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Hypothesis

The Industrialisation of Sustainable Construction: A Transdisciplinary Approach to the Large-Scale Introduction of Compacted Mineral Mixtures (CMMs) into Building Construction

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Abstract: Increasing demand for sustainable, resilient, and low-carbon construction materials has highlighted the potential of Compacted Mineral Mixtures (CMMs), which are formulated from various soil types (sand, silt, clay) and recycled mineral waste. This paper presents a comprehensive inter- and transdisciplinary research concept that aims to industrialise and scale up the adoption of CMM-based construction materials and methods, thereby accelerating the construction industry's systemic transition towards carbon neutrality. By drawing upon the latest advances in soil mechanics, rheology, and automation, we propose the development of a robust material properties database to inform the design and application of CMM-based materials, taking into account their complex, time-dependent behaviour. Advanced soil mechanical tests would be utilised to ensure optimal performance under various loading and ageing conditions. This research has also recognised the importance of context-specific strategies for CMM adoption. We have explored the implications and limitations of implementing the proposed framework in developing countries, particularly where resources may be constrained. We aim to shed light on socio-economic and regulatory aspects that could influence the adoption of these sustainable construction methods. The proposed concept explores how the automated production of CMM-based wall elements can become a fast, competitive, emission-free, and recyclable alternative to traditional masonry and concrete construction techniques. We advocate for the integration of open-source digital platform technologies to enhance data accessibility, processing, and knowledge acquisition; to boost confidence in CMM-based technologies; and to catalyse their widespread adoption. We believe that the transformative potential of this research necessitates a blend of basic and applied investigation using a comprehensive, holistic, and transfer-oriented methodology. Thus, this paper serves to highlight the viability and multiple benefits of CMMs in construction, emphasising their pivotal role in advancing sustainable development and resilience in the built environment.

Keywords: decarbonisation; circular economy; recycled materials; demolition wastes; low-carbon construction; building with earth; compressed earth; rammed earth; sustainable construction

1. Introduction

Before the advent of industrialisation, traditional construction methods relied on locally available, renewable materials that had minimal impacts on the environment. It is essential to consider the fact that sustainable building practices were intrinsically linked to the availability of resources and the capacity of the environment to regenerate them [1].

The concept of sustainability itself can be traced back to forestry practices in Saxony, Germany. In the early 18th century, Saxonian forester Hans Carl von Carlowitz [2–4] formulated the principle of sustainability in his book, "*Sylvicultura Oeconomica*". His work emphasised the importance of harvesting timber at a rate that would not deplete the natural resource base, thereby ensuring that future generations could continue to benefit from forests. This early understanding of sustainable resource management laid the foundation for the broader concept of sustainability that we know today.

Before the First Industrial Revolution, construction methods typically utilised natural and locally sourced materials, such as timber, adobe, and stone. These materials not only were abundant but also had low environmental impacts. For instance, timber, a renewable resource, can be harvested sustainably by maintaining a balance between the growth and harvesting of trees. Adobe and stone, similarly, can be sourced and used with minimal processing, reducing their overall environmental footprint.

However, the First Industrial Revolution brought about a significant shift in construction practices, as it introduced new materials and energy-intensive processes. The widespread use of non-renewable resources, such as steel, concrete, and bricks, resulted in increased greenhouse gas emissions and resource depletion. This shift marked a departure from the sustainable building practices that had been prevalent for centuries.

In light of current environmental challenges, there is an urgent need to return to the sustainable construction methods and materials that characterised pre-industrial societies. By revisiting and adapting traditional techniques, we can work towards developing innovative solutions that reduce our ecological footprint while ensuring the long-term availability of resources for future generations.

The construction industry plays a critical role in shaping the built environment, accounting for significant shares of global energy consumption, greenhouse gas emissions, and waste generation. In light of the global climate crisis and the increasing demand for affordable housing, there is an urgent need for a paradigm shift towards sustainable construction practices. This concept paper is based on a comprehensive research proposal that seeks to advance the field of sustainable construction through the development and implementation of innovative construction materials, techniques, and technologies. This proposal is grounded in interdisciplinary collaboration between academic, industry, and policy stakeholders, recognising the importance of holistic approaches in addressing the complex challenges facing the construction sector.

This proposed concept aims to revolutionise the construction sector with a multifaceted approach targeting sustainable development and efficiency. Our primary objectives are:

1. To advocate for the utilisation of earth-based materials as alternatives to conventional construction resources, thereby promoting sustainable building practices (Figure 1).
2. To formulate and scrutinise the performance of circular, low-carbon construction materials and methods, collectively termed Compacted Mineral Mixtures (CMMs), which offer environmentally friendly alternatives with the potential for widespread adoption.
3. To capitalise on digital technologies, particularly Building Information Modelling (BIM) and the Urban Mining Platform (UMP). These tools enhance material optimisation, minimise waste, and amplify overall efficiency in the construction process.

4. To encourage the implementation of automation and robotics within the construction industry, aiming to increase productivity and reduce human-related errors.
5. To facilitate open-source knowledge sharing and capacity building via educational programs, training opportunities, and collaborative engagements. This transdisciplinary approach should foster a community-wide understanding and acceptance of the proposed sustainable construction methodologies.

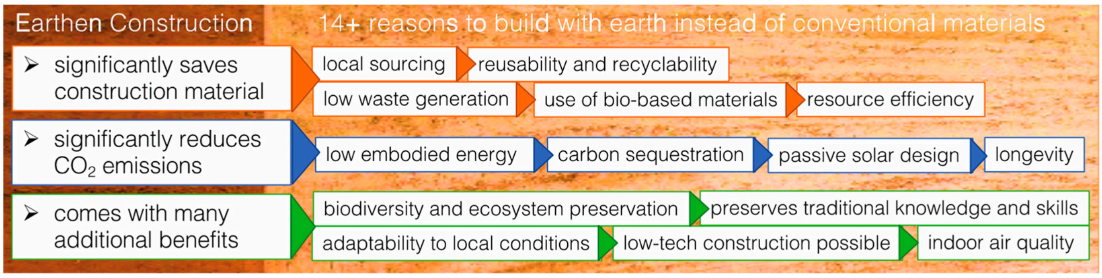

Figure 1. Fourteen plus reasons to build with earth instead of conventional materials.

