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To cite this article: E Pelicaen *et al* 2023 *IOP Conf. Ser.: Earth Environ. Sci.* **1196** 012062

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Challenges to upscale earth block masonry in Western Europe from a life cycle perspective

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Abstract. Earth block masonry (EBM) has the potential to be reintegrated as an environmentally sound alternative to conventional masonry systems. However, applications with EBM are rare in highly industrialised contexts. Therefore, overcoming the obstacles impeding its entrance into mainstream construction is critical to enable upscaling. This study aims to identify the priority challenges of EBM in Western Europe. Literature on the barriers to upscale earth construction and EBM was reviewed and verified by interviewing earth block manufacturers in Belgium, France, Germany, and Switzerland. The challenges were grouped into six categories: technical, environmental, economic, sociological, political, and organisational. The data were analysed from a life cycle perspective in light of the transition to a circular built environment. The results show a discrepancy between research and practice to meet the current needs and ambitions of the manufacturers. Despite being largely unexplored, knowledge of end-of-life (EOL) scenarios may catalyse the upscaling of EBM. This outcome implies the importance of integrating the EOL phase in future studies on the barriers of EBM and matching research topics with the demands from practice following a multidisciplinary approach.

1. Introduction

Although earth is still a widely used building material worldwide, it has only seen a revival in Western Europe in the past few decades. Earth construction was ubiquitous for millennia until the Industrial Revolution, after which it fell into oblivion due to the mass production of fired bricks and cement. With growing awareness of resource depletion and climate issues, academics and practitioners' interest in earth as a circular building material has increased in the past few decades [1–3]. However, architectural applications with earth remain limited in the Western European context and climate. Although multiple earth construction techniques can be applied for interior and exterior and loadbearing and non-loadbearing purposes, the construction sector is reticent towards its adoption in mainstream construction [4,5]. Especially for interior non-loadbearing applications, earth may have a higher upscaling potential since it is protected from the elements and its mechanical performance is less demanding. Based on many years of practical experience, [6] presents a roadmap for upscaling earth construction in which the perceived vulnerability and labour-intensive process of earth construction and the lack of norms and education are the primary challenges to overcome. However, research about inter- and intra-relationships between barriers and drivers is lacking to confirm this statement [5]. In addition, most studies consider the challenges of earth construction in general [4,5,7]. Nevertheless, according to [8], every technique may have unique hurdles that should be identified. Moreover, [8] underlines a potential bias in literature considering earth in a linear economy while the construction sector needs a paradigm shift towards a circular system. For instance, no study defining barriers or drivers for the end-of-life

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phase of earth construction has yet been conducted [8]. To fill these gaps in the literature, this study focuses on earth block masonry (EBM) to identify technique-specific challenges and validate them with practitioners. The scope is refined to interior and non-loadbearing EBM, as these applications have high upscaling potential according to the authors' insights from practice. Moreover, this study aims to identify EBM's priority challenges according to professionals' needs and ambitions to upscale earth block masonry in Western Europe. Facing the urgency to shift towards a circular built environment, the challenges are approached from a life cycle perspective to identify in which process stages they occur and what life cycle phases are underexplored.

2. Materials and methods

Insights from the literature were verified by interviews with earth block manufacturers. First, literature was collected in Scopus containing synonym keywords for 'challenge' and 'opportunity', such as 'obstacle' and 'driver'. After gathering studies on earth construction in general, the search was further specified to EBM. Additional papers known by the authors were selected when they were similar to the specific context of this study. Second, four manufacturers of earth blocks were interviewed: BC Materials in Brussels, Belgium; Cycle Terre in Paris, France; Claytec in Viersen, Germany; and Terrabloc in Geneva, Switzerland, hereafter abbreviated as BEL, FRA, GER and SWI, respectively. The interviews were held online in French and Dutch. After preliminary questions about their experience, opinion and approach towards EBM, the interviewees were asked to sort the challenges found in literature according to their urgency to allow their entrance into mainstream construction using a Miro board. As challenges can differ regarding the technique and application, the manufacturers were asked to consider earth block masonry infill walls (EBMIWs) specifically. Opportunities, drivers or enablers identified in the literature were rewritten as challenges to avoid confusion during the interviews. Third, the literature review and interview results are analysed and discussed from a life cycle perspective to identify research gaps in the different life cycle stages. Parallels and disconnections between research and practice are highlighted to reflect the current needs of the manufacturers.

