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Circular, Local, Open: A Recipe for Sustainable Building Construction

Asimina Kouvara [1,*], Christina Priavolou [1], Denise Ott [2], Philipp Scherer [3] and Verena Helen van Zyl-Bulitta [4]

[1] Ragnar Nurkse Department of Innovation and Governance, Tallinn University of Technology (TalTech), Akadeemia Tee 3, 12618 Tallinn, Estonia; christina.priavolou@taltech.ee
[2] EurA AG, 99084 Erfurt, Germany; denise.ott@eura-ag.de
[3] Polycare Research Technology GmbH, 98528 Gehlberg, Germany; p.scherer@polycare.de
[4] Independent Researcher, 13403 Berlin, Germany; verena@bulitta.com
* Correspondence: asimina.kouvara@taltech.ee

Abstract: In response to the construction sector's contribution to the climate crisis and exacerbation of social inequalities, we explore sustainable alternatives in building construction, informed by the illustrative case study of the Polycare construction system. First, through a Life-Cycle Assessment (LCA) method, we show that the ecological footprint of circularity-oriented buildings based on polymer concrete is significantly lower than that of conventional cement concrete buildings. Despite the drawbacks of polymer concrete, its high-performance properties and the possibility to integrate secondary materials in its recipe can result in a reduced carbon footprint. When coupled with design-embedded modularity that facilitates circular processes (e.g., the disassembly and reuse of building components), buildings similar to those in the case study demonstrate potential for transitioning towards comprehensive sustainable building practices. Further, we discuss how this sustainability potential could be enhanced, drawing from interviews with Polycare's stakeholders and key literature findings. In this direction, we provide a set of proposals anchored in the argument that threefold "circularity, localisation, and openness" is vital for sustainable and affordable alternatives, with openness being a crucial element for fostering innovation, adaptability, and scalability in building processes.

Keywords: circularity; localisation; openness; sustainable building; polymer concrete; life-cycle assessment

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1. Introduction

The construction sector accounts for a large share of the climate crisis and social inequality. Conventional building practices follow linear production models, which depend on global value chains and the extensive use of unsustainable materials. The most crucial environmental consequences of dominant practices are significant carbon emissions, natural resource exploitation, high energy demands, and waste production [1]. Other implications include labour-intensive activities, illegal or unmonitored mining and waste export, gender discrimination, and corruption [2–4]. Additionally, increasing costs for building construction and energy, coupled with the lack of policies to support sustainable building materials/practices, have hindered access to decent housing for middle- and low-income households, even within affluent economies [5–11].

With the demand for urban housing projected to rise substantially by 2050 [11], there is an urgent need to develop sustainable and affordable building solutions that address both environmental and social concerns [9,11–13]. The relevant literature suggests that holistic changes encompassing the entire life cycle of buildings are crucial [7,14,15]. Such changes mainly promote the adoption of circular (e.g., recycling, remanufacturing, repair, and reuse), localised (e.g., local material resources and the manufacturing of building components), and open (e.g., open-data, open-design, and open-software/hardware) practices. In this way, it is possible to extend the lifespan of building components [16–18], increase resource efficiency [19,20], yield socio-environmental benefits [21,22], and ensure the transparency of supply chains and sustainability assessment methods [7,23,24].

In this article, we argue that the integration of circularity, localisation, and openness, is fundamental for achieving comprehensive sustainability in building construction. To substantiate this claim, we explore the sustainability potential of "Polycare" and their "Polyblock" system, a construction system oriented towards circularity. Selected as a representative case, Polycare addresses multiple aspects and current challenges associated with sustainable building construction. In short, Polycare's Polyblock system is a modular structural system made of polymer concrete, an alternative to conventional cement concrete, which shows potential for developing sustainable and affordable housing solutions. We employ the Life-Cycle Assessment (LCA) method to assess the ecological impact of Polycare structures and compare it with that of conventional cement concrete structures of identical shapes and sizes. This quantitative analysis is supplemented with a qualitative assessment informed by literature and interviews to discuss how initiatives, like Polycare, could enhance their socio-environmental impact. The discussion is centred on threefold "circularity, localisation, and openness", suggesting ways for their further adoption by Polycare and similar initiatives. Lastly, we pinpoint obstacles and deliberate on how institutional support and strategic partnerships could catalyse sustainable transitions in the construction sector.

The article unfolds as follows: Section 2 summarises key literature findings regarding the three critical elements for sustainability in building construction, i.e., circularity, localisation, and openness. Section 3 delineates the methods and tools utilised, while Section 4 provides an overview of the Polycare construction system. Section 5 presents the results of the comparative LCA analysis followed by a critical discussion regarding the sustainability potential of Polycare and similar initiatives. The conclusion, in Section 6, reflects on the preceding sections, addresses the limitations of this study, and offers recommendations for future research and action.

2. Tracing Sustainable Approaches to Building Construction

Maintaining a balanced relationship between environmental, social, and economic aspects of sustainability in building construction is a burning issue on a global level [9,11,12]. Despite the need for integrated approaches to sustainability issues, the focus is usually on the building's environmental performance and energy efficiency, primarily to minimise their life-cycle carbon footprint [14,15,24–28]. However, buildings are complex systems that involve several stakeholders, and their impact extends beyond the environmental dimension. In this direction, several studies also address the socio-economic aspects of sustainability in building construction, particularly in the case of housing. These aspects include affordability, addressing local needs and capacities, as well as enabling the participation of various actors in the building process [6,7,29–31]. Through a literature review on sustainable building construction, we identified three main focus areas that address different aspects of sustainability throughout the building's life cycle and may indicate more sustainable ways of organising building production, namely, circularity, localisation, and openness, which are explained next.

2.1. Circularity

Transitioning from the linear to the cyclical construction process is deemed necessary for realising sustainable construction [20,32]. Circular Economy (CE) principles are widely applied in the construction industry to achieve Sustainable Development Goals [33,34]. The EU action for CE recommends implementing reuse and recycling methods to enhance the circularity of building materials and wastes [35]. Such methods, like the repair, reclaiming, and repurposing of building materials and components, aim to increase resource efficiency by retaining product value [17,36] while reducing waste and demand for energy consumption and new material inputs [16,18,37]. Indicatively, reusing building components three times can lead to a 60% saving [38]. However, when material recycling is highly energy intensive or used for applications of lower value than the material's initial purpose, a process known as downcycling [39] may contribute negligibly to circularity [17,40,41]. Selective disassembly and selective demolition are methods that can facilitate the effective reuse of building components and materials [42–47]. The former means that building components can be reclaimed, reused, and maintained throughout the building's life cycle [46,47]. The latter refers to the separation of construction waste on site [42].