In this concept paper, we will provide an overview of this research proposal's main components, including data handling and management, long-term perspectives, and the potential economic and social impacts of this project. We will also discuss the added value of this proposal to the participating universities' research profiles and strategies. Ultimately, this paper aims to contribute to the growing body of the literature on sustainable construction and serve as a starting point for future research and collaborations in this critical field.

2. Revolutionising Traditional Construction: Integrating Advanced Methods for Scalability, Efficiency, and Sustainability

The primary objective of this proposed research concept is to revolutionise the traditional empirical "builder" approach in earth construction by seamlessly integrating advanced geotechnical engineering methods, rheological science, and state-of-the-art data analytics and informatics. By leveraging the synergies of this multidisciplinary fusion, this research aims to achieve unprecedented levels of scalability, resulting in cost and time efficiency as well as the creation of sustainable, high-quality circular building elements.

This transformative approach is poised to usher in a new era of environmentally friendly construction practices, characterised by 100% circularity, CO_2 neutrality, and enhanced economic efficiency. This research's potential impact is significant, considering that walls for commercial and residential buildings represent a substantial market share, estimated at 95 billion EUR per annum in the European Union and 10 billion EUR per annum in Germany, based on 2021 estimates; assuming that about 40 to 50% of the total construction costs of residential and commercial buildings are related to shell costs and that the total costs of walls can be estimated at between about 30 and 40%, it can also be assumed that walls account for between 12% and 20% of the total construction costs. The market size of walls for residential and commercial buildings can therefore be conservatively estimated to be 10.6 billion EUR in Germany, 95.4 billion EUR in Europe [5], and 866.1 billion EUR worldwide [6,7], with 66.5 billion, 596 billion, and 5.413 billion EUR total construction markets in 2021, respectively [8].

By transforming conventional construction methods, this research concept has aimed to contribute meaningfully to the broader goal of sustainable development within the construction industry. It has sought to redefine the future of construction by offering innovative, eco-friendly, and economically viable solutions, paving the way for a more sustainable and resilient built environment.

2.1. Motivation, Scientific Goals, and Scientific Innovation Potential

The motivation of this project was to aim for a systemic transformation of the construction industry towards circular, emission-free, decarbonised, and competitive construction methods. The proposed concept is committed to working towards the latest statements of the UN Global Status Report for Buildings and Construction (2022) [9]: " . . . the most promising approaches toward extending material lifespan is the circular economy, . . . to reduce greenhouse gas emissions associated with construction material . . . ", aiming for "reducing the use of high-volume, carbon-intensive materials . . . " (p. 75). Moreover, this concept supports the ambitious amendments of the German Climate Protection act of 2021 [10], demanding an emission reduction of 65% compared to that of 1990 and anchoring of climate neutrality by 2045. These higher ambitions directly influence the CO_2 reduction targets for individual sectors such as industry, buildings and agriculture [11]. On the international and domestic levels, this concept assists in achieving sustainable development goals (SDGs) and Agenda 2030, more specifically SDG 12, SDG 9, SDG 8.2, 8.4, SDG 4.3, 4.4, SDG 17, and SDG 11 [12], and is fully aligned with the European Green Deal (p. 11) [13].

The overall scientific goal is to establish a technical–scientific basis for scaling industrial circular construction based on mixtures of different soil types (sand, silt, clay) in combination with larger aggregates from recycled mineral waste (recycled materials and industrial by-products). Local, sustainable binders (plant ash, plant polymers) can be added to improve tamped or compacted mineral materials (CMMs) to meet the strength and durability requirements of structures, including weatherability and long-term stability.

The following research questions have been operationalised through work packages:

Q1. How can an easy-to-use method for planning, manufacturing, and quality control of CMM wall elements that quickly evaluates the suitability of natural and recycled materials be integrated into practice?

Q2. How can digital technologies be used to create a CMM Centre of Excellence that digitally captures circular material flows and process strategies and facilitates sourcing, trading, production, quality control, standardisation, tracking, and reuse of materials?

Q3. How can advanced mass production technologies (prefabrication, 3D printing, robotics, etc.) be leveraged and (technical/socio-economic/psychological) application barriers removed (collaboration, information sharing, capacity building, etc.) to promote and improve the scalability, productivity, and reach of CMM construction?

Q4. How can the benefits of open-source technology and scalable, accessible, and contemporary teaching methodologies (e.g., Massive Open Online Courses) be leveraged to enable and promote access to education for all, creating co-creative learning processes and collaborative knowledge dissemination and sharing?

The proposed concept's scientific innovation potential is remarkably high, expertly combining geotechnical engineering, rheological science, and powerful data-driven technologies to revolutionise the earthwork process and envisaging a breakthrough in the large-scale use of new, innovative CMMs made from natural mineral soil components and recycled aggregates as building materials. The unique selling points are (a) radical decarbonisation and a circular economy approach starting from waste as feedstock, (b) the industrial scaling of a niche product, (c) a digital Urban Mining Platform for dynamic matchmaking between disposers and buyers, and (d) access for all through a consistent open-source/open-innovation approach.

2.2. Agile Research and Transdisciplinary Organisation: An Iterative and Adaptive Approach to Construction Innovation

The overarching transdisciplinary organisation (Figure 2) ensures an agile research methodology and collaboratively coordinates and oversees the budgeting, communication (internal/external), quality assurance, process evaluation, documentation, and dissemination of research results and transfer activities, whereas three thematically interlocking research areas of the proposed concept answer the research questions above.