3. Results

Before conducting the interviews, the manufacturers were inquired to fill in a short questionnaire about their background and approximate data from their enterprise. The results are shown in **Table 1**.

Table 1. Approximate background data from interviewed manufacturers in Western Europe.

	BEL	FRA	GER	SWI
Number of employees	9	6	90	4
Number of years active in earth block production	5	5	30	10
Surface area of manufacturing unit [m²]	500	6 000	13 000	500
Annual number of produced earth blocks	50 000	400 000	2 800 000	200 000

3.1. Manufacturers' approaches to EBM

Regarding the extraction of resources, GER is the only manufacturer mining clay quarries near its production unit. BEL, FRA and SWI recover excavation soils from construction and infrastructure sites in Brussels, Paris and Geneva, respectively, forming the basis for their earth block mixes. The manufacturers use different techniques to produce earth blocks. While BEL and FRA make compressed earth blocks (CEBs) using a semi-automated hydraulic press, GER produces moulded earth blocks (MEBs) and extruded earth blocks (EEBs). SWI abandoned its production of CEBs and established an industrial co-production with a paving stone manufacturer to make vibro-compacted earth blocks (VEBs). BEL is planning an industrial co-production with a fired brick manufacturer to produce EEBs and a concrete block manufacturer to produce VEBs. GER produces exclusively non-stabilised earth blocks, while BEL produces non-stabilised CEBs and lime-stabilised CEBs on demand. FRA produces non-stabilised CEBs and lime or cement-stabilised CEBs for base layers and fragile angles. SWI mainly produces cement-stabilised VEBs and non-stabilised VEBs on demand. In terms of commercialisation, all manufacturers employ a business-to-business (B2B) model, wherein GER is additionally business-to-consumer (B2C), having multiple European distributors. FRA and SWI are mainly active in the public sector, whereas GER's primary revenue comes from the private market and self-builders. Although BEL's main CEB clients are kiln builders, they expect higher demand for EBM applications once their industrial EEB production line is launched. All manufacturers provide training, workshops, consultancy or lectures to diversify their activities, spread knowledge and interest, and stabilise their business. Earth blocks from BEL, FRA and GER are exclusively purposed for interior applications, whereas SWI sometimes employs VEBs in exposed walls. All manufacturers produce earth blocks for load-bearing and non-load-bearing applications. The manufacturers frequently supervise the construction process to manage the on-site stocking of the earth blocks and verify the blocks' laying to avoid constructive pathologies. Regarding the end-of-life phase, none of the manufacturers has experienced the demolition or dismantling of EBM, nor the recycling or reuse of earth blocks. This is probably because their monitored EBM projects are relatively young, and the question of EOL has not yet occurred. SWI recovers transportation-damaged earth blocks by recycling them back as granulates.

3.2. Manufacturers' evaluation of EBM challenges

According to the manufacturers, the application potential of EBM is highest for interior architectural purposes due to poor resistance against weathering, especially when not stabilised. The manufacturers mention earth block masonry infill walls (EBMIWs), partitioning walls, and inner cavity leaves as the main applications that have the potential to be upscaled. All manufacturers spontaneously mention the benefits of EBM in combination with wood construction, especially regarding the synergy between a lightweight wooden frame structure and a heavy EBM infill acting as a thermal buffer. However, based on the literature, six main groups of challenges hindering the application of EBM in mainstream construction in Western Europe are identified: technical, environmental, economic, sociological, political and organisational. **Table 2** summarises the challenges with the corresponding urgency according to the manufacturers. According to FRA, some of the challenges related to EBM can be seen as qualities that limit its over-democratisation since the peril of earth construction going mainstream can be its misuse and transformation towards low-grade concrete to fit conventional building methods. However, SWI departs from stabilisation to convince and establish trust in EBM from building actors before non-stabilised earth can gain acceptance.

Table 2. Urgency of challenges for EBMIWs according to manufacturers in Western Europe.

