth building literature and claims about reusability should therefore be treated with care. Furthermore, circular indicators specific to earth construction, such as calculated erosion and erosion checks to improve durability, may be needed to complement existing frameworks in order to perform a more rigorous assessment.

By reflecting on the assessment of the two cases, some remarks must be made. First, in this research project, a new circular assessment matrix was developed because a framework including the desired scales was not available in literature. However, the framework development was not the main focus of this study. It is also noteworthy that the qualitative assessment does not attribute weight factors to the principles, ignoring the possibility that reversibility may be more important than say manageability. Second, the selected cases are somewhat out of the ordinary. Since the Bio Class is situated inside a warehouse, it is protected from the weather, and therefore the durability of the earth may be significantly higher than if the building were exposed to precipitation. The Bee Hall is a small building for seasonal events and does not contain insulation, thereby presumably increasing simplicity and speed of disassembly. The cases are still very recent, and therefore maintenance, adaptation or disassembly have not yet occurred (and may never occur). Thus, statements made by the architects related to these phases are based on their intuition and not on practical experience. Besides, BC architects have extensive expertise with earth building and incorporated lessons learnt and insights from other projects in Bio Class. Another comment is the fact that no specific benchmarks were defined as more research is needed to state clear definitions of the indicators applied to the case of earth construction.

By reflecting on the methodology, a more in-depth analysis of the cases prior to the interviews would have allowed discussing some constructive features more in detail with the interviewees. Then again, case-specific probing questions are time-consuming in an interview, and this might be avoided by a questionnaire beforehand. A final remark to be made is the difficulty for the respondents to estimate all the indicators at each scale, level and principle correctly.

5. Conclusion

This research aimed to assess the circularity of two contemporary earth buildings in Belgium, in order to contribute to a better understanding of the circular potential of earth as a building material. Based on a qualitative assessment of the two cases, it can be concluded that the circular potential found in literature was generally confirmed in practice. The circularity of the two cases is highest on the material scale, relatively high on the building element scale and relatively low on the building scale, although the buildings were not intentionally designed as circular buildings. The main differences between the studied construction techniques (CEB and RE) are in terms of manageability, independence and speed of disassembly of components. Particular potential lies in the low impact, toxicity and scarcity, and the high purity, biodegradability, reversibility and simplicity. However, more cases must be studied to provide more evidence to support these statements. From a circular point of view, it remains unclear whether disassembly and reuse of earthen building components are more desirable than demolition and disposal or recycling and remanufacturing. Future research (lab tests, LCA) may support the decision-making processes for circular building with raw earth.

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