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Earth as construction material in the circular economy context: practitioner perspectives on barriers to overcome

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Summary

The need for a vast quantity of new buildings to address the increase in population and living standards is opposed to the need for tackling global warming and the decline in biodiversity. To overcome this twofold challenge, there is a need to move towards a more circular economy by widely using a combination of alternative low-carbon construction materials, alternative technologies and practices. Soils or earth were widely used by builders before WWII, as a primary resource to manufacture materials and structures of vernacular architecture. Centuries of empirical practices have led to a variety of techniques to implement earth known as rammed earth, cob, and adobe masonry amongst others. Earth refers to local soil with a variable composition but at least containing few percentages of clay that would simply solidify by drying without any baking. This paper discusses why and how earth naturally embeds high-tech properties for sustainable construction. Then the potential of earth to contribute to addressing the global challenge of modern architecture and the need to re-think the building practices is also explored. The current obstacles against the development of earthen architecture are examined through a survey of current earth building practitioners in Western Europe. A literature review revealed that, surprisingly, only technical barriers are being addressed by the scientific community; two-thirds of the actual barriers identified by the interviewees are not within the technical field and are almost not addressed in the scientific literature, which may explain why the earthen architecture is still a niche market despite embodying all the attributes of the best construction material to tackle the current climate and economic crisis. This article is part of the themed issue 'The contribution of soils to the UN Sustainable development goals'.

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1. Introduction

The building sector consumes approximately 48 % of global world energy use and a large volume of natural resources, extracting over 30% of the total resources (Dixit 2019). Consequently, the building sector is a major producer of greenhouse gases that contribute to climate change. As an example, sand and gravel are the most extracted group of materials (Bendixen et al. 2019) and their mining has a strong impact on biodiversity (Park et al. 2020). The construction sector is also responsible for about 50 % of wastes produced in the European Union, 25% of solid waste globally, and the management of these wastes have a negative environmental impact (Benachio et al., 2020). Among these wastes, about 75 % are natural soils and stones (Cabello Eras et al. 2013). Excavated soils, also called earth, are regarded as wastes in Western countries but earth has been used since, at least, the very beginning of the Neolithic revolution by human beings to build their shelters and dwellings (Sauvage 2009). Earthen architectures, regarded as fragile, perishable and made for the poor, are not compatible with the "ideology of progress" that prevailed during the 20th century and fell into disuse (Hamard et al. 2016).

Despite biodiversity and ecosystems having been widely forgotten in the 20th-century development schemes, however, people have started to come back to an awareness of its benefits to living quality and health. In particular, the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystems Services (IPBES) has been launched jointly with governments, academia and civil society to inform policy formulation on the topic. IPBES is promoting a framework based on eighteen recognized "Nature's Contribution to People" (NCP). A major challenge today is to secure "the beneficial contribution of nature to a good quality of life for all people" (Díaz et al. 2018).

This article is part of the themed issue "The contribution of soils to the UN Sustainable Development Goals" and analyses the contribution of soils to the thirteenth Nature's Contribution to People (NCP): "Materials, companionship and labour" as defined in (Díaz et al. 2018). Soil plays a major role in NCP by providing many ecosystem services and requires careful management (Smith 2018). Most of conventional building materials are quarried from bedrocks and geological deposits, chemically modified during the manufacture process, hindering their capacity to be recycled at low energy cost. On the contrary, for earth architecture, earth is quarried from the subsoil. Raw earth materials are completely recyclable without any loss through the value chain and suit perfectly with the circular economy principles (Bui and Morel 2015). However, the development at a large scale of earth architecture, in particular areas, could have an impact on soil availability and could compete with its other NCPs.

This article aims to develop why and under which conditions soils could provide a combination of alternative materials, technologies and practices compatible with the UN Sustainable Development Goals. Additionally, the current obstacles to the extensive use of earth in modern architecture will be explored, as revealed through responses from interviewed practitioners in earthen construction. Addressing those barriers would allow using soils to build millions of single-family houses or multifamily residential buildings worldwide, including in high-income countries, offering a sustainable and circular solution to the housing crisis encountered worldwide.