	Ref.	BEL	FRA	GER	SWI
Technical					
Extraction and classification (earth)					
Lack of standards	[9]	•	•	•	⬤
Availability, suitability and variability of (local) soils	[8]	●	•	•	●
Need for stabilisers to correct granulometry	[10,11]	•	•	•	●
Need for laboratory equipment	[11]	⬤	•	⬤	•
Preparation and production (earth blocks)					
Lack of standards	[2,8]	⬤	⬤	•	●
Long drying time	[11]	•	•	●	●
Lack of quality control	[11]	•	•	●	•
Lack of (conditioned) storage space	[11]	•	⬤	⬤	⬤
Lack of experienced technical staff	[11]	●	•	●	•
Design, construction and use (EBMIWs)					
Lack of standards	[4,5,8,12]	⬤	⬤	⬤	⬤
Lack of technical support	[8]	●	•	•	⬤
Unpredictable performance	[1,12]	•	●	•	•
Regular maintenance	[4]	•	●	•	•
Need for stabilisers to improve technical performance	[10]	●	•	•	●

Lack of data on technical performance	[13]	⬤	⬤	•	●
Low strength, durability and water resistance	[4,8,13]	•	•	•	●
Need for finishing layer	[1]	•	•	●	•
Environmental					
Lack of EPDs	[14,15]	⬤	•	⬤	•
Lack of circular approach	[8]	⬤	⬤	⬤	●
Lack of knowledge about end-of-life scenarios	[8,16]	⬤	⬤	⬤	⬤
Lack of (comparable) LCA studies	[15,17]	●	⬤	⬤	●
Lack of awareness about the impact of stabilisers	[8]	•	⬤	●	●
Lack of data to quantify energy performance and durability	[17,18]	●	⬤	⬤	●
Economic					
Higher costs than conventional building systems	[4,7,11]	⬤	⬤	⬤	⬤
Lack of/difficulty with quality certification	[11]	⬤	⬤	●	●
Lack of client demand	[5,7,11]	⬤	•	●	●
Fluctuating supply and demand	[11]	•	•	●	•
Increased time and cost to train labourers	[11,19]	•	●	•	⬤
Niche market	[11]	•	●	●	●
Labour intensity	[4,11]	•	●	•	•
Sociological					
Resistance to change	[8]	⬤	⬤	●	⬤
Negative material perception	[1,4,5]	●	•	⬤	•
Conservative safety factors	[8]	⬤	⬤	●	⬤
Lack of awareness/interest in material benefits	[4,5,7]	●	⬤	⬤	●
Lack of advertisement	[5]	•	•	⬤	•
Lack of exemplary projects	[5]	●	⬤	⬤	•
Lack of stakeholder engagement	[8]	●	⬤	●	•
Scepticism	[8]	●	⬤	•	⬤
Political					
Lack of fiscal incentives	[7,20]	•	•	⬤	⬤
Difficulty obtaining building permits and insurance	[4]	•	⬤	●	●
Complicated process to create new regulations	[8]	•	⬤	•	●
Lack of regulations	[4]	⬤	⬤	•	⬤
Inadequate standards	[8]	●	⬤	•	●
Lack of policies against carbon-intensive building materials	[5,11]	⬤	•	⬤	⬤
Organisational					
Lack of coordination and communication with stakeholders	[1,8]	•	●	●	•
Complicated construction process	[1,4,8]	•	●	•	●
Lack of education	[5,11]	•	⬤	●	●
Lack of (inefficient) technology transfer	[8,11]	●	⬤	●	•
Lack of training programs	[11]	●	⬤	⬤	⬤
Lack of knowledge and skills	[8]	●	●	●	⬤
Time-consuming construction process	[1,4,8]	•	●	•	⬤
Lack of skilled professionals	[4]	•	●	⬤	●
Disorganised supply chain	[5]	⬤	•	•	●

• not urgent ● urgent ⬤ very urgent

3.3. Technical challenges

Most scientific articles related to earth construction and earth block masonry address its technical barriers [13,20]. From a life cycle perspective, these occur mainly during the extraction, production, construction and use phases. Except for one study on the recyclability of compressed earth blocks [21], no literature was found related to the end-of-life phase. Since the end of last century, the development of normative documents for different earthen construction techniques has emerged worldwide.

Nevertheless, the lack of standards is generally cited as the primary technical barrier [8,12]. According to the RILEM on the standardisation of earth construction on a European scale, creating new codes and standards is essential to encourage designers to build with earth and to persuade regulatory bodies [12].