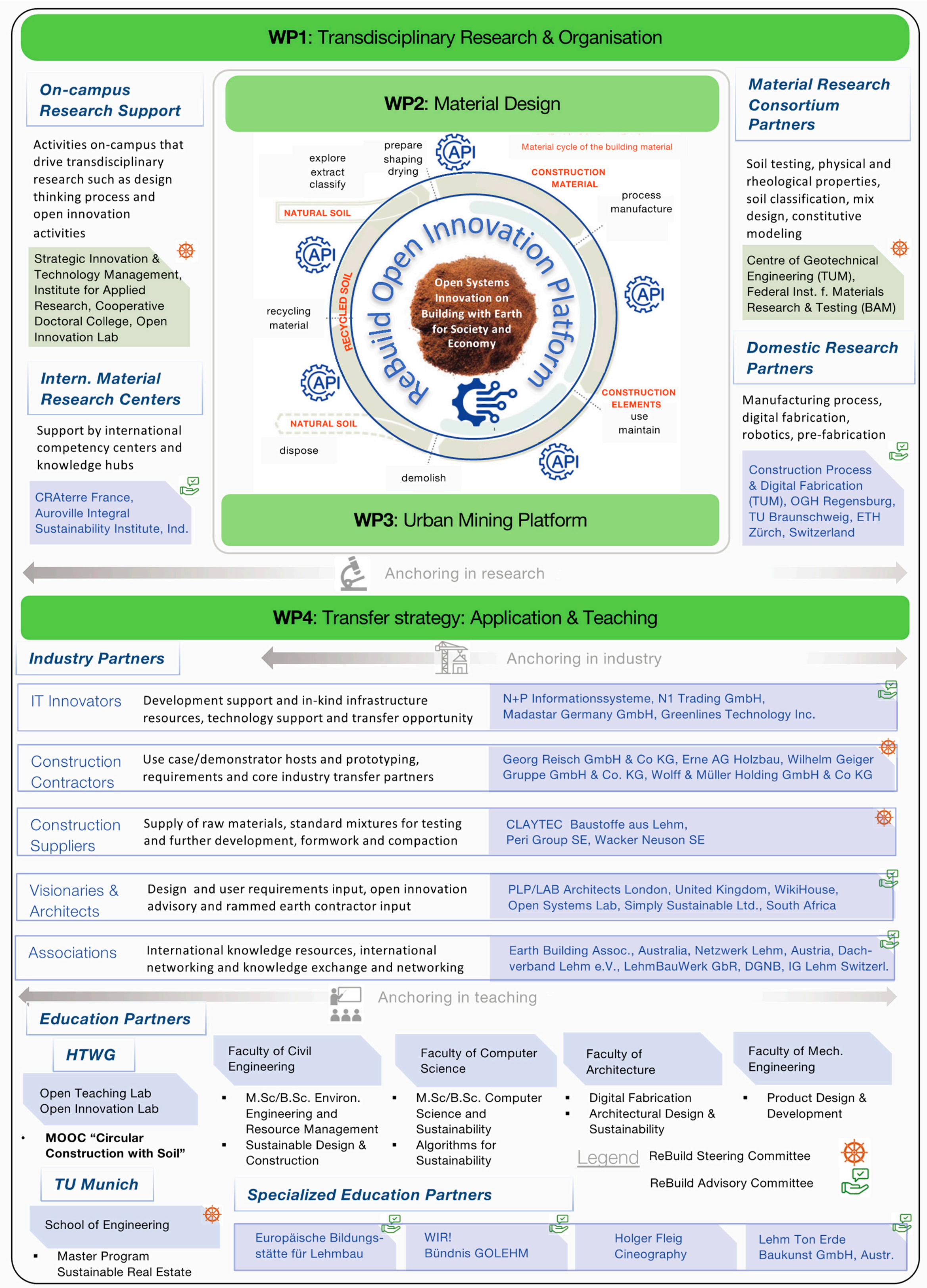

Figure 2. Agile organisation and transfer management structure.

Transdisciplinary organisation and agile management: Transdisciplinary organisation focuses on the organisation, design and management of six transdisciplinary co-creation workshops that apply design thinking; it is a use-centred research approach including iterative and lean processes that span across different technology readiness levels, supported by a co-creative approach and individual topic-related sprints. Agile research is a methodology of conducting research that is iterative and adaptive to changing circumstances to respond to the complex and rapidly evolving challenges anticipated in the context of the proposed concept project. The agile research methods applied within this project involve close collaboration between researchers and industry partners to rapidly prototype and test material mixtures, sourcing capabilities, and automated construction methods that use CMMs for wall elements. The iterative and adaptive nature of agile research allows for continuous testing and refinement of these methods, with feedback from external research and industry partners incorporated into the research process. To support the agile research process, open-source digital platform technologies would be used to facilitate data access, processing, and knowledge gain. This enables all researchers and industrial partners to quickly analyse data, identify trends or issues, and adjust the research process as needed. In addition, the holistic and transfer-oriented approach of the proposed concept project has also been supported by agile research, as it would enable researchers to rapidly respond to new challenges and emerging opportunities as they arise and ensure that this research is continuously aligned with the overall goals and objectives of this project.

The prioritized goal is to ensure a continuous transfer of research results to practice, as well as the transfer of new requirements from practice to research. Regular meetings—online and in person—should be organised to secure exchanges, adjustments, and co-creation. Hackathons and the definitions of the requirements and specifications for Technology Readiness Levels (TRLs) are key aspects to adjusting this research and to differentiating the technical core and validating the technical solution concept in the following step. Accompanied prototyping and user validations would lead up to a complete first prototype. Testing the prototype with transfer partners would ensure its efficacy in real-world situations and result in an MVP in the next step.

The core is the continuous documentation, evaluation, and dissemination of results. This includes the planning of accompanying action research, as well as documentation, scientific open-access publications, and the production of online handbooks and guidelines. Results and activities would be continuously transferred.

2.3. Material Selection, Characterisation, Quality Control, and Procurement: A Co-Creative Approach towards Sustainable Construction Materials

Material selection, characterisation, and quality control: These works would be conducted with a co-creative and participatory approach that would integrate relevant research and industry partners through online and in-person meetings as well as in material tests (in situ and laboratory). This would allow direct interventions, adjustments, and co-learning, with a high implementation quality applied.

Material selection and quality control methodology: To achieve standardised and competitive CMM-base-building materials, known as industrially produced materials such as steel, wood, concrete, mortar, and bricks, evaluations and extensive testing would be conducted to develop a quality control methodology based on laboratory and in situ material testing.

Material properties database: To ensure design assumptions regarding material homogeneity, strength, deformability, and durability, a quality control methodology would significantly improve the confidence of CMM-building techniques. We acknowledge the complexities of natural soils and those mixed with additives and the profound influence these complexities have on the mechanical behaviour of Compacted Mineral Mixture (CMM)-based construction materials. The strength, deformability, and durability characteristics of such materials can significantly vary with time, loading rates, ageing, and other factors. Based on the highlighted studies by Maqsood et al. [14] and Shaikh et al. [15], we have acknowledged the profound impacts of hardening characteristics and loading rate dependencies on the mechanical behaviour of gypsum-mixed sand and other fine-grained soils. These aspects underscore the inherent variability of such materials and the need for a robust quality control methodology that can accommodate this variability.