The design phase of building construction is decisive in optimising the building's environmental performance and the effectiveness of circular practices [48–51]. Design-embedded modularity appears to be a popular approach to effectively implementing CE principles in building construction [52–54]. More specifically, a modular building consists of independent components (modules) planned for selective disassembly [46,47,55–58]. Thus, modularity enables circularity because independent building components can be easily replaced, repaired, and rearranged without damage [57]. It also empowers people to participate in the construction process because modules can be examined independently, allowing for distributed problem-solving processes and boosting innovation in production [55,59]. Limited studies have been carried out proving that modular buildings present better life-cycle performances when compared with identical conventional counterparts [27,60–62].

Sustainability provides a broad and diffused framing and agency and holistically treats the three dimensions—environment, economy, and society at large [63]. Additionally, research indicates that CE stresses the economic and environmental benefits of less resource depletion and pollution [63,64]. As a result, circularity is a vital element for sustainable building construction, which, however, alone, cannot ensure sustainability. More holistic approaches should be applied to assess buildings, illuminating diverse aspects of sustainability in building construction over the entire life cycle [27].

2.2. Localisation

In the pursuit of integrated sustainable building practices, localisation emerges as a prominent direction, encompassing the construction and operational stages of a building's life cycle. Although the construction industry is dependent on industrial cement concrete and global value chains, and prioritising labour cost reduction, various forms of localisation address the environmental footprint and social impact of the current trajectory [3,65–67]. Characteristically, the sector is responsible for the depletion of approximately 60% of the natural resources annually (e.g., sand, gravel, and water), primarily to cover the global demand for cement and steel—70% and 30%, respectively [12,50,68]. Nevertheless, cement concrete remains a dominant and relatively affordable choice mainly because the environmental costs associated with its production are externalised and, hence, excluded from pricing [66].

Introducing alternative materials to replace industrial cement and improve the performance of building components is at the centre of efforts towards sustainable building construction. Such materials (e.g., geopolymers) aim to mitigate the exploitation of depletable natural resources and reduce embodied carbon, solid waste production, and domestic energy consumption [69–71]. In the context of the CE, emphasis is laid on the utilisation of industrial side streams and waste, recycled materials (e.g., plastics), and construction and demolition waste (CDW) [71–76]. Similarly, the use of agricultural residues (agro-waste) and other bio-based materials is popular [67,77–83]. However, to further enhance the environmental performance and affordability of buildings, particularly for low-income households [22], emphasis is placed on developing strategies aimed at utilising locally available resources and at locally manufacturing building materials/components [22,31,52,79,84–91]. In addition to the aforementioned advantages of alternative materials, utilising local resources, such as abundant raw materials, flowing secondary materials, and locally grown biomaterials (e.g., hemp), can foster a strong connection between construction and the agricultural sector and local waste management, contributing to the implementation of CE schemes and the reduction of construction costs [22,31,52,79,84–86,88–91].

Additionally, training a local workforce and involving local residents in manufacturing, building, and maintaining materials, components, and buildings creates employment opportunities favouring local economies and the development of a sustainable career for local construction workers [21,31,67,79,85,92]. Relevant research has shown that organisations and employees serving their community are more productive and offer higher-quality services benefiting all stakeholders [92]. Furthermore, establishing a local community at work fosters local resilience by promoting independence from material and technology imports and enables the advancement of the local knowledge/skill capacity and the utilisation of existing local construction knowledge [22,31,79,85,93,94].

In summary, the local context (e.g., climatic conditions, resources, workforce, and land tenure) plays an important role in devising sustainable and affordable building practices that meet region-specific needs and demand for buildings [95,96]. Localising different phases of the building's life cycle, from material sourcing to construction waste management, and the engagement of the local community can help address socio-environmental impacts of the current situation. Further research and institutional support are required, though, to assess the performance of such localisation-oriented efforts in the long run and to introduce them as viable alternatives in the current market [31,79]. Last but not least, the involvement of local governments is pivotal for effectively assessing the availability (region-wise) of local resources and monitoring material flows and waste, as well as facilitating local supply chains and CE strategies [96,97].

2.3. Openness

Openness emerges as another pivotal attribute of sustainable and affordable building construction [98], addressing the challenges associated with conventional construction practices, such as limited collaboration, lack of transparency, and unsustainable material choices. Theoretical frameworks, such as the Open-Source Movement and the Circular Economy Principles, underpin the concept of openness in building construction. In this context, openness refers to transparency regarding the building's life cycle and denotes accessibility to information, knowledge resources, tools, and processes through which a building is designed, built, demolished/disassembled, and assessed in terms of its sustainability [99,100]. Essentially, it involves sharing information about designs, materials, building methods, etc., as digital commons through the internet [101], while design tools and physical production infrastructures, such as factories, makerspaces, and hardware equipment, can also be open-source and shared [58,102].

Relevant research on initiatives employing open-building practices has demonstrated the socio-environmental benefits of openness in building construction [58]. More specifically, the active and collective participation in building development, improvement, production, and maintenance are promoted through open designs, fostering sustainability in building construction [103], and safeguarding the right to housing [7]. Openness allows local communities, organisations, individuals (e.g., designers, engineers, producers, and users), and governments to autonomously monitor, study, and participate in the building process while being supported by a global knowledge network [104–107]. In that sense, open-building practices enable knowledge exchange and collaboration in synchronous and asynchronous formats, both locally and globally, promoting cross-sectoral and trans-regional cooperation.

Implementing openness in building construction poses challenges, such as intellectual property issues or standardisation difficulties and resistance from traditional construction stakeholders. Despite these challenges, transparency through openness in the building's life cycle (e.g., supply chains and labour conditions) facilitates the application of evidence-informed life-cycle sustainability assessments and the evaluation of alternative solutions [24]. This aligns with net-zero objectives and the effective management of the building's life cycle [108,109]. Furthermore, keeping the design open for others to access and use is usually the most inexpensive solution, with various benefits for both the innovator and users [110–112].