Regarding the resources, a challenge listed by [8] is to find local soil with the recommended proportion of clay, silt, sand and gravel, particularly in urban areas, whenever one wishes to avoid environmental impacts due to transportation, which is the case for all manufacturers. The manufacturers do not consider this a particular challenge, as was equally pointed out by [5] for practitioners in the UK. Consequently, the need for hydraulic stabilisation to correct the granulometric distribution and clay content is not necessary to produce earth blocks. A lack of laboratory equipment for small and medium-scale manufacturers was mentioned as a barrier by [11] and confirmed by BEL. Indeed, it is costly for BEL to wait for laboratories to carry out the necessary tests. This statement is supported by FRA, which possesses the equipment but wishes to sophisticate it. Although standards on soil selection are mainly qualitative and use different approaches and criteria according to [9], the manufacturers can sufficiently rely on soil mechanics and geology expertise to obtain desired earth block mixes.

The lack of standards is more urgent for the production of earth blocks, as BEL must rely on foreign standards, leading to conflict with certification institutes. Regarding the drying time needed for the blocks, FRA mitigated this issue by installing a drying tunnel using residual heat, while BEL can rely on infrastructure from its industrial co-production with a manufacturer of fired bricks. Additionally, this partnership will allow BEL to rely on vast storage spaces, a challenge still valid for FRA despite their much larger manufacturing unit. Hence, an additional challenge added by BEL is to establish more partnerships to outsource their earth block production. Quality control of the produced blocks was mentioned as a barrier by [11]. However, BEL specifies the lack of technical professionals experienced in earth construction to perform the quality control, not the lack of quality control itself.

Regarding the design, construction and use phases of earth block masonry infill walls (EBMIWs), the lack of standards is considered an urgent challenge by all manufacturers. Indeed, a lack of coherence among standards forces designers to fend for themselves in obtaining building approvals [12]. Additionally, technical data on technical performance, such as hygrothermal behaviour, is lacking to support the manufacturer’s claims of reduced energy demands for HVAC. GER claims to have performed tests proving better thermal inertia for earth blocks than for concrete, although research is lacking on this matter [13]. Moreover, BEL and FRA underline the difficulty of knowing the admissible height and length of EBMIWs, requiring data for slenderness, bending resistance and shear strength. In the construction phase, relating on-site performance, such as compressive strength, to prior laboratory testing [8] has only been complex in the beginning, says FRA. Chemically improving technical performance is rejected by BEL, FRA and GER, as they are against stabilisation at the cost of environmental performance [10] and moisture buffering capacity [22,23]. Indeed, the debate on the necessity of stabilisation is splitting practitioners into two groups [8]. However, BEL suggests the need for additives as a barrier to compromise the mechanical performance and environmental impact. During the use phase, regular maintenance prevails as a barrier in literature [4], yet for EBMIWs, it can be solved by a cellulose coating if needed, according to BEL. The same goes for the need for a finishing layer [3], which all manufacturers agree is only for aesthetic preferences. Finally, the repeatedly cited low strength, durability and water vulnerability of earth [8] is not an issue for non-loadbearing EBMIWs, according to the manufacturers, as they are protected from weathering agents.

3.4. Environmental challenges

Upscaling earth construction faces obstacles in convincing stakeholders about the environmental benefits of building with earth [18]. Environmental Product Declarations (EPDs) are needed since manufacturers cannot count solely on intuitive environmental claims to maintain success in an increasingly competitive industry [14]. Indeed, researchers should provide evidence to support the ecological arguments for earth-building by comparing earth-building products with conventional materials [8,15]. For instance, GER notices more and more clients demanding environmental certifications going beyond the scope of their Cradle to Cradle label. Possible reasons explaining the lack of EPDs for earthen building products are their local character and heterogenic properties from site to site and the small production scale [15]. Additionally, EPDs are still voluntary in many European countries, involving skilled professionals to acquire quantitative data and perform complex calculations [8]. However, while BEL and GER are outsourcing LCA studies, FRA has already obtained EPDs for load-bearing and non-load-bearing CEB wall systems. Another issue is the comparability of LCA studies since they can diverge from the standardised method or use industry-wide averages instead of specific location, material and process data [15,17]. Indeed, the EPDs from FRA do not sufficiently approach reality in their opinion and are not readily comparable to Belgian national LCA methods. As stated by [17], another environmental hurdle is the lack of technical data to quantify energy performance. Moreover, completing LCA studies with hygrothermal and durability models is considered a key research issue by [13] since thermal inertia and moisture buffering capacity of EBMIWs may reduce HVAC energy demands. Durability depends on stabilisers and occupant behaviour, among other factors [13,24]. Besides, BEL adds the challenge to communicating qualitative properties to convince stakeholders about the benefits of earth, such as its safe processing and occupant well-being in earthen buildings, which are not yet backed up by scientific studies.