The core idea behind our proposed material properties database is to capture these diverse characteristics and behaviours. This database should encompass data not only on the immediate properties of these materials, such as their composition and homogeneity, but also on their mechanical behaviours under various conditions and over time. It should incorporate data on the impacts of ageing, loading rates, and other influential factors on the strength and deformability of these materials. To ensure the comprehensiveness of the material properties database, we propose the incorporation of various mechanisms. These include:

1. Extensive field and lab testing to gather accurate and diverse data on the behaviours of various CMM materials under different conditions. Such tests could include uniaxial compression tests, triaxial shear tests, and direct shear tests, among others, conducted under varying load rates and over different periods.
2. Collaboration with research institutions and industry partners can help expand the database by including data from different geographical locations and different types of projects. This would help enrich the database with diverse sets of data on various types of soil and additive.
3. Inclusion of existing research data, as we propose the incorporation of relevant findings from existing research studies, such as those highlighted by reviewers, into the database. This approach can help capture the impacts of factors such as hardening characteristics and loading rate dependencies on the mechanical behaviours of various materials.

The ultimate aim is to create a dynamic and continually evolving database that can serve as a reliable resource for engineers and construction professionals working with CMM materials. It should provide them with comprehensive and up-to-date information to make informed decisions regarding the selection and use of these materials. By incorporating the rich complexities of soils and soil mixed additives into this database, we hope to significantly improve the confidence and reliability of CMM building techniques and contribute to the wider adoption of sustainable construction practices.

Experimental tests: These would be performed to determine the suitability of materials (first stage) and to check quality during the construction of CMM structures (second stage).

The first stage would focus on determining the chemical and physical properties of the raw materials, assessing suitable mixtures of these materials (e.g., natural clay, natural aggregates, recycled materials, industrial by-products) and the necessity of mechanical or chemical stabilisation to fulfil requirements regarding strength and durability. At this stage, the material composition, the optimum water content, and eventually the required dosage of additives, as well as the relevant mechanical and hydraulic properties of the compacted materials, including their statistical distribution, would be specified. The use of biopolymers as rheology modifiers would be further investigated in the CMM context. The tests in this stage would comprise standard tests for the classification of basic materials as well as compaction tests to find the best compaction technique and advanced soil mechanical tests on compacted specimens for the determination of their mechanical and hydraulic behaviours. For the analysis of durability, the following laboratory tests have been planned: cyclic wetting and drying tests, cyclic freezing–thawing tests, erosion tests, and permeability tests.

The advanced soil mechanical tests in our study refer to a series of specialised tests designed to assess the properties and performances of compacted mineral mixtures (CMMs) under various conditions. They encompass:

1. Strength and deformation tests: These include triaxial compression tests, direct shear tests, and unconfined compression tests, which would aim to determine the shear strength parameters (cohesion and angle of internal friction) and the compressive strengths of the compacted specimens. Additionally, we would employ oedometer tests to analyse the compressibility and consolidation characteristics.
2. Permeability tests: These involve constant and falling head tests for determining the hydraulic conductivities of CMMs. These test results would be crucial in assessing the materials' suitability for applications requiring specific levels of permeability or impermeability.
3. Durability tests: Beyond the previously stated cyclic wetting and drying tests, cyclic freezing–thawing tests, and erosion tests, we would also conduct slake durability tests and weathering tests. These assessments would simulate the long-term impacts of environmental factors on CMM structures.
4. Specialised tests: These tests would be employed to analyse specific characteristics of biopolymer-modified CMMs. For example, Atterberg limit tests can provide insights into the plasticity changes brought about by biopolymers. Additionally, spectroscopic and microscopic analyses (like FTIR, XRD, SEM) may be employed to better understand the physicochemical interactions and the microstructure of the modified soil.

This proposed set of advanced soil mechanic tests aims to provide comprehensive data on the mechanical, hydraulic, and durability characteristics of CMMs influenced by various additives. This approach ensures a holistic assessment of material performance, which is crucial in optimising the use of CMMs in sustainable construction.

Strength Parameters of CMM-Based Wall Elements: A crucial aspect of developing CMM-based construction materials and wall elements is understanding their strength parameters, which predominantly include compressive strength, flexural strength, and shear strength. These strength parameters are not only indicators of a material's ability to withstand loads without failure but also crucial in assessing its overall performance and durability.

The strengths of CMM-based materials, especially wall elements, largely depend on the types of soil used, the mix ratios of various constituents, the compaction, and the curing conditions. In general, a well-designed CMM should exhibit satisfactory compressive strength for load-bearing applications and sufficient flexural strength to resist cracking or breakage under bending stresses. Moreover, shear strength is vital for the structural stability of wall elements under lateral loads.

In our research, we aimed to develop a comprehensive testing protocol to evaluate these strength parameters for CMM-based wall elements. These tests would encompass unconfined compressive strength tests, three-point bending tests for flexural strength, and direct shear tests or triaxial compression tests for shear strength.

Moreover, it is also important to note that the strength parameters of CMM-based wall elements can significantly vary depending on the type and proportion of waste materials used. For instance, the inclusion of recycled aggregates or industrial by-products may influence a mix's workability and subsequently its compactability, ultimately affecting the strength parameters. Hence, our research has also focused on optimising the mix design to ensure a balance between sustainability and performance.

By systematically studying and quantifying the strength parameters of CMM-based wall elements, we aim to provide insightful data that can guide the design and construction of durable, efficient, and sustainable buildings.