The importance of collaborative knowledge-sharing practices that improve design performance has also been stressed [113]. Such practices could be supported by integrating project participants, commonly understood design objects, and geographically separated designs to achieve the best design [114]. In particular, design integration and a shared understanding between participants in building construction have been reported as key enablers for optimal design performance and project success [115,116]. Also, using open-source codified databases could catalyse the creation of a common language for sharing building components [23].

Finally, the term Open Construction Systems (OCSs) has been used to grasp the concept of open processes in building construction, allowing for an ecosystemic perspective of buildings as complex systems [98]. The design principles of OCSs endorse sustainable material choices and modularity, alongside open sharing and other open-source values. In fact, global sharing and local manufacturing are key points in such initiatives. More specifically, the WikiHouse and the Open Building Institute constitute two examples that fall under the umbrella of OCSs. In this regard, they exemplify how continual innovation enabled through open sharing can generate exponential advancement by building on others' contributions or proposed iterations. The diversity of participants' backgrounds especially brings about diverse contributions; and, hence, such communities become highly innovative [117]. In this context, openness that permeates all the phases of building development has been identified as a pivotal attribute for reducing environmental impacts and enhancing social benefits [98,104].

3. Materials and Methods

The aim of this study is twofold: i. to compare the ecological impact of circularity-oriented construction buildings (based on polymer concrete) versus conventional (cement concrete) buildings of identical sizes and shapes and ii. to critically assess how initiatives like Polycare could enhance their environmental benefits, while scaling their social impact [118]. The latter assessment was based on the desk research of global initiatives working on sustainable construction and unstructured interviews with key stakeholders from Polycare. These interviews were informal and open-ended, allowing the interviewees to express their thoughts freely and provide detailed insights into their goals, practices, challenges, and future plans. The interviews were conducted via video conferencing and lasted approximately 60 min. Figure 1 illustrates the research methodology that was adopted.

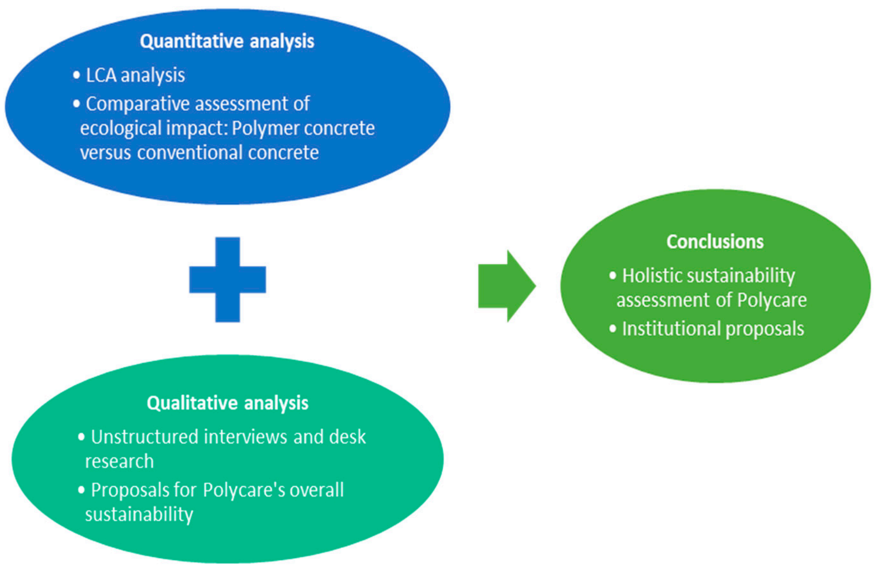

Figure 1. Summary of the methodology.

First, we evaluate the environmental footprint of the Polycare construction system by applying the Life-Cycle Assessment (LCA) methodology, a well-established approach to deal with the quantification of the life-cycle environmental impacts of technologies [109,119–122]. Life-Cycle Assessments, according to DIN EN ISO 14040 [123] and DIN EN ISO 14044 [124], are scientific methods to evaluate products, processes, or services with regard to their environmental impact over the entire life cycle ("from the cradle to the grave"). This encompasses all the stages from raw material exploration and supply, processing, distribution, and use to recycling, reuse, and disposal. LCA enables the quantification and objective assessment of anthropogenic environmental influences occurring during the life cycle. This methodology is instrumental in identifying weak points in a product's or process' environmental characteristics along the process chain, making ecological optimisations, comparing alternatives, and supporting decisions made between alternative processes and routes. Consequently, LCA serves as an important planning and decision-making tool and can also be employed as an information basis for marketing purposes (e.g., by a company advertising its products' environmental compatibility).

According to the DIN standards, the LCA procedure consists of four phases (Figure 2) as follows:

- Objective and Scope Definition: This initial phase involves defining the objective and scope of the study, which includes determining the system boundary and the level of detail. These elements are contingent on the subject and the intended application of the study. Additionally, the functional unit and spatial and temporal limits of the system are established. The functional unit, as defined by DIN EN ISO 14040 [123], is the quantified benefit of a product system utilised as a comparison unit/reference basis;
- Life-Cycle Inventory (LCI) Preparation: This phase involves quantifying the input and output flows (energy and mass flows) throughout the entire life cycle;
- Impact Assessment: This phase entails quantifying the potential effects of the material and energy flows on the environment in the impact categories defined at the beginning;
- Evaluation: This final phase involves interpreting the results, making conclusions and decisions, or deriving recommendations for further action.

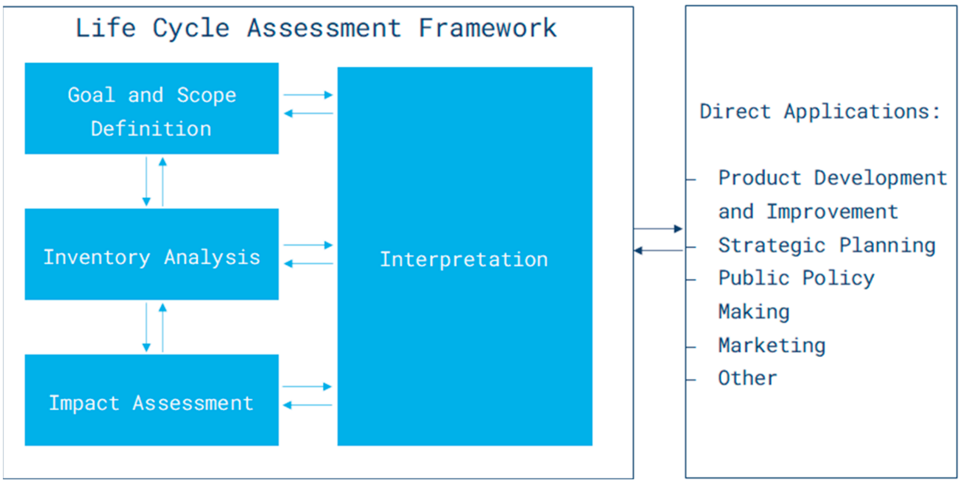

Figure 2. Phases of a life-cycle assessment according to DIN EN ISO 14040.