Recent LCA studies on EBM show promising results for earth blocks compared to conventional building materials in nearly all life cycle phases. The highest environmental impacts are attributed to transportation and the amount of stabiliser if any [18]. Thus, minimising transportation using locally available resources and reducing or refusing an amount of stabiliser such as lime and cement can significantly improve the environmental footprint of earth blocks [25]. Moreover, stabilised earth blocks have a reduced capacity to passively contribute to humidity regulation, thus requiring more energy to achieve hygrothermal comfort during the use phase [18,23]. In addition, stabilisation is an irreversible chemical process, whereas non-stabilised earth blocks can be crushed or plasticised with water, dried and sieved to return to their original constituents [3,16]. One study on the recyclability and durability of earth blocks shows that non-stabilised CEBs maintain similar mechanical performance after recycling, while cement-stabilised CEBs show remarkable stiffness and strength reduction [21]. Nevertheless, most scientific studies focus on technical improvements of earth blocks through stabilisation methods, while [11] argues that this marginally improves strength and durability. According to FRA, architects should be sensitised about the environmental impact of stabilisers as they are more likely to employ stabilisation to reduce architectural constraints and for the sake of simplicity.

In terms of circularity, using excavated soils from construction sites is an environmental opportunity since the impacts associated with earth extraction can be avoided [18]. The recoverability of earth is also cited as an opportunity [4,18] and supposedly infinite [3,8,26], at least for non-stabilised earth. However, empirical evidence is lacking to support this statement [15], and LCAs only consider inert landfill scenarios instead of recycling or reuse [18]. Earth is perceived as easily recyclable in a closed-loop system and can be disposed of at a small environmental cost [15]. However, quantifying the recovery potential of earthen building materials remains unexplored [8,15]. Then again, from an environmental perspective, there is no evidence on whether recycling and remanufacturing earth blocks are preferable to disassembly and reuse or even demolition and disposal [16]. BEL expects extruded earth blocks more likely to be reusable than compressed earth blocks due to a much higher cohesion, yet research should determine whether this results in a higher environmental performance. FRA completes this statement by declaring circular approaches and end-of-life possibilities with EBM as still being too theoretical. For instance, in a planned project to convert athletes' dormitories into offices after the Olympics of 2024 in Paris, FRA mentions the demolition-recycling-remanufacturing scenario of EBMIWs as being the easiest solution thus far. According to BEL, an additional circular opportunity of EBM lies in its low-impact temporality potential as a consequence of its ease to be recycled, especially when buildings are prematurely adapted or demolished.

3.5. Economic challenges

As indicated by [8], there is a high discrepancy between research on technical factors and other perspectives. Especially within the circular economy context, studies on the whole lifecycle costs of earth construction are lacking. From a life cycle perspective, challenges are prevalent during production and construction in countries with high labour costs, such as those studied. When earth blocks are prefabricated off-site, commercialisation challenges add to the cycle [11]. Compared to conventional building materials, the higher costs for earthen materials can be explained by the lack of standards increasing the construction time and engineering costs [8], the higher labour intensity [4], and the uncompetitive unit price of earth blocks [11]. Additionally, perceived higher upfront costs are a barrier for clients, according to [7]. Furthermore, GER mentions that the high costs to perform tests, such as for fire safety, hinder their expansion potential. The lack of demand and limited market for earth blocks is often cited as a barrier [8,11]. While FRA has a substantial demand from clients they cannot satisfy due to perceived higher up-front costs, GER blames their lack of clients on a lack of information and ignorance of EBM by contractors. BEL believes quality certifications will reduce the general lack of trust in the material. BEL expects the unit price of EEBs to decrease significantly since about half of the price of fired bricks is attributable to the baking process. Indeed, upscaling production through industrialisation is seen as a cost-reducing opportunity in countries with high labour costs [27]. The fluctuating supply and demand of earth blocks, as cited by [11], is not considered a particular challenge for BEL, FRA and GER. Then again, to enter mainstream construction, the client demand is still too low, according to the manufacturers. However, BEL is convinced that once large-scale contractors start implementing their industrialised extruded earth blocks in a small percentage of their projects, others will follow, and the market cannot be considered niche. An additional economic challenge, according to BEL, is the in-house working efficiency, as their vast range of relatively new activities is restraining their productivity. Indeed, manufacturers are sometimes forced to diversify their activity to maintain stability in a niche market [11]. Finally, there is growing economic interest in using excavated soils from conventional construction and infrastructure sites to manufacture earth blocks, as these are legally considered waste [18]. Indeed, BEL and FRA have a win-win situation with excavation contractors providing raw materials earth block production while the contractors avoid increasing landfill costs.