2. A high-tech multi-function material for architecture

Most of earthen building techniques have a several thousand years old history and earthen materials have been used to construct structures of qualities ranging from palaces to temporary shelters. In antiquity, means of transport were limited and builders had to adapt to locally available materials (both the raw materials for construction and those to form the temporary works, for example, formwork). Modern construction, however, boasts the benefit of ease of transport and on-site manufacture automation (Figure 1). Earth building should, therefore, be more popular now than it has ever been. However, this is not the case; rather, earth is perceived to be a low-quality material, suitable only for construction in developing countries or for bespoke architectural ventures for the wealthy. Engineers have recently examined the technical performance of these materials (section 2) but, despite considerable intake in interest from that community, little increase in the use of earthen materials in practice has emerged. To achieve that increase in interest, those latent barriers to adoption must be brought to light (section 3).

Figure 1: the "Orangerie" rammed earth building during its construction in the centre of Lyon (top, © Fabrice Fouillet). The arches are load-bearing structure holding the timber floor and the flat roof. The timber floors are ensuring safety against earthquakes by tying the facades together and connecting them to the vertical timber structure around the lift (in the middle, of the photo). The partial on-site automation of the construction enabled to deliver the project with reasonable cost and time. Down left: A single-family house in rammed earth, Burgundy, France (© Nicolas Meunier).

(a) Description of earth material

Most earth materials are excavated from subsoil horizons and some of them are excavated from alterites or soft rock deposits (Hamard 2017). Topsoils are sensitive to shrinkage and decay and are therefore unsuitable for building (Maniatidis and Walker 2003).

Not all subsoil horizons are suitable for building purpose. Earth is a cohesive and frictional material in terms of geotechnique; it means that its mechanical behaviour is a combination of cohesion and friction. Cohesion is provided by colloidal particles, mainly clay minerals, and friction is provided by the contact between the particles of the granular skeleton of the earth, i.e. silts, sands, gravels and stones. Although several recommendations are available in the literature regarding the clay/silt/sand/gravel content of suitable earth for construction, most of the earth employed by past masons fell outside these recommendations, which highlights their inaccuracy (Pagliolico et al. 2010; Rojat et al. 2020).

Earth is an unsaturated porous medium, containing adsorbed water and capillary water in equilibrium with the internal and atmospheric relative humidity. In normal operating conditions, an earthen wall always contains a small amount of water. The cohesion is generated by three different attractive inter-particle surface forces that are the Van Der Waals dispersion force, capillary force, and ionic correlation forces (Van Damme and Houben 2018). Among those forces, the capillary forces, also called matric suction (when expressed as a pressure) in geotechnique, are the main contributors to cohesion. Nanoscopic adsorbed water films bridge the gap between clay minerals, and larger water menisci the gap between clay minerals and coarser aggregates (silt, sand), (Van Damme and Houben 2018).

The strength of the cohesion is driven by the clay types, the clay content, the microstructure and the hydration state (water content). Clay minerals exhibit a large diversity. For example, their specific surface ranges from 20 $m^2.g^{-1}$ for a kaolinite to 850 $m^2.g^{-1}$ for a montmorillonite (Meunier 2005). For the same clay content, two different earths can have very different behaviours. Moreover, the microstructure of the earth matrix is driven by the implementation type (Kouakou and Morel 2009). To propose prescriptive suitability thresholds for earthen architecture, it would require thorough, long and expensive tests. Consequently, it is not possible to predict the performance of an earthen wall from its intrinsic composition like it is possible with concrete; their performance should be measured through performance-based tests. Nevertheless, it is possible to propose decision tools for planning authorities and earthwork contractors to assess the potential of excavated soils for construction (Hamard et al. 2018; Rojat et al. 2020). However, the technical validation of the material remains the role of a project manager specializing in earthen architecture.

(b) The different processes of manufacturing earth materials

Earth is a natural and variable material offering a myriad of building techniques that can be classified according to the water content of the earth at the time of the implementation. Three different states can be identified: a solid-state, a plastic state and a liquid state. For plastic-state techniques, earth mixture is employed in a plastic state and mechanical strength of the material is provided through drying shrinkage densification. For solid-state techniques, earth mixture is employed at an optimum water content for compaction and mechanical strength is provided through densification and drying. For the liquid-state technique, an earth slip is used to bind plant particles. However, there is no gap between these approaches due to the diversity of earthen construction techniques: rather, a continuity exists as might be described by the following list (Kouakou and Morel 2009).