Herein, different functional units are discussed. On the one hand, the production of (polymer) concrete was comparatively assessed cradle-to-gate, i.e., from the cradle (exploration of the raw materials) to the factory's gate. Initially, the recipes were compared on a mass basis, excluding the subsequent process steps. Further, the functional unit was set to a 1 m^2 wall. The basis for the evaluation is the comparison of Polycare construction elements with coated polystyrene insulation filling to conventional concrete blocks with a plastered thermal insulation system (polystyrene insulation panels) that have the same thermal insulation effect and ventilation heat losses. This makes aspects such as energy demand negligible in the use phase. On this basis, a simplified life-cycle assessment is permissible. Although this approach does not provide a complete ecological picture of the systems, it clearly highlights different ecological effects.

A comprehensive comparison of polymer concrete to conventional concrete was conducted within a cradle-to-grave framework, referencing a construction project in the South African region and considering a typical Polycare standard house. Only differences (processing steps, materials, service life, disposal aspects, etc.) in the individual life phases were considered. Components, such as windows, doors, roofs, plastering, intermediate slab/concrete ceilings, and paints, were assumed to be similar in both cases and, therefore, were not considered. The mortar, foundation, and a 20% overproduction in cement, in the case of the cement concrete building, were assumed as, typically, more concrete had to be provided owing to waste, scrap, grinding dust, or excess production. The investigation time frame was 50 years, corresponding to the assumed service life of a polymer concrete building in arid, subtropical conditions. Under these climatic conditions, the lifetime for a cement concrete building is around 25 years and 50 years for a Polycare building if adequately maintained after 25 years (e.g., new plastering). However, the foundation in the case of a cement concrete building was assumed to last 50 years and that at the end of life, the building materials would be dismantled, shredded, and deposited in landfills, with comparable expenses for both buildings. Mineral building materials are considered as non-hazardous waste and may be disposed of in building debris landfills or used as filling material or hardcore. It was assumed that 100% of the polymer and 30–100% of the concrete could be used as new recycling materials. If the reuse of building materials is considered, only polymer concrete can be completely recycled in the same life cycle and used as fully functional polymer concrete again, while conventional concrete is often used in secondary ways (other life cycles, e.g., used as a sub-base foundation). This would probably result in further advantages for polymer concrete, which were not considered in this study owing to a lack of data on the demolition and processing of both concrete types.

The energy and material flows required for the LCI of the polymer concrete formulation were provided by Polycare Research Technology GmbH. The life-cycle inventory data for conventional concrete (unreinforced normal concrete based on CEM) were sourced from the ecoinvent database. Where data were unavailable, life-cycle inventory data were substituted or modelled as far as possible. This procedure was followed in our case and used to establish LCI data for LCI databases [124]. Generic datasets on energy and water consumption, reaction and recycling rates, infrastructure, transport routes, and waste strategies were utilised. Although mass flows of less than 1 wt.% relative to the mass of the desired output were present within the scope of the study (e.g., organometallic catalysts acting as accelerators), no flows of a considered process were cut off because they were of interest for the entire life-cycle assessment. As far as possible, the materials supply in the countries of origin specified by Polycare, including corresponding transport processes to the next processing step, was considered.

The material and energy flows were modelled using GaBi TS v8.7 software, integrating inventory data from the ecoinvent database for raw materials, energy, or transport processes. The emission factors of all the materials, energy sources, and transport processes were based on the ecoinvent database. The impact assessment was carried out according to ReCiPe 2016 v. 1.1 [125,126] using midpoint indicators at the hierarchic level. Eight impact categories were considered: climate change (also referred to as global warming potential), consumption of abiotic resources (fossil depletion), freshwater ecotoxicity, metal depletion, human toxicity, terrestrial and freshwater ecotoxicity, terrestrial acidification, and land use. These impact categories were selected as they were assumed to be decisive indicators with regard to political, entrepreneurial, and social interests in the context of the construction industry. The effect categories were not weighted.

Nonetheless, the lack of access to LCA data on the demolition and processing of the examined buildings, combined with focusing on specific impact categories, may render the LCA method reductionist. The analysis is limited to using a certain set of indicators and building stages. Thus, considering the need for comprehensive approaches to sustainable construction, integrating qualitative tools to critically review the LCA results, and providing a more holistic sustainability assessment are important [24,127,128]. For this reason, the resulting socio-environmental benefits of Polycare are critically discussed in Section 5.2.

4. Case Study: Polycare Construction System

The Polyblock system from Polycare is an innovative construction system developed by Polycare Research Technology GmbH in Germany, aimed at providing affordable and sustainable alternatives to traditional cement concrete. It leverages locally sourced natural materials and industrial residues in a circularity-oriented approach. The company offers a comprehensive business package to potential investors (private, cooperatives, communities, etc.) interested in establishing a local factory. The package includes the manufacturing infrastructures, a customised machine for Polyblocks, design software, knowledge transfer, local workforce training, and marketing support for building Polycare structures locally.

Notably, Polycare Research Technology GmbHis not the owner of the physical factories but receives a licence fee per ton of blocks produced in each factory. So far, only private investors have initiated Polycare factories, with operational sites in Namibia and Germany, and potential expansions in the EU, African countries, and South East Asia. The reason for focusing on developing African countries is strategic, given their rapid urbanisation, abundant desert sands that are appropriate for producing polymer concrete, and expedited permit acquisition for building Polycare structures. For instance, obtaining a material permit for polymer concrete took six months in South Africa compared to seven years in Germany.