3.6. Sociological challenges

Earthen materials suffer from a negative perception and could be perceived as not aesthetic, be associated with dirt, seem inferior in quality, and look primitive rather than innovative [4,8]. However, it is FRA's opinion that, at least in France, the negative perception of the material has been significantly reduced since the beginning of this century. Scepticism towards earth construction can arise from professionals in the building sector, banks and insurance agencies, governments and standardisation bodies [8]. According to BEL, control agencies granting technical certifications are most sceptical towards EBM, followed by clients and engineers, while architects are commonly the first willing to collaborate. Additionally, a lack of awareness about the benefits of using earth as a building material is usually the cause for scepticism [4,7], which can be due to a general lack of awareness or interest in environmental sustainability from clients [8,28]. Furthermore, scepticism results in highly conservative safety factors for EBM due to undervaluing the mechanical properties, as repeatedly experienced by the manufacturers. Resistance to change in the construction industry acts as a roadblock to applying sustainable building practices [8]. Moreover, the risk-averse and cost-driven strategy results in a conservative industry with little room for innovation [8]. BEL indicates that quality certifications can alleviate the building sector's resistance to change and eliminate perceived risks. Furthermore, the building sector's strong emphasis on cost-effectiveness can discourage practitioners from adopting sustainable building solutions [8]. GER mentions that large contractors are least open to working with unfamiliar materials. Finally, tackling the lack of exemplary projects and promoting earth construction may boost the popularity of the material among clients and practitioners, which in turn may increase the demand [5]. Then again, FRA is wary about advertisements reaching professionals who are more prone to using stabilisers and thereby abusing the environmental benefits of earth. GER adds the lack of visibility as an additional challenge, as masons are more likely to refuse an EBM project if they have never seen it before or have no experience in the execution.

3.7. Political challenges

Regulations for EBM and earth construction, in general, are still deficient in number compared to conventional building materials and systems [4,11]. Although this number has increased in Western Europe, some authors cite the absence of supporters of earth construction on regulatory commissions [4]. In addition, creating new standards can be complicated, and designers sometimes must adhere to concrete or masonry standards, leading to structural and environmental inconsistencies [8]. While BEL is highly dependent on foreign standards and normative documents, GER does not consider this an urgent challenge given the EBM design standard DIN 18940 that is about to be published. As structural engineers are accustomed to highly predictable and standardised materials, the lack of codes forces them to develop new methods for each construction project, thus requiring a complicated, time-consuming and costly process of obtaining technical certifications [1]. These obstacles often result in difficulty obtaining building permits and insurance for earthen constructions [4] and municipal constructions authorisations for EBM specifically [11]. While BEL and GER did not encounter this, FRA graded this as a highly urgent matter. In addition to the previously mentioned mechanical underestimation of EBM, thermal regulations are generally inadequate to assess the thermal performance of earth since thermal inertia is often overlooked [8]. Finally, a lack of government support through fiscal incentives [7] and policies against carbon-intensive building materials [5] were cited. BEL adds the lack of political courage as a barrier since politicians fail to install new regulations and policies to implement regenerative building materials. GER and BEL repeatedly mention that the lack of policies to minimise carbon-intensive materials should be turned around by supporting low-impact materials. In France, the environmental regulation RE2020 imposes new rules to reduce the environmental impact of the construction sector, paving the way for bio- and geo-sourced materials. Besides, BEL pleads for LCA-subsidising to allow EBM and other low-impact building systems to enter mainstream construction.