Constitutive model: This is intended to analyse the applicability of existing constitutive models for numerical simulation of the thermo-hydraulics and the mechanical behaviours of unsaturated CMMs. Thereafter, a suitable constitutive model would be adopted and implemented in a commercial Finite Element Code to create 2D and 3D digital twins of a CMM structure and predict its structural response to external actions. A variety of constitutive models have been developed to predict the strength and deformation characteristics of natural and stabilised soils. However, when dealing with Recycled Earth

(RE) materials and, in our case, Compacted Mineral Mixture (CMM) materials, we must account for certain unique attributes that are not necessarily present or pronounced in natural soils. These can include variable composition, the possible presence of organic content, susceptibility to ageing, and differing responses to loading, among others. These complexities necessitate the development of more tailored and comprehensive constitutive models. Our primary objective for advancements in this area involves creating constitutive models that encapsulate the intrinsic characteristics of CMMs as well as their responses under different load and environmental conditions. Our strategy involves:

1. Data-Driven Modelling: With advancements in machine learning and AI, data-driven models, such as neural networks and support vector machines, have shown promising results in predicting complex soil behaviours. We plan to use the wealth of data generated from our extensive testing regimen to train such models that can predict the behaviour of CMMs under various conditions with high accuracy.
2. Hybrid Modelling: Considering the merits of traditional constitutive models, we aimed to develop hybrid models that would integrate empirical relationships derived from traditional models with the flexibility and adaptability of data-driven models. This approach allowed us to leverage the strengths of both methodologies and enabled us to handle the heterogeneity and complexity of RE materials more effectively.
3. Incorporation of Time-Dependent and Environmental Factors: Our proposed models will account for factors such as time-dependent strength and deformability changes, ageing effects, and responses to environmental factors such as moisture content and freeze–thaw cycles. This comprehensive approach will help us predict the long-term performances of CMM structures.

Through these advancements, we aim to establish robust, accurate, and versatile constitutive models that can significantly enhance our ability to predict and optimise the performances of CMMs in sustainable construction projects.

Material processing: This is intended to control the technical specifications of laboratory and field tests during construction (second stage). Laboratory tests would be carried out with samples taken from CMM structures including rammed earth and/or compressed earth. In addition, destructive and non-destructive field tests would be carried out. These experimental results would establish a methodology to model the behaviour of CMM structures as required to fulfil the structural design requirements in the serviceability and limit states elaborated.

2.4. Harnessing the Urban Mining Platform (UMP) for Streamlined Procurement, Material Optimisation, and Sustainable Practices in Construction

The Urban Mining Platform (UMP) and Digital Material Procurement: The UMP (Figure 3) can scrape together knowledge, output, and findings. In addition, it can build on the digital material BAM platform MaterialDigital [16,17], which includes the material optimisation artificial intelligence algorithm "Sequential Learning App for Materials artiDiscovery SLAMD" [18], which is applicable to soil materials and mineral aggregates. On the other hand, the UMP can streamline the procurement, processing, and distribution of earth-based building materials. It includes the following functionalities and illustrated high-level architecture:

Material procurement: To increase construction supply chain efficiency, digital representation and automation of material procurement are essential. Persistent data storage and management of material information ensure transparency and traceability throughout the material lifecycle. Suitable algorithms that optimise material availability help to develop suitable sources, avoid waste, and reduce material needs. A test integration of suitable Internet of Things ("IoT") sensors (e.g., GPS location determination) would support material extraction aiming for sustainable procurement processes.

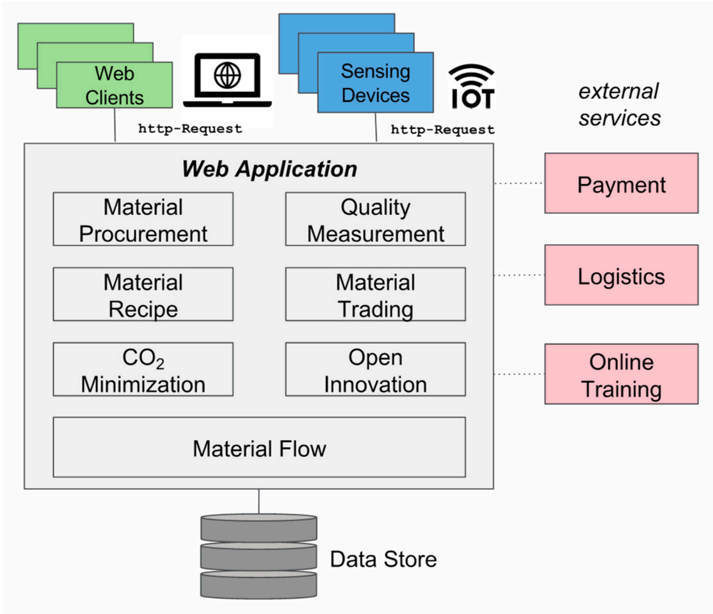

Figure 3. UMP architecture; our own illustration, 2023.

Material flow: Two core functions are (a) a material flow diagram to clearly display and track the statuses of all process steps, such as sourcing, procurement of raw materials, processing, and delivery, with automated notifications to relevant user groups (processors, suppliers, buyers, and sellers) to optimise the material flow, counteracting bottlenecks, and (b) a dashboard to simulate material flow, including various parameters aiming to efficiently estimate the final building material volume.

Quality measures: These involve the digitisation of quality determination through specialised sensors that would measure, monitor, optimise, and enable precise assurance of material quality. Internet-connected technology supports measurements over long distances by sending measuring devices to places of examination. The collaboration and integration of specialised laboratories back up comprehensive analyses to assure high levels of quality. Open-source digital training supports better understanding, interpretation and evaluation of the quality of each material and its complex analyses.

Material recipe: To improve material mixtures and recipes, continuous data analysis using appropriate algorithms (e.g., neural networks) would identify trends in project results and user feedback, enabling digital mapping and optimisation. The integration of real-time sensors to monitor material quality during the production process would further improve material control and quality assurance.

Material trading: To optimise logistics and the supply chain, a simple store functionality would bring together material trading partners such as sellers, buyers, suppliers, and processors, as well as suitable algorithms from the field of operations. A rating system would provide transparency and increase trust, supported by the integration of information and communication tools to enable a smooth exchange. To ensure competitive prices, suitable algorithms for price optimisation would be used and adapted. Digital payment options would be handled via external services to simplify and accelerate the process.

CO_2 emission determination and minimisation: This would be used to digitally map, monitor, and analyse CO_2 emissions in the entire material flow and identify and minimise potential savings. Integrated functions would measure recycling and reuse capabilities as well as identifying possible waste or contamination advancements to reduce final waste amounts and associated CO_2 emissions. In addition to the functional components, the UMP's web-based client–server architecture would apply to established web standards (e.g., REST, JSON, HTTP) to allow access to users in different technical contexts through a conventional browser. Related but machine-readable standards would connect sensor devices (GPS, soil quality measurement) to the web. Figure 3 illustrates a possible architecture of the UMP.