4.1. Materials

Polycare structures are made of Lego-like stackable blocks, the Polyblocks. These blocks consist of a polymer concrete shell and a thermal insulation core made of expanded polystyrene or mineral wool (Figure 3A). Polymer concrete is composed of 88% filler materials and 12% binders. The fillers are flowing local materials, including desert sands or (industrial) secondary raw materials (e.g., foundry sand, slag, tailings, building rubble, or overburden). These materials are mixed with the resin and then cast into moulds. The binder is unsaturated terephthalic polyester resin containing up to 38% recycled polyethylene terephthalate (PET) (e.g., recycled bottles or industrial rejects), provided by a partner company. The accelerated polymerisation process does not require an external energy supply.

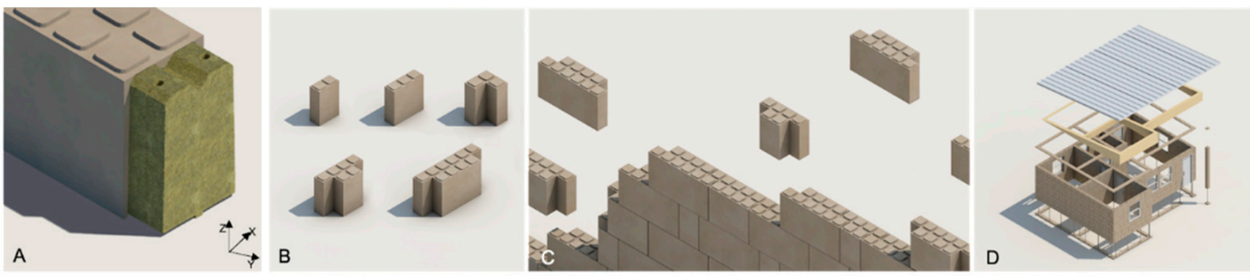

Figure 3. Modular design of the Polyblock system; (**A**) section of a typical Polyblock, (**B**) five different types of Polyblocks, (**C**) a straight wall configuration built with different Polyblock types, (**D**) assembly of a typical rectangular Polyblock building.

Compared with cement concrete, polymer concrete has superior physical properties. Its long lifetime is expected to exceed 100 years owing to its high durability and weathering resistance. Polycare's polymer concrete has a mechanical strength that is 4–5 times higher than that of cement concrete, with a compressive strength (σ,c) of 90–130 MPa and a flexural strength (σ,f) of 20–40 MPa, depending on the composition of the polymer concrete mix. Hence, only 20% of the Polyblock's volume is polymer concrete, which forms the outer, load-bearing shell of the Polyblock. The inner core of the Polyblock is thermal insulation, i.e., expanded polystyrene (EPS) or mineral wool (Figure 3A). Consequently, the overall material input is reduced by approximately 80%, resulting in lightweight blocks that have a maximum specific weight of 18 kg per Polyblock. A completed Polyblock wall has a compressive strength of 4.5–5.0 MPa and thermal insulation properties of U = 0.4–0.55 $W/m^2 * K$, depending on the insulation material that is used.

Regarding further building performance requirements, the Polyblock wall system fulfilled the requirements of the fire resistance classes REI 60 in terms of load-bearing capacity, room closure, and thermal insulation, depending on the plaster that was used (according to DIN EN 13501-2:2010-02 [129]). Polymer concrete, as such, is classified in building material class B1 (flame retardant) according to DIN 4102 [130]. The sound insulation of polymer concrete is equivalent to the sound insulation of cement concrete, which corresponds to a very good sound insulation.

Simulation tests for the durability performance of Polyblocks (e.g., in a climate chamber) showed no change in mechanical or physical properties within the simulation for 30 years. Polyblocks are expected to retain their full properties for >80 years, which would allow for multiple construction cycles.

At the end of the building's lifecycle, the Polyblocks can be reclaimed, crushed, and separated into their constituent materials. For example, it is possible to separate the insulation core from polymer concrete and obtain different grain fractions through sieving. Additionally, more advanced technologies, like electro-dynamic fragmentation, can be used to separate aggregates from the binder. Although obtaining the raw materials (e.g., fillers, resins, and the insulation core) in their original form may not be feasible, they can be repurposed as aggregates for producing fresh polymer concrete.

4.2. Design

Polycare has developed a proprietary customised design software called Polybuilder to translate (rectangular) buildings into Polyblock structures through an optimisation algorithm. The software converts architectural plans into 3D models incorporating the Polyblocks' specifications and structural requirements, while calculating the optimal use and composition of Polyblocks. The aim is to produce efficient solutions using the largest block type. In addition, Polybuilder provides building plans for on-site assembly and disassembly, along with all the relevant information for the downstream processes (i.e., production, logistics, and delivery), thus facilitating environmental footprint estimations.

Modularity is a design-embedded attribute of Polycare enabled by the Polyblocks. There are five differently dimensioned and shaped Polyblocks (excl. special blocks) that allow the construction of various rectangular wall structures. These "micro-modules" (Polyblocks) have dimensions of 200 mm thick (Figure 3A, x-axis), 200–600 mm long (Figure 3A, y-axis), and 300 mm high (Figure 3A, z-axis). Polyblocks are stacked and statically fixated with threaded rods, facilitating easy assembly, selective disassembly, and reassembly (Figure 3C,D). This allows the removal, repair, and replacement of damaged blocks or storage of blocks for future reuse without material destruction.

4.3. Manufacturing and Assembly

Constructing Polycare structures does not require specialist knowledge, heavy machinery, or significant heat and energy consumption. Solid walls are built by lining up the Polyblocks, stacking them by hand, and clamping them together with threaded rods, without using glue or mortar jointing. Threaded rods are also used to fasten Polyblock walls to the ring beam (typically constructed from wood), which is, in turn, connected to the roof framework (Figure 3D). The ground bar, serving as the foundation for the wall, can be positioned atop various foundation types or directly on compacted ground. A practical, low-impact solution is recommended, like a screw-in foundation that can be easily disassembled. Other structural components, like doors, windows, and additional facade elements, can be integrated into the overall structure in a conventional manner.

Polyblocks are manufactured in local micro-factories using customised extruder machines through a straightforward casting and curing process. Polycare Research Technology GmbH supplies these factories globally and collaborates with a partner company specialising in extruder machines for polyester resins. They have jointly developed the current machine, which fits into a shipping container and can produce enough Polyblocks to build a 60 m^2 house in one day. This production rate equates to one house per 8 h shift and generates 30 local jobs at a cost of approximately 25,000–30,000 EUR.