- Rammed earth consists in compacting earth at the optimum water content, layer by layer, in formwork with a rammer (Figure 1). This technique was already prevalent in Carthage (Tunisia) in 814 B.C. It then spread around the Mediterranean and North Africa as part of the Carthaginian and Roman empires and again to Europe with the expansion of Islam in the 8th century AD.
- Compressed Earth Block (CEB) is a quite modern technique that was developed in the middle of the nineteenth century. It consists of compacting earth at its optimum moisture content inside mould using a manual, a mechanical, or a hydraulic press. The resulting blocks are assembled with earth-based mortar to produce masonry walls.
- Cob is a building technique that emerged during the early Neolithic times. It consists in stacking clods of earth at plastic state, usually fibred, layer by layer, to build a monolithic wall. Vertical surfaces are eventually rectified by cutting off excess material after short drying time.
- Adobes are unfired bricks shaped by hand or moulded. They are made of earth mixed with water and most often with organic material such as straw or dung. They also appeared during the early Neolithic times and are one of the most widely used earth building materials.
- Extruded blocks are produced according to the same process than fired bricks except they are not baked. This type of brick is quite recent and is the result of the desire of brick makers to diversify their production.
- Earth mortars are probably the first mortars employed by mankind. They are used to lay unfired bricks (Adobes, CEB, and extruded blocks) and stones masonries.

- Wattle and Daub are made of a mixture of earth at plastic state and fibres, implemented wet, to fill a timber frame load-bearing structure. This is probably one of the oldest earth building technique as well as the technique most familiar to the public. Earth plasters are employed to coat interior and exterior wall surfaces. Plasters can be stabilized with sand, fibres, biopolymers or lime.
- Light earth is the most recent commonly used earth building technique. It arose in Germany after 1920 and was designed to improve the thermal insulation of walls by significantly increasing the fibre content of wattle and daub mixtures, to reach densities lower than 1200 kg.m^{-3}. It consists of binding bio-based aggregates or fibres with an earth slip (light earth).

Baked clay-bricks and stabilised earth with cement or lime are excluded from the scope of the article because they require a high embodied energy and are non-reversible processes.

(c) Properties of earthen buildings

The key parameters when dealing with the mechanical performance of building materials are their compressive strength, that is the maximum axial load that can be reached when the material is submitted to uniaxial compression, and its modulus of deformability, which is the slope of the linear part of the axial stress- axial strain curve during this test. It is quite difficult to give standard values of these parameters for earthen materials since they strongly depend on the earth's nature and the implementation method. As a result, notable differences can be found on recommended design values, which are reported in the various existing codes. For example, for rammed earth, while a maximal compressive load of 0.5MPa for a thickness higher than 0.25m is prescribed in the New Zealand code (NZS 4297 1998), values of 0.4MPa to 0.6MPa are given in the Australian handbook (Walker 2002) and eventually 0.2MPa is recommended in the French best practice guide (TERA 2018). Anyway, despite their differences, these values might appear quite low when compared to conventional materials like concrete, stones, timber, etc., which generally exceed 10MPa. Nonetheless, it is sufficient to design at least two-storey building, with 50cm thick walls (TERA 2018).

However, these values refer to normal operating conditions, for which the amount of water within the material remains quite low (the water content commonly ranges between 1% and 4% by dry weight, while the water content at saturation is commonly around to 20%). An increase of the water content from 2% to 12% leads to dividing the compressive strength and the stiffness by, at least, four for soils of several compositions compacted according to the Proctor procedure (energy of compaction equal to 0.6kJ/dm^3, Bui et al. 2014). It follows that any abnormal increase of water content would induce lower strength values threatening the wall stability. Furthermore, Scarato and Jeannet (2015), writing based on the analysis of more than hundreds of ancient rammed-earth buildings, identified one of the main cause of wall collapse as being an abnormal increase of the water content at the interface between the earthen wall and the basement. This can be induced by the conjunction of several factors as backfill elevation, implementation of an impermeable coating or floors, back slope near the building of road and pavements, which are composed by impermeable material like bituminous concrete…, which will lead to an increase of the capillary rises through the basement towards the earthen wall.

This durability issue may be even more prejudicial when it is associated with freezing and thawing processes. For example, Scarato and Jeannet (2015) reported that major collapses of earthen constructions in the Auvergne-Rhone-Alpes region in France had been recorded after thawing periods. They also underlined that earthen constructions should be avoided during winter periods because of the great risk of frost damage at an early age in which earthen material presents a high liquid saturation degree.