2.5. Transfer Strategy, Transfer Activities, Networking, and Utilisation

This concept aims to leverage recent advances in soil mechanics, rheology, and automation to support the construction sector in developing innovative construction methods for the manufacturing of wall elements. This will enable a more efficient and cost-effective construction process, increasing the competitiveness over traditional building materials such as concrete and masonry. Specifically, the construction industry will be enabled to have load-bearing walls and interior walls produced using machines with a construction method that is not only emission-free and circular compared to the conventional approach but also economically competitive, i.e., faster and cheaper. Furthermore, it would contribute to thermal performance due to its mass and a healthy indoor environment. To achieve this, the overall goal of WP4 is to widely disseminate and exploit the created open-source UMP tool as an industrial application and resource competence interface that would transform soil from a niche building material to a scalable and competitive mass product. The WP would include different steps to bring forth a user-friendly, needs-oriented, and co-created open source that would organically continue to grow and flourish internationally. Applying qualitative participatory methods, WP4.1 will assess and analyse the needs of relevant transfer partners to develop needs-based and stakeholder-oriented transfer and DACH networking strategies. Furthermore, the UMP will support the professionalisation and transfer of knowledge into practice to secure continued education and knowledge production on CMM standardisation, materiality, quality assurance, building techniques, and architectural designs. WP4.2 will encompass the planning and creation of a collaborative Massive Open Online Course (MOOC) on "Circular Construction with Soil", promoting and fostering the UMP's digital education component in close collaboration with existing and newly established international education, practice, and policy networks within the community for circular buildings with soil. Additionally, the theoretical and methodological educational WP4.4 contains an into-action component. Together with different project cooperation partners and students, its aim is to plan, design, and build CMM prototype(s) based on industry requirements and goals, therewith proving the practicability of the UMP tool and the automation of CMM construction processes.

Similar action components are planned with cooperation partners in India and South Africa to assess transferability into different country and soil contexts. Our research group is active in African networks of standardisation bodies; for example, we are working with the president of ARSO (African Standardisation Organisation) on new standards. Among other things, we are conducting a pan-African interlaboratory test with about 60 laboratories from more than 25 African countries, which we will use as a multiplier platform for multilateral and bidirectional transfer of our findings. In addition, we are already working with GIZ on a green building academy concept to be implemented in the coming years as a potential knowledge multiplier. Last, WP4.5 will foresee the organisation and implementation of an international conference to apply methods that will foster active exchanges, co-creation, and attentive learning on "Circular Building with Soil" with the cooperation partners PLP Architecture and DGNB.

2.6. Rough Estimate of Potential CO_2 or Raw Material Savings

Rammed earth and compressed earth block (CEB) building methods can provide significant CO_2 and raw material savings compared to conventional construction methods (see Table 1 and Appendix A, with Table A1 listing more materials).

Table 1. CO_2 footprints of rammed earth compared to conventional building methods. Data sourced from ÖKOBAUDAT [19]. Global warming potential by life cycle stage (in kg CO_2 equivalents).

Material	Unit	Production (A1–A3)	Demolition (C1)	Transport (C2)	Disposal (C3)	Recycling Potential (D)	Total Global Warming Potential
Rammed Earth	kg CO_2/m^3	9.3	1.6	6.0	6.8	−2.9	20.8
Concrete Brick	kg CO_2/m^3	242.4	1.3	5.1	13.5	4.1	258.2

These estimates may vary depending on factors such as regional conditions, construction techniques, and the specific materials used in both conventional and CEB building. The reductions in carbon emissions (CO_{2e}) and embodied energy (EE) in the life cycle by replacing individual components with the proposed CMMs is significant. Potential savings vary between 86% and 95% [20]. In the case of stabilised compressed earth (using 4% hydraulic lime), more conservative assumptions have claimed that CEBs can lead to CO_2 savings of about 73% and 57%, respectively, compared to conventional construction methods using traditional cavity brickwork or brick veneer [21,22]. For a typical building, 86.7% of CO_{2e} (i.e., 10.1 t of CO_{2e}) was found to be attributable to structural components made of concrete, aluminium, structural steel, and mild steel [23].

By replacing structural elements (e.g., non-load-bearing walls, interior walls, flooring, etc.) with CMMs and assuming a conservative 90% reduction in CO_{2e} and EE for each replaced component, an overall CO_{2e} reduction of up to 24% was estimated (from 11.8 t of CO_{2e} to 9.0 t of CO_{2e}): figure that can drastically be increased if rammed earth or CEBs are used as the load-bearing material.

2.7. Aspired Application Possibilities

The applications proposed for this concept are diverse, with a high potential to revolutionise the global construction industry by supporting achievement of the internationally set goal of a Zero Built Environment System by 2050. In the following, we suggest two application possibilities in more detail:

Standardisation and mass production: In the project process, our proposed concept will make use of and apply the UMP components—procurement of material, quality control methodology, open-source design, and planning—to produce a prototype on campus. Close-by available materials will be identified and mixed with local earth and tested for their usability and quality (proof of WP2). With the support of an industrial robot with an electric vibratory end effector, students, together with project partners, will produce in situ pre-fabricated building modules that will fulfil standardisation requirements and prove the concept of automated CMM production. Co-created architectural designs for a prototype will be downloaded through the open-source UMP, and various tutorials will support the actual built implementation. The integration of innovative CMMs into mass-production techniques such as automated processes with 3D printing or robotics will elevate the production volumes of pre-fabricated wall elements and bricks, enabling the construction industry to build more sustainably and faster. This way, CMMs will become competitive, as they are highly predicable in their construction material availability, economic costs, construction planning, temporal implementation, and calculability of emission consumption.

International usage of the Urban Mining Platform—education and prototyping: As open-source UMP is transferable into different country and material contexts. With cooperation partners in India and South Africa, the UMP applicability will be tested in a twofold approach:

Education: In the first step, students and volunteers from the practice will be trained and educated by attending an online course on innovative CMM building approaches. Furthermore, co-creative and human-centred methods will be applied to develop a technical design for prototype construction that will remain open-source for further usability and adaptation.