3.8. Organisational challenges

A consequence of the lack of codes and guidance for builders is the time-consuming and complicated design and construction process, albeit dependent on the applied technique [1,4,8]. On-site production of earth blocks can increase organisational complexity and costs [27], yet all manufacturers consider this method a hindrance to upscale EBM. In the construction phase, BEL considers only minor challenges for EBM, such as proper site management to prevent earth blocks from getting wet and avoiding leaks after the installation EBMIWs. BEL sees an opportunity to use biodegradable glue to speed up the construction process to compete with conventional masonry systems. According to [8], one of the most cited barriers is the general lack of knowledge and skills among all stakeholders in the design and construction process. The lack of skilled professionals [4] may result from the historical decline in technical knowledge of earthen building methods brought on by modern materials [3]. Lack of education in earth construction by architects and engineers can lead to conflict and rejection as it does not match their training and practical experience [5], while the resistance from experienced builders towards EBM was observed [11]. However, BEL argues the relative simplicity of EBM with minor differences compared to conventional masonries, such as wetting earth blocks before laying and different workability of the mortar. End-users may also be uninformed and wrongly use and maintain earthen building elements. Integrating masons in the design process [1] may further avoid coordination and communication problems between stakeholders [8]. Infrequent and discontinuous events of training programs on EBM [11] are worsened by a mismatch between training organisms finding skilled professionals and vice versa [8]. The lack of EBM projects also restrains the occasion to organise informal on-site training. Lastly, the technological transfer of EBM is impeded by the selection and complexity of the transmitted content for the target audiences' profile, as training modalities of technical staff and labour are scarcely addressed in research [11]. FRA and GER insist on the lack of financial support to organise efficient technology transfer and training programs for EBM. Regarding the lack of organisation of the earth supply chain [5], BEL adds logistics as the most urgent organisational challenge, specifically minimising transportation between resources, manufacturing units, and construction sites. Indeed, the weight of CEBs obliges to reduce distances since excessive breaking may occur in transit, harming the material's reputation [11]. Since little volume can be transported by lorry, BEL sees a logistical opportunity in its network of industry partnerships to reduce transport distances to the construction site and to increase transportation volumes of resources by using waterways. GER motivates a well-organised supply chain through an extensive network of distributors and resellers of earth blocks in Germany. BEL also adds the organisation of take-back programs to transport reusable or recyclable materials as a cost-saving circular opportunity.

4. Discussion

Several hotspots were identified, reflecting the urgency of the challenges found in the literature that were confirmed by practice. According to the manufacturers, the most urgent technical challenge with EBM is the lack of standards for design and construction. From a life cycle perspective, the lack of standards represents a knowledge gap in EBM's design and construction phase. Although manufacturers and designers can rely on (foreign) normative documents and technical guides, unification is needed to mitigate the risks of constructive pathologies, simplify and speed up the design process, and obtain building permits and insurance. Moreover, a high discrepancy exists between the amount of academic research on the technical optimisation of earth blocks and the need for standardisation of EBM from the manufacturers. The most urgent environmental challenge is the lack of knowledge about end-of-life (EOL) scenarios. While none have already experienced the EOL stage of EBM, all manufacturers agree on quantifying the recoverability of EBM to catalyse its upscaling potential. As non-stabilised earth blocks may have the capacity to be fully recovered multiple times, multiple-use LCAs may significantly favour the environmental impact mitigation potential of EBM versus conventional building systems. The most urgent economic challenge is the higher cost of conventional building systems. Higher costs for EBM occur primarily during the production and construction phases. One way to reduce costs in the production phase is to establish an industrial co-production with manufacturers of conventional building materials granting their machinery use and storage space for earth blocks. The most urgent sociological challenge is the resistance to change from various stakeholders, which may result from scepticism and lack of awareness about the benefits of EBM. From a life cycle perspective, this challenge is most observed during the design and construction phase as the manufacturers encounter difficulties with clients, architects, engineers, contractors and control agencies granting technical certifications. If not refusing EBM applications, building actors tend to mitigate risks through conservative safety factors leading to higher costs or stabilisation leading to higher environmental impact. The most urgent political challenge is the lack of policies against carbon-intensive building materials. According to all manufacturers, this should be reversed to support the use of regenerative building materials leading to potential advantages in all life cycle stages. The most urgent organisational challenge is the lack of training programs. Manifesting itself mainly during construction, the lack of training relates to the lack of technology transfer, calling for academic reflection to satisfy the needs of the manufacturers.