Another durability issue caused by water is the progressive erosion caused by the wetting-drying (and possibly freezing-thawing) of the wall surface due to its exposure to rainfall. The importance of these cycles has been studied experimentally by (Bui et al. 2009) on different types of unprotected rammed earth walls exposed during 20 years to external climatic solicitations in a wet continental climatic environment (Grenoble, France). This work eventually demonstrated an extrapolated lifetime, which is over 60 years (mean erosion of 6.4 mm, or 1.6% of the thickness of the wall after 20 years of exposure) without any mineral stabilization of the earth.

In addition to these wetting-drying cycles, during their lifetime, earthen walls have to face important variations of indoor and outdoor relative humidity, that induce adsorption-desorption of the water molecules on the surface of the pores by water exchange with the surrounding air. This behaviour is due to their quite high permeability (Fabbri et al. 2019) caused by the existence of a network of connected macropores, combined with their high specific surface area resulting from the presence of clay minerals and, possibly, vegetal fibres. Even if these adsorption-desorption processes do not significantly change the water content of the material (generally 1% to 3% of water content increase when the relative humidity varies from 20% to 80%), they can induce noticeable strength variations and even induce shrinkage and swelling processes (Xu et al. 2018). These modifications in behaviour however strongly depend on the clay content and its activity.

These interactions between the material and the water molecule, which drive the complex mechanical behaviour of earthen materials, also make it an excellent candidate to regulate the indoor humidity passively if it is not covered with an impermeable coating. The latent heat associated with these adsorption-desorption processes also impacts the heat transfer processes through earthen walls, which may thus modify the overall thermal behaviour of the building. An increasing number of research publications have already focused on assessing these heat, air and mass phenomena within hygroscopic walls and modelling them (for example Labat and Woloszyn 2016). Today, one of the main goals within this topic concerns the development of accurate software that can predict their impact on the building scale. This task requires the evaluation of the production and exchange of vapour within a building. And this latter may be impacted by the occupancy scenario of the inhabitants (Bui et al. 2019), which is in turn potentially impacted by their feeling. The question thus is not trivial, because this feeling is not only attributable to the objective parameters of the material including its hygrothermal capabilities but also depends on elements of strongly coupled contexts (history and sensitivity of the occupant, conditions of indoor and outdoor atmospheres…).

Finally, as it was pointed out by Soudani et al. (2017), the solar irradiance on the non-insulated earthen wall may have a significant impact on the thermal balance of the habitation. In particular, this study underlined that south-oriented walls can resituate with a shift around to 12h a part of the solar heat stored by the walls, even in winter, for an appropriately designed structure. With a change in that design, this shift can drop to as low as one hour (Beckett *et al*. 2018).

(d) The benefit to people

Earthen materials are perfectly in line with the Circular Economy (CE) principles through their infinite reuse and recyclability with the only downside to add, if required, recyclable components. The use of earth as construction materials have several immediate benefits. First, a significant amount of excavation waste ends up in landfills whereas they can be revalued as construction materials, having as seen above the potential to regulate the indoor air quality (IAQ) and the hydrothermal comfort. Earth material contains zero volatile organic compounds (VOCs) compared to many other materials (paint, adhesives, sealants among others) affecting the IAQ and exposing occupants to health risks through the building life span, (Akom et. 2018). It was recently scientifically established (although already well known by end-users) that earthen architecture, when properly implemented in the construction phase, generates an excellent IAQ especially due to its passive capacity of moisture buffering (McGreggor et al. 2016). Moreover, the clay particles remove the pollutants (Darling et al. 2012) due to the properties of clay nanoparticles. In the context of the 2020 COVID-19 outbreak, the IAQ is crucial because people will spend much more time at home during the lockdown rules (Abouleish 2020) and it is established that a poor IAQ worsens underlying health conditions (Derbez, et al. 2014), making people less resistant to COVID-19 (Chow et al. 2020). Moreover, even after the outbreak, it is suspected that in the long term, people will prefer to work from home more than ever.

3. The obstacles against modern earthen architecture

With the increasing demand of society about more sustainable materials, numerous scientific investigations have focused on earth materials during the last two decades. Examining publications related to earth from 1998 to 2019, in Scopus's database, the result showed that more than 98% of the publications related to earth are classified in the field of engineering (Morel and Charef 2019). Therefore, the search of publications on steel, concrete and earth was performed in the Engineering subject area, search limited to title, keywords and abstract. Since there are different techniques of earth materials, the keywords for the earth-based structures are limited to some specific techniques ("earth blocks" OR "rammed earth" OR "cob house").