Prototyping: Students will work with local partners to put their knowledge into practice. Local mineral materials will be tested using the UMP quality control method, and suggestions will be made for innovative material mixes that achieve high quality, durability, and strength. Local sources of larger aggregates from recycled mineral waste will be identified, and an innovative, locally adapted CMM will be created. Mass production technology such as additive manufacturing [24,25] will be identified and used to begin the in situ production of pre-fabricated CMM modules that will be assembled into the proposed prototype.

3. State of Research and Technology

3.1. Significant National and International Developments in the Relevant Research Area

The proposed concept is a cutting-edge research project located at the intersection of four critical focus areas: (1) sustainable building materials, (2) standardisation, (3) open sources as innovation drivers for digitisation, and (4) transformative knowledge production and innovation management. Through this research, our proposed concept addresses the research gaps identified in the field of building with CMMs: (a) standardisation of material mixtures, (b) low-threshold methods for quality control of CMMs, (c) Urban Mining Platform and lifecycle tracking of CO_2 savings and circularity in earthen construction, and (d) automation and digitalisation of material flows throughout the lifecycle and optimisation of the production process (scalability and pre-fabrication).

3.1.1. Sustainable Construction Material

From a geotechnical point of view, mineral materials for rammed earth (RE) constructions consist of compacted and partially saturated aggregates with particle sizes in the range of gravel, sand, silt, and clay [26]. So far, mainly fine- and mixed-grained natural soils in the form of clayey sands and gravels have been used as RE materials, which can be improved with fibrous organic materials (jute, hemp, sisal, etc. [27]) and/or with binders (e.g., cement, lime, geo-/biopolymers, resins). A few individual studies have been conducted on the use of mineral residues, e.g., recycled materials for RE constructions, with promising results demonstrating the potential of these materials for such use [28,29]. Especially, reinforced concrete building materials and industrial by-products, which have post-hardening potential due to the formation of carbonate phases, appear to be particularly attractive for use as RE materials. Since RE constructions are usually designed without hydraulic binders ("non-stabilised"), the water content of the construction materials is of particular importance [30], showing that these materials exhibit significantly different strengths and stiffnesses as a function of CMM moisture content. Similarly, structures made of non-stabilised RE building materials exhibit great water sensitivity and frost sensitivity [31]. As with the mechanical properties, water and frost sensitivity depend largely on water content. Various studies [32,33] have shown that stabilisation with binders has a very positive effect on mechanical properties and resistance to water and frost stress.

For the design of RE constructions, the thermos-hydro-mechanical behaviour of the material, which would be governed by the physical and chemical properties of the aggregates and so-called "state variables", must be described. The main state variables are the density, the structure of the particle arrangement, the water content, the degree of saturation, and the suction. Promising approaches to describing the behaviours of RE materials have been based on the principles of soil mechanics on unsaturated soils [34,35]. However, in comparison to most applications in geotechnics, compacted RE materials have very low water contents near the residual state after drying. Existing material models for unsaturated soils have been developed to describe these properties at comparatively high saturation levels but not for very dry soils or building materials, such as those found in rammed earth structures [36]. Thus, there is still a significant need to establish appropriate constitutive models for RE materials.

3.1.2. Standardisation

The most important national developments in earthen construction in Germany include the publications of DIN 18945 [37] and DIN 18948 [38] in 2018. This second generation of standards in earthen construction has covered, among other things, earthen blocks and earthen boards. A future third generation of standards in earthen construction will include a construction and design standard for earthen masonry, which is currently being developed. Earthen building materials not yet covered by DIN standards are regulated in the Lehmbau Regeln (clay-building rules) [39]. At the international level, similar standards are under development [40–45]. However, although structures made of CMMs are built worldwide [46], there is still a considerable lack of uniform specifications and regulations both for the suitability testing of the materials used and for quality monitoring [47,48]. Consortium and cooperation partners are working with international associations and researchers in the fields of international standardisation efforts and processes (see partner list) for the following aspects: material selection; manufacturing techniques; extents and types of suitability testing; field tests and quality control; and durability against mechanical, thermal, and hydraulic actions.

3.1.3. Digitalisation and Open Source

The digital transformation, as well as open-source technologies, has significantly impacted the construction industry [49,50]. These improve process efficiency, reduce costs, and promote collaboration between stakeholders. The key developments in this area include the following aspects:

The introduction of Building Information Modelling (BIM) has revolutionised the construction industry [51]. BIM enables the virtual design, construction, and management of buildings and optimises processes and communication between stakeholders. This technology has also been applied to earth-based construction projects [52] to enable better decision making and coordination during the construction process. The development of digital platforms for urban mining [53] has enabled more efficient procurement, processing, and distribution of sustainable building materials. By cataloguing and mapping available resources, these platforms help construction professionals identify locally available materials and make them accessible, reducing transportation costs and associated environmental impacts.

Automation technologies such as robotics [54] and sensors, partly connected to the Internet [55], are being integrated into earth construction to improve efficiency and scalability. These technologies allow for faster and more precise construction, making earth-based materials more competitive with conventional building materials. Open-source platforms have proven to be powerful tools for promoting knowledge exchanges and collaboration among stakeholders in the construction industry [56]. By providing broad access to research results, design tools, and best practices, these platforms drive innovation and facilitate the widespread adoption of sustainable building practices.

3.1.4. Transformative Knowledge Production

To address the complex challenges of sustainable construction, researchers are increasingly adopting agile, interdisciplinary, and transdisciplinary approaches that promote innovation and transformative knowledge production [57,58]. Interdisciplinary research will advance our understanding of earth-based construction materials and methods and will develop new solutions. Thus, researchers will interconnect insights from diverse fields such as materials science, civil engineering, mechanical engineering and robotics, architecture, computer science, and environmental sciences.