4.4. Future Improvements

Polycare is actively working on developing a next generation Polyblock system; a geopolymer-based masonry system containing a completely inorganic binder. This development aims to address the resin's significant environmental impact and to decouple from unpredictable oil-price fluctuations, which may impact the affordability of Polyblocks. Thus, the 62% of the polyester resin that is not recycled PET will be replaced. Moreover, the geopolymer concrete recipe aims to utilise up to 99% of secondary raw materials (currently between 60–90%). Compared with polymer concrete, geopolymer concrete will require less primary raw material input and produce fewer CO_2 emissions and non-hazardous wastes, which can be safely stored in building debris landfills.

Furthermore, research is being conducted to explore ecological and locally sourced alternatives for insulation materials, such as locally produced hemp. This initiative aligns with regional development strategies that seek to connect the construction and agricultural sectors. Studies on industrial hemp indicate its potential for better environmental performance and its ability to complement the circular value chain approach of Polycare [131–133].

Lastly, Polycare is investigating leasing and renting models for Polyblocks to facilitate reclamation at the end of their lifecycle. However, implementing such experimental models presents challenges due to limited financial support from private banks or other sources.

5. Results and Discussion

5.1. LCA Results

The LCA results indicated that the ecological sustainability of polymer concrete is largely influenced by the resins that are used, contributing to up to 90% of the ecological impact, depending on the recipe and impact category. Meanwhile, the contributions from transport, infrastructure, solvent supply (for machine cleaning), or electricity were found to be negligibly low.

When compared to cement concrete in terms of mass, i.e., on the basis of a functional unit of 1 kg, polymer concrete does not exhibit any ecological advantages, mainly owing to the resin's environmental impact. However, the results are different when considering the physicochemical properties of polymer concrete, such as low density, low specific weight, and high compressive and bending tensile strengths. In this case, polymer concrete offers ecological advantages comparable to those of cement concrete, as the material requirement per 1 m^2 of wall surface is reduced by 80% (Figure 4).

Moreover, additional ecological benefits are observed when taking into account the construction and disposal phases. Polymer concrete outperforms cement concrete in all the assessed impact categories (Figure 5). The key factors affecting this result are (i) a significantly longer service life compared with that of cement concrete, especially under harsh climatic conditions, (ii) no waste during the construction phase, and (iii) the absence of standard building sand [134].

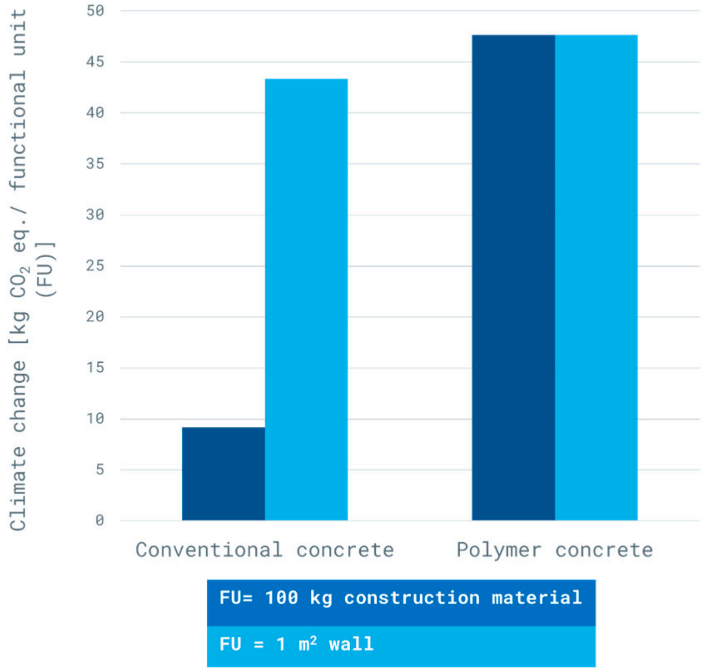

Figure 4. Comparative assessment of the ecological effects (scaled) of the production of 100 kg (dark blue bars) and a 1 m^2 wall (thickness of 0.2 m) (light blue bars) of cement concrete and polymer concrete for the impact category of climate change.

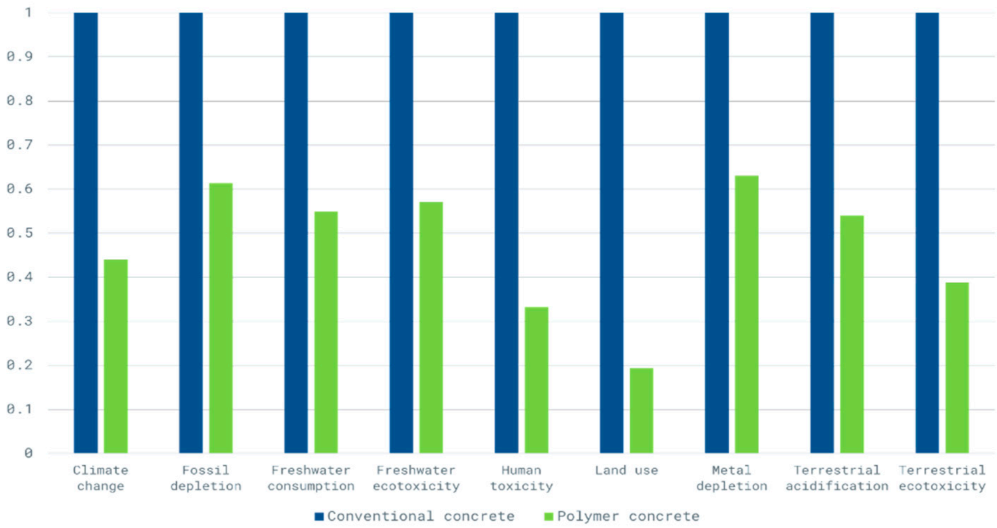

Figure 5. Comparative assessment of the ecological impacts (scaled) of the construction, use, and disposal phases of a conventional concrete-based (unreinforced) and a polymer concrete-based building. Note: highest (worst) values are normalised to 1.

An assessment of environmental performance requires the absolute or comparative measurement of a range of indicators. Contribution to global warming is the most impactful for climate change. The results of the climate change category (Figure 6) show that a polymer concrete building has a reduced impact on global warming by approximately 60% throughout its life cycle, compared to a conventional concrete structure of an identical shape and size.

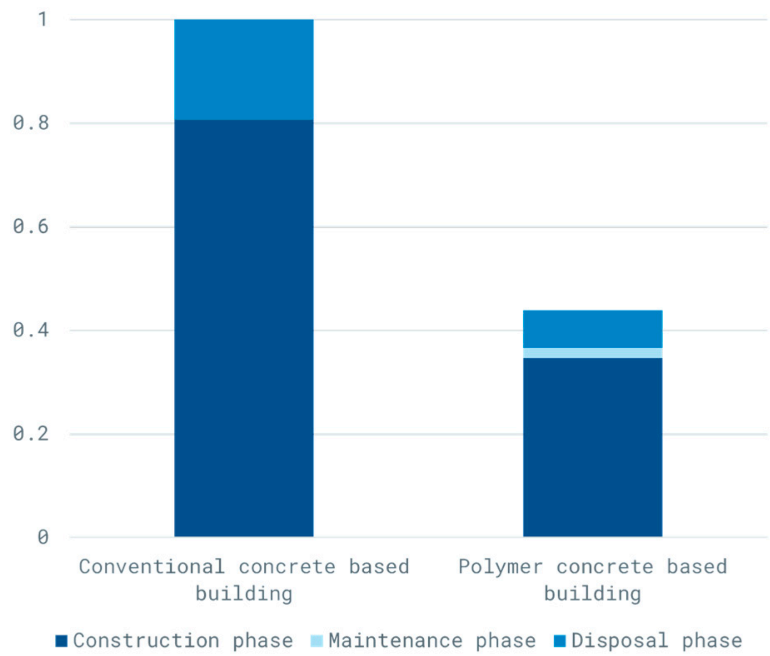

Figure 6. Comparative assessment of the global warming potential of a solid concrete-based building and a polymer concrete-based house, considering the life-cycle phases of construction, maintenance, and disposal.

To sum up, considering the significant contribution of cement production to anthropogenic CO_2 emissions, polymer concrete buildings show great potential in reducing the ecological footprint of the construction sector.

5.2. Discussing the Sustainability Potential of Polycare

This study revealed that Polycare's buildings, combining the advantages of polymer concrete with design-embedded modularity, perform better than a conventional counterpart across all eight impact categories from an environmental aspect. However, it is crucial to recognise that this achievement alone may not suffice to attain sustainability within planetary boundaries [61]. In addition, the LCA method has been criticised for being reductionist, as explained in Section 3, and, thus, insufficient for a comprehensive assessment of sustainable construction. For instance, it overlooks socio-economic dimensions of sustainability. In this subsection, we attempt to critically discuss the sustainability potential of Polycare as a non-conventional building system by emphasising interviewees' statements and key literature findings regarding sustainable transitions in building construction.

The primary goal of Polycare is to develop sustainable and affordable building solutions that contribute to local circular economy schemes. The stakeholders expressed a strong commitment to environmental sustainability, local economic development, and community empowerment. In this direction, Polycare necessitates and facilitates the establishment of regional/local supply chains and a trained local workforce, having adopted practices that align with circularity and localisation, as described in Sections 2.1 and 2.2, respectively. Polymer concrete (and potentially future geopolymers), the design-embedded modularity of Polyblocks, and the ability to establish a local workforce allow for the utilisation of locally sourced materials, substitution of conventional building sand, and contribution to circular economy schemes, cross-sectoral collaborations, community empowerment, and autonomy.

Polyblocks are manufactured locally, considering biophysical conditions, local capacity, and needs. The manufacturing process as well as the material are under constant optimisation and adaptation. The polymer concrete recipe is adaptable to different contexts, regarding the availability of material resources, industrial residues, or recycled materials. Furthermore, the modular design of Polyblocks enables selective disassembly, which can lead to great environmental benefits, as described in Section 2.1. Hence, Polyblocks can be reclaimed, repaired, and reused at the end of their life cycle. In other words, the design-embedded modularity of Polyblocks can foster the effective implementation of CE principles in building construction [53–55]. Similarly, given that manufacturing and building with Polyblocks are relatively easy and do not require expert skills, it is possible to establish distributed networks of Polyblock technicians and further support local economies and the community's autonomy by creating a local workforce; yet, the current infrastructure (factory and customised extruder machine) and resins are imported. Also, Polycare oversees the reclamation or disposal of Polyblocks post-use and profits from local Polyblock production. Thus, although Polyblock manufacturing and building construction are localised, some crucial operations of Polycare remain external to local contexts.

In this light, we pose that Polycare could further leverage the benefits of localisation and circularity by incorporating different degrees of openness regarding software, hardware, and design. In fact, using open-source software to customise designs for the optimal use of Polyblocks is one of Polycare's future goals. Moreover, Polycare could share the knowledge required to manufacture the extruder machine locally instead of providing it as a part of the factory deal (see Section 4.3). This approach could decrease logistic and environmental costs, limit technology imports, and further support local participation, capacity building, and autonomy. By adopting open-design practices, local community networks could benefit from a global knowledge-exchange network, fostering innovation regarding Polycare's adoption and adaptability to diverse local contexts. In that sense, global sharing could enhance the local manufacturing capacity for Polycare buildings, partially boosting the local economy while facilitating the widespread adoption of this building system.

Various established initiatives have demonstrated the socio-environmental and economic benefits of such open-source software, open-hardware, and open-design approaches [7,59,104]. Open practices enable initiatives active in building construction to innovate effectively in the current market and augment their social impact through collaborative efforts. More specifically, open sharing facilitates continual innovation and, subsequently, exponential advancement by leveraging the diverse contributions of others [117]. However, ensuring the viability of initiatives that embrace openness requires the development of business models and frameworks, which are currently in progress and vary across national contexts. The absence of frameworks or other kinds of institutional and financial support impedes the adoption of open practices, particularly by businesses that currently rely on patented technologies, such as Polycare.

In this light, institutional support at national and international levels is necessary to address legal complexities or the absence of regulatory frameworks [98] and to facilitate investments in alternatives to cement concrete [119]. For example, Polycare currently faces legal obstacles in acquiring permits for innovative building materials and financing/implementing the rental business model for Polyblocks (see Section 4.4). From that perspective, institutional support is fundamental to overcome legal and economic challenges and to stimulate a transition to open-source practices.

Furthermore, public investment could also promote the adoption of sustainable practices in building construction. To this end, public–private partnerships could be established. In Polycare's case, for example, public investment could support the research and development of geopolymers, addressing the drawbacks of polymer concrete, such as dependency on fossil fuels and oil-price fluctuations (see Section 4.4). Additionally, different fees could be applied for community-led initiatives, such as cooperatives, social enterprises, and open-source communities, that adopt or invest in alternative approaches. As indicated by the interviewees, local communities could be empowered to invest in Polycare factories, enhancing the social impact of this building model and counterbalancing profit-led investments by private actors. Moreover, public rewards (e.g., tax incentives) could incentivise private companies to adopt ecological and open practices without jeopardising their economic viability. In Polycare's case, public investment could also facilitate the implementation of circularity-oriented rental models (for example, the one proposed for Polyblocks), which are challenging to fund via private banks (see Section 4.4). Furthermore, public investment is crucial for connecting different sectors, locally and regionally, with numerous mutual benefits. For instance, linking the agricultural sector with the construction sector by utilising agricultural residues to produce sustainable building bio-materials.

The interviewees stressed the importance of partnerships with institutions and entities in the construction industry to advocate for the necessary support in dealing with the aforementioned legal and financial challenges. Through such collaborations, they claimed to have strengthened their political voice and, to some extent, expedited the typically protracted building permit process and legal obstacles. In that sense, joint efforts can encourage policy changes relevant to different national/regional contexts. Also, as demonstrated by initiatives employing open practices [102,104] to boost their scalability and social impact, a strategic plan for companies, like Polycare, could include establishing local, regional, global, and cross-sectoral partnerships. Research has indicated that combining top-down, institution-driven organisations (e.g., municipal/local governments) with bottom-up, society-driven ones (e.g., communities, companies, and citizens) is essential for fully implementing circularity and benefiting all the parties that are involved [135–137]. By uniting diverse actors, the strategic planning of buildings' life-cycle management, identification of local demand, and organisation and distribution of production networks can be facilitated, enabling multi-level innovation [136–139]. In these ways, a more sustainable—circular, local, and open—construction ecosystem could evolve, as summarised in the subsequent figure (Figure 7).

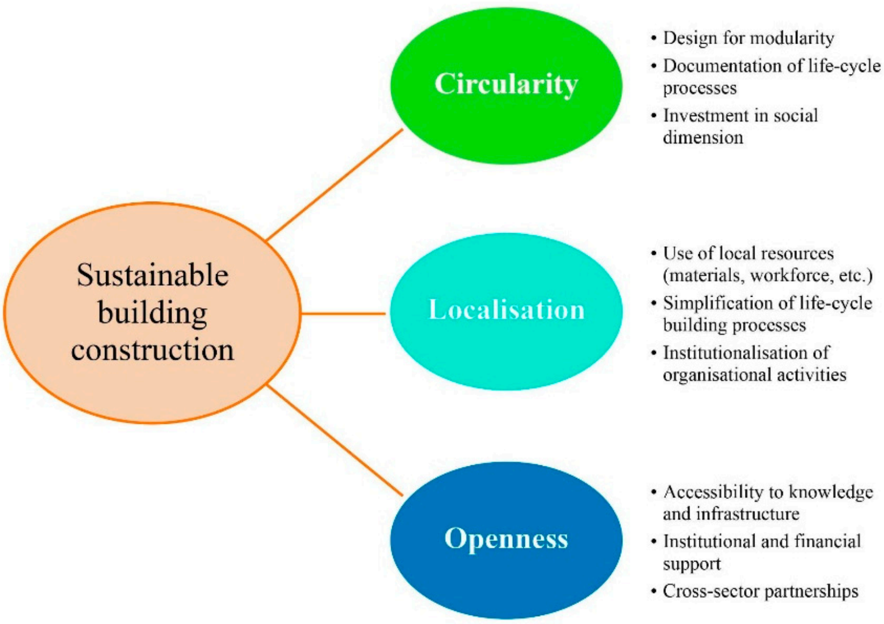

Figure 7. Critical issues for enhancing sustainable building construction.

6. Conclusions

In a plurality of perspectives towards sustainable building construction, this study focused on "Polycare", a novel modular construction system using polymer concrete blocks. Employing both quantitative and qualitative approaches, this case study aimed to (i) contrast the environmental impact of polymer concrete-based structures with that of conventional concrete-based structures of identical dimensions and (ii) suggest ways to enhance the sustainability of such initiatives.

The LCA results verified the environmental advantages of polymer concrete over conventional concrete, when considering the physicochemical properties of the former. That is mostly attributed to the 80% reduction in material required per square metre of a polymer concrete wall surface. Additional benefits include the durability and reusability of polymer concrete blocks and the substitution of traditional building sand. Moreover, we highlighted the significance of Polycare buildings' design-embedded modularity as a key feature to facilitate circular processes. Furthermore, drawing from the literature and interview insights, we posited that the integration of circularity, localisation, and openness is fundamental for creating sustainable and affordable building solutions, particularly for housing.

The Polycare construction system is already aligned with circular and local practices. However, further action has been suggested to better align with diverse local contexts, support local economies/communities, and facilitate cross-regional cooperation. Suggestions referred to exploring ways for reducing existing imports in terms of manufacturing and materials and integrating openness. Despite recognising openness as a critical factor for enhancing sustainability in a broader context, Polycare has yet to embrace open practices. In this direction, we call for strategic collaborations, institutional support, and public investment to facilitate the sustained operation of such novel initiatives within the existing market, creating space for the development or adoption of non-conventional building practices and business models to flourish.

The limitations of this study include the inherent disadvantages of the Life-Cycle Assessment (LCA) method, which estimates the ecological footprint of a building based on specific data, while neglecting other sustainability dimensions (e.g., social and economic). Additionally, because Polycare is a relatively new market entrant, there is a lack of tangible evidence regarding the entire life cycle of Polyblock buildings, which is estimated to be between 25 and 50 years. Furthermore, the limited number of operating Polyblock factories provides scarcesolid evidence on how the Polycare system would function across a range of local contexts and legislative frameworks. Lastly, despite that Polycare is exploring geopolymers to address conventional polymer concrete limitations and considering biomaterials for thermal insulation, the sustainability potential of such materials/components remains untested under real circumstances.

In conclusion, achieving comprehensive sustainability transitions in the construction sector entails addressing numerous questions beyond the scope of this article. To this end, future research could investigate different contexts and account for differences in the environmental performance of housing projects and institutional structures. Additionally, future studies could examine holistic sustainability assessment frameworks applicable to building construction, accounting for the life-cycle impacts of buildings.

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