From a life cycle perspective, EBM's end-of-life (EOL) represents a major gap in scientific research, confirmed by the manufacturers' lack of experience with recycling, reusing and disposal of EBM. Moreover, the lack of knowledge of EOL scenarios with EBM manifests as an environmental challenge and implies obstacles in other challenge categories. Technical know-how on the reusability of earth blocks is an entirely new research topic, whereas influential organisational factors such as take-back programs are also lacking. Additionally, economic savings of initial resources through material reuse are unknown, while political support, such as fiscal incentives for reused materials, may further boost the need for knowledge on the EOL of EBM. Even the sociological perception might favour reclaimed earth blocks compared to conventional materials, yet only research can disclose a statement as such.

Some remarks must be made on the interpretations of the challenges by the manufacturers. First, some challenges were not considered a barrier when the manufacturer had already overcome them. For instance, the lack of EPDs was rated as very urgent by BEL and GER, whereas FRA does not consider this urgent as they already obtained EPDs. Second, several challenges may be interpreted differently, depending on the building actors considered (clients, architects, end-users or other actors), making it challenging to rate the urgency. Further research from different stakeholders' perspectives is therefore needed. Third, the manufacturers' views may be influenced by their different backgrounds and education. For instance, the manufacturers' opinion on the "lack of a circular approach" depends on their knowledge and interpretation of circularity. Moreover, SWI confused EPDs with ecological certifications and therefore rated it as not urgent since they possess ecolabels. Furthermore, some challenges, such as "lack of knowledge and skills" and "lack of education", might have been interpreted as having the same meaning, while the latter refers to schooling rather than professional training. Finally, the manufacturers may be biased by their conviction in the benefits of EBM. For instance, the manufacturers did not rate regular maintenance as an urgent challenge for EBM, although this is frequently cited as a barrier in literature. Additionally, the manufacturers' frequent contact with stakeholders that are interested in regenerative building materials may lead to biased results for challenges such as negative material perception and being part of a niche market. In contrast, players in the conventional construction industry may not share those beliefs. Therefore, more research is needed on the perception of EBM from other building actors with different ideologies.

Next, some notes must be added to the analysis of the challenges. First, distinctions between barriers were needed to ensure comprehensiveness, yet many interact. For instance, resistance to change may result from the lack of training programs, resulting in a lack of skilled professionals and increased costs during design and construction. Moreover, resolving the lack of standards may eliminate the need for technical certifications. Hence, more research should be conducted on the correlations between challenges to identify priorities that may induce a snowball effect. Second, the challenges found in the literature were not always related to EBM, let alone EBMIWs. Therefore, it is recommended to distinguish challenges that influence EBM and EBMIWs from those on earth construction, such as most sociological and political challenges. The same goes for stabilised versus non-stabilised earth blocks, as the use of stabiliser affects the need for maintenance or the durability and water resistance, for example. Third, newly mentioned barriers by the manufacturers, such as the "need for additives", "developing partnerships", and "material logistics", deserve to be included in future research on upscaling EBM. Finally, a larger sample size of manufacturers will alleviate some of the limitations mentioned earlier and therefore contribute to data reliability.

5. Conclusion

This study aimed to identify priority challenges to upscale earth block masonry (EBM) in Western Europe from a life cycle perspective. Six challenge categories were derived from the literature: technical, environmental, economic, sociological, political, and organisational. Verifying research with practice revealed the most urgent challenges for EBM according to earth block manufacturers respectively: the lack of standards for design and construction, the lack of knowledge about end-of-life (EOL) scenarios, the higher cost than conventional building systems, the construction sectors' resistance to change, the lack of policies against carbon-intensive building materials, and the lack of training programs. From a life cycle perspective, the EOL of EBM represents a significant gap in scientific research, as choosing between recycling, reuse or disposal impacts other challenge categories. Regarding the transition towards a circular built environment, future research should at least include this life cycle stage to define barriers, drivers and enablers of EBM in mainstream construction.

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