Transdisciplinary research goes a step further by additionally engaging stakeholders from academia, business/industry, government, and civil society in the co-creation of knowledge and solutions [59–61], which has not yet been fully exploited in the proposed research field of building with earth. This collaborative approach ensures that research findings are relevant and applicable to real-world problems, enhancing the potential for sustainable and transformative impacts. For the use of purely basic science findings (not infrequently abstract and theory-driven) for real-world problems, "application-oriented basic research" from Pasteur's quadrants offers a promising approach. It is based on the premise that scientific knowledge about a real-world phenomenon will require clear evidence for solving problems in practice. At the same time, these scientific findings are only effective if the needs, interests, and knowledge of users from the practice are integrated emphatically into the research process from the outset [62].

The creation of living labs and real-world testbeds can therefore be seen as an effective means of ensuring direct, value-adding application in practice and in society as part of the research process. In the case of the proposed project, this approach will ensure the development and evaluation of innovative building materials and methods [63,64].

3.2. Inter/National Important and/or Competing Research Groups in Relevant Field(s)

Increasing numbers of existing and recently formed international and domestic scientific and practice project groups and associations in the area of construction with rammed/pressed earth materials are emphasising the urgency of the proposed research project. With an inclusive mindset, the proposed concept will cooperate with numerous partners from business and academia.

4. Research Data Concept

The research data concept aims to establish a systematic and transparent approach to managing, storing, and sharing the research data generated throughout this project. This concept adheres to the FAIR data principles (Findable, Accessible, Interoperable, and Reusable) to ensure the effective use and reusability of research data by the research team and the broader scientific community that is achieving the advancement of knowledge creation in the field of sustainable construction and related areas.

Concepts for Handling the Research Data

A comprehensive data management plan (DMP) is to be developed at the beginning of this project, with regular review sessions and updating to accommodate any changes in the research data landscape or project requirements. The following aspects and specific procedures are outlined in Table 2:

Table 2. Concepts for handling research data.

Data	Handling Concept
Collection and Documentation	Primary and secondary data collection, such as experiments, simulations, surveys, and interviews. Documentation of all data, applying standardised metadata formats and ensuring consistency, comparability, and rigor analysis.
Storage and Security	Data being securely stored on the university's centralised data storage system or a trusted external data repository in accordance with the DFG Code of Good Scientific Practice 2019. Access being controlled through user authentication and authorisation mechanisms, ensuring confidentiality.
Backup and Preservation	Regular backups that would prevent data loss and long-term data preservation strategies that would ensure the availability of research data beyond this project's duration. Data repository or storage solutions that would adhere to established data preservation standards and best practices.

Table 2. *Cont.*

Data	Handling Concept
Sharing and Access	Research data being shared with project members and, where appropriate, external collaborators throughout this project. Upon completion of this project, data being made publicly available through trusted data repository or open-access platform(s).
Licensing and Reuse	Research data being made available under open data licenses, such as Creative Commons or similar licenses, that encourage reuse and sharing while providing appropriate attribution to original data creators.
Compliance	The handling of research data adhering to all applicable ethical guidelines and legal requirements, such as data protection regulations, intellectual property rights, and informed consent from research participants. The research team consulting with the university's ethics committee or legal department as needed to ensure compliance with these guidelines and requirements.

5. Long-Term Perspective and Scientific Outlook

5.1. Concrete Measures for Continuity

The open-innovation UMP will secure easy transferability into different systems, such as research, practice, and the industry. Inter/national research and cooperation partners will form long-term strategic alliances with construction and IT industry stakeholders, academic institutions, and associations specialised in earth construction to ensure a continuous exchange and growth of knowledge and the sustainability of the UMP as a recognised and highly accepted resource and practice application. The active engagement of the earth construction industry and its association partners, on one hand, emphasises the practical relevance of the topic; on the other hand, it ensures the optimisation of the UMP, leading to economically viable processes. The development and production of an inter- and transdisciplinary MOOC will lay the foundation for long-term continued education programs and training workshops accessible to various stakeholders from the science and practice inter/nationally. Research findings will be integrated into curricula at the university, at academic partner institutions, and in the training and workshop plans of transfer partners/professional associations.

Follow-up funding opportunities are intended to target inter/national funding opportunities from various sources, including government grants, industry collaboration, and private investment (PPP). In the long term, our proposed concept consortium aims to establish a recognised research centre or institute that will serve as a competence and knowledge hub for ongoing applied research, inter-and transdisciplinary collaboration, and theory practice innovation.

5.2. Added Value for the Strategy and Research Profile of the University

Our proposed concept offers significant added value to the strategy and research profile of the university by aligning to its current strategy and contributing to enhancing the reputation of involved faculties and institutes as leaders in the sustainable circular construction, automation, digitalisation, and scaling of building with earth. Specific added values for the strategy and research profile are depicted in Table 3:

Table 3. Added values for the strategy and research profile.

Area	Description
Real-World Impact and Social Responsibility	Focusing on transferable, applied, circular, and sustainable solutions to decarbonise and minimise emissions in the construction industry, our proposed concept supports the university's commitment to addressing real-world challenges in co-creating knowledge and solutions to achieve social and environmental sustainability.
Research Excellence	Conducting cutting-edge inter/national research of sustainable construction materials, digitalisation, and transformative knowledge production, our proposed concept will contribute to enhancing the university's research profile, reputation for research excellence, and visibility in academia and the industry. This will lead to attraction of top-tier researchers, students, and funding opportunities, further bolstering the university's status as a leading applied research institution.
Educational Opportunities and Workforce Development	Creating open-source access for knowledge sharing, continued knowledge creation and learning, and professionalisation, our proposed concept will also create a meaningful basis for new educational programs and training opportunities with broad outreach potential and transferability into different sectors on various scales, reinforcing the university's commitment to workforce development and lifelong learning.
Economic Development and Industry Partnerships	Driving innovation and growth in the sustainable construction sector will strengthen the university's relationships with industry partners, contributing to regional economic development. This will enhance the university's reputation as a valuable partner in promoting sustainable economic growth.

6. Industry Transfer and Scalability

The university will provide our 33 partners with a collaborative, pre-competitive space where industry partners with different levels of maturity in, e.g., robotics technology, from observers to early adopters, will find roles to expand their knowledge bases or identify business opportunities for collaboration. In this regard, the research community will benefit from the expertise of the industry, and in turn, the industry will benefit from our proposed concept's research findings. The main focus of the multidirectional and multilateral transfer activities and opportunities are (A) materials, e.g., between experts in mineral recycled materials, and (B) digital urban mining, e.g., with transfer between academia and IT innovators