Figure 2 illustrates the number of publications divided by the publications published in 1998, respectively for each material investigated. The result shows that while there are linear increases of publications on steel and concrete, there is an exponential growth of the publications related to earth material, which shows the particular scientific attraction of earth-based materials in the last years. The question therefore arises as to why academic interest in these materials has increased so rapidly, and seems set to do so for some time, but why earthen construction has made so little impact in the construction sector. To examine this, interviews were conducted with professionals from Western Europe to identify what barriers they are facing in their day-to-day practice for the implementation of their circular approaches and the use of reclaimed materials.

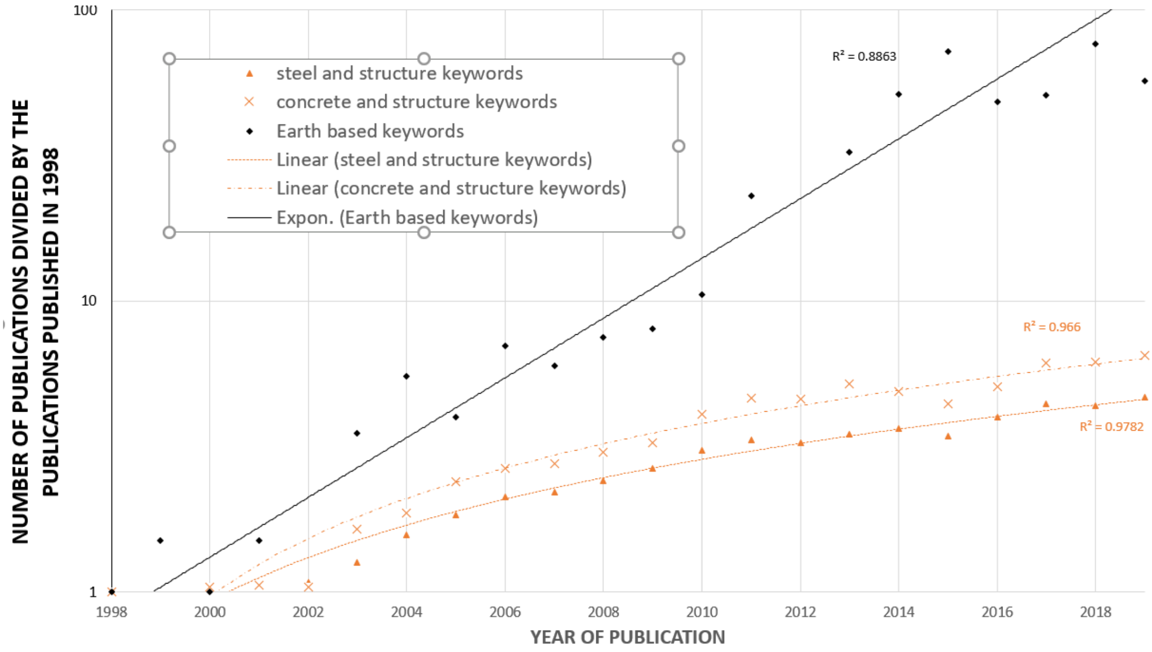

Figure 2: Rate of growth for the last two decades of publications on dominant structures (concrete and steel) compared to the publications related to earthen architecture found in Scopus ©.

Interview framework

The data presented in this section is extracted from a large-scale research project on the current CE approaches in the construction sector, reported by authors in two journal papers, where the methodology adopted is deeply explained (Charef et al., 2021; Charef and Emmitt, 2021;). To strengthen the results and increase the transferability, interviewees having international experiences have been selected. Moreover, the generalizability has been addressed by seeking experts, playing keys roles in the asset lifecycle and having worked internationally..

The interviewees' responses indicated that the earthen architecture faces many obstacles, e.g staying marginal within the construction sector, reputed to be fragmented, having a lack of efficiency and damaging the environment. The necessity of having a holistic view of the building is claimed by construction experts, particularly, in terms of cost, management and become compulsory to embrace a circular economy approach. Buildings must be designed mindfully to make sure that their components are reusable or recyclable and no more waste is generated through the lifespan of the buildings. Six categories of impediments were identified: (i) economical, (ii) organizational, (iii) sociological, (iv) technical, (v) political and (vi) environmental, which are each explored in detail below. Technical barriers to the use of earth as a building material have aroused the interest of researchers since the 90s and have multiplied since (Figure 2). Whereas the other categories of impediments, whether social, economic, organizational or political are almost not specifically addressed in the literature except recently by Charef et al. (2021) who reported approaches embracing the CE principles, including earthen architecture among others. Nonetheless, as shown in the Sankey diagram summarising the interview results (Figure 3), those barriers were highlighted by the interviewees, in almost similar importance (the number of barriers identified (n=36) for technical aspect and in the comparable range for other aspects).

(a) Technical barriers

The interviewees noted that to gain more momentum, earthen architecture has to fight against technical obstacles, whether related to buildings, data, materials or technologies. Earthen buildings have the particularity to use less finishing works (e.g. plaster or paint) and to allow users to benefit from the aesthetic purity of the structural walls. Similar to conventional construction, the earthen architecture follows the shearing layers concept (site, structure, skin, services, space plan and stuff), having different timescales (Brand, 1994), except that the layer of the finishing work may not exist. Therefore, this requires attention during the design and arrangement phases. Specific requirements compulsive by the material itself must be known by the construction team but also by the client and the end-users for the maintenance of the building. The complexity and size of buildings are also obstacles for the use of earth materials for their construction. Moreover, the size and access of the site are central, whether earth is processed onsite or off-site, due to the considerable size of the blocks (masonry units or rammed earth wall units) that can be handled using machines. When earth excavations come from the site where the construction is planned, sufficient space is required to store them.

Assessing the technical ability for construction of excavated earth can appear, at a first glance, a barrier easily overcome by doing simple civil engineering tests, either in laboratory or onsite. However, the picture is not so simple. One main reason is the difficulty to establish the link between the parameters which are measured in laboratory and the real on-site performance of the material. For example, earthen walls exhibit, in service, quite important heterogeneities and variations in water content. Since, this parameter significantly impacts the mechanical performance of earthen materials, the use of the compressive strength value obtained on dry and homogeneous samples to design earthen constructions may appear quite questionable. To solve this problem more researches are notably needed to have a better assessment of water dynamic within the material. One other sound example concerns the lack of consensus to evaluate some major durability issues such as fire and freezing-thawing resistances. At last, the impact of hygrothermal processes on inhabitant comfort are not yet totally understood by the scientific community, which leads to some difficulties in order to properly assess thermal performances of earthen buildings.

Regarding the sanitary quality, it is achieved by checking if the source site has hosted polluting activities. Conversely, it is more complicated when the materials, from different sites, are sent and piled up in landfills. Indeed, the earth waste must be tested in a laboratory to make sure that the material was not polluted. The easiest and best way is to use excavations' earth from the construction site itself or coming from nearby sites to limit transportation and their related environmental impacts and access to the site history. This makes it possible to know and plan in advance the quantities, availability and location of materials

(b) Organizational barriers

Earthen architecture has to overcome a set of organizational barriers, requiring to apply changes in programming, design, construction and "in use" phases. The fragmented nature of the construction sector appears as a brake and has to be addressed differently to increase the efficiency and improve the communication between the stakeholders, considered as crucial by the interviewees. As an example, the involvement of masons during the design phase is central to adapt the design according to the material limitations, such as the thickness of the walls, and the avoidance of finishing work leading to think upfront about the finished surface not being obscured by artefacts or services (water, heating, electricity, furniture, etc.). Moreover, earthen construction systems are different compared to common architecture and must be studied with the stakeholders concerned. End-users must also be warned on how they can use their earth walls and maintain the facade of the building.

The earthen architecture sector is also facing a lack of skills, education and training, particularly among designers and builders. As discussed above masons play a central role in earthen projects, specifically during the design phase. As a result, the overall budget of the project is distributed differently. Similarly, the responsibility of each stakeholder must be adapted and contractually agreed. The contract must have been, upfront updated according to the specific needs for earthen architecture and projects developed within the CE framework.

(c) Political barriers

In the CE context, in addition to the individual level responsibilities, the lack of responsibilities at a territorial level was also raised by the interviewees as an important concern that must be addressed. Incentivising measures should be set up to encourage local governments to develop their territory according to the CE principles and switch to the use of more circular materials. Therefore policies and regulations must be strengthened to support the move towards a circular-thinking society.

Several political shortfalls and regulations' complexity related to earthen buildings have been pointed out by the interviewees, as being critical barriers for the growth of the use of "non-common" materials, such as earth. Lack of regulations for non-common techniques, lack of appropriate standardization and incentives are examples of policies' weaknesses that must be addressed urgently to decline drastically the environmental impact of the construction sector and improve human well-being; often earthen architecture has the potential to achieve these goals and should be encouraged (see section 2).

The difficulty to get the insurance for the use of reclaimed materials, including excavation earth is also a struggle faced by practitioners willing to adopt a circular approach and most of the time they must get a technical certification. Moreover, getting technical certification is a "veritable obstacle course "for applicants, a costly, time consuming and sometimes biased process due to the unawareness of certification bodies.

(d) Socio-Economic barriers

Earth construction must emerge in a complex economic context and an unbalanced market where the recovered materials are not plebiscited. There is a lack of interest and demand for earthen construction, although experts note some emulsion around this material. The absence of a structured market obliges one to prepare the market upstream of projects, particularly when the project requires specific materials with specific expectations in terms of reuse and recycling. Also, a lack of awareness of the benefits of this material is keeping earthen construction behind. Real estate financing enforces clients to focus on their budget and to have a very short vision of the building leading them to make decisions based on that. Except for very few clients, profit-seeking and consume linearly is mainly the motto of our current society. In parallel, the lack of automation and regulations keep earthen architecture more expensive and time-consuming, compared to other types of architecture. Wherefore, earthen architecture struggles to bloom and with the lack of a holistic view, clients are not ready upfront for using more circular materials and embracing the CE approach.

To stimulate earthen architecture demand, some false beliefs must be corrected, and exemplary projects (like the one in Figure 1) require more advertisements to build up a better and modern social image of earthen architecture and show its beneficial and intrinsic response for humans and environment needs. Notably, the interviews' results indicated that environmental concerns permeated all of the assessed categories but that environmental barriers specifically were not considered to be a significant factor preventing the uptake of earthen construction. This is reasonable, as an environmental benefit should, by its nature, be expressed in context of the relevant activity rather than existing in isolation. The increase of awareness, understanding and potentials of earth as a construction material will create, as a result, an emulation around it and address the scepticism, lack of trust, and lack of concerns for the end-of-life of buildings.

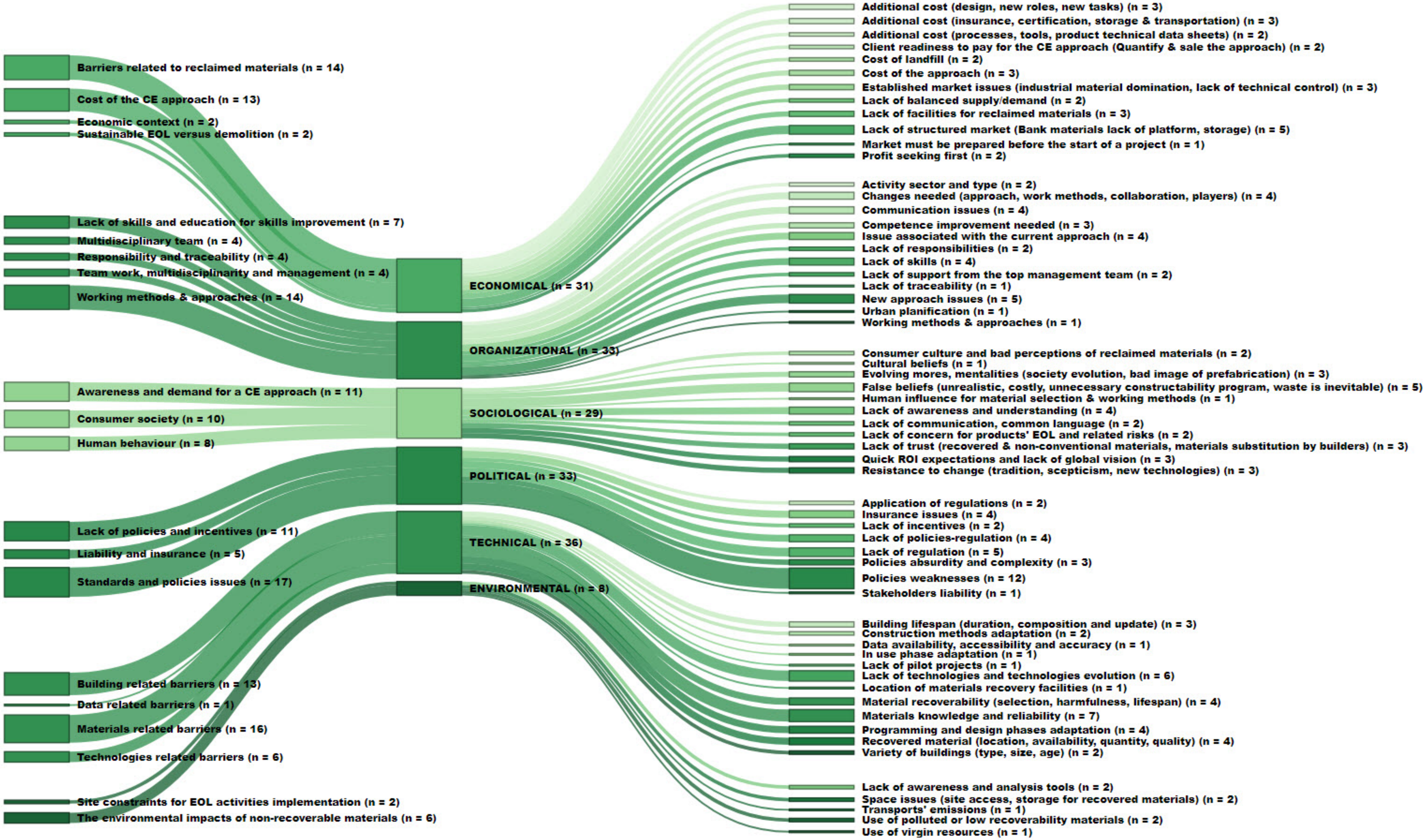

Figure 3: The barriers for the use of earth as a construction material in the circular economy context, (n) stands for the number of occurrences reported by the interviewees, in the categories, subcategories or sub-subcategories

4. Conclusion

This paper presents an overview of the role of soils in the provision of materials for construction, in the context of an urgent need for the construction sector to switch from the linear to a circular economy. First, descriptions about the characteristics of earth-based materials were presented, then obstacles against modern earthen architecture were also developed. It has been shown that the five main types of barriers for the application of earth-based materials in the circular economy context were: economical; organizational; sociological; political; environmental; and technical related-topics.

Although the technical area is the most studied, there are still numerous topics needing further investigations, such as how to assess properly the material performance of earth-based materials in which the tests on representative elementary volumes are complicated (eg. cob and rammed earth walls with the presence of big elements like gravels, stones, fibres). Similarly, the real impact of earth-based materials on building thermal behaviour and indoor air quality must be further explored. Research is also needed in the areas of control and prediction of the drying kinetics of the wall and its impact on mechanical behaviour (creep, strength) and on durability (freezing-thawing and fire resistance). Moreover, the identification of the conditions leading to durability issues requires particular attention and tools to control them should be developed. The assessment of the inhabitant comfort and the impact of earthen walls on it are also one of the many technical uncovered areas that should be explored in the future. The scientific results obtained on the technical aspect will surely bring useful information for the studies raising the barriers from other non-technical aspects.

As the Sankey diagram illustrates, there are other four categories of obstacles faced by earthen architecture: organizational, sociological political and economic barriers. In the current context, tackling these non-technical obstacles is crucial and urgent to address the climate and economic crisis. Surprisingly, they have almost not been studied although they are equally important. Therefore, in parallel, those grey areas should be prioritized and investigated. The lack of exploration of those areas could explain why the earthen architecture is still a niche market although it embodies numerous attributes of a sustainable construction material to tackle the current climate, economic and societal crisis. Notably, the sixth category "environment", although not being addressed directly, was found to permeate all other categories.

Recently, the construction sector engaged in its fourth industrial revolution, embracing its digitalisation by changing how buildings are designed, constructed, operated and maintained. Technologies such as the use of Building Information Modelling, Internet of Things, Artificial Intelligence, Blockchain, automation and robotic are emerging technologies having a huge potential to support the entire construction industry. However, how the earthen architecture could benefit from the digitalisation and automation of the construction sector are areas needing investigation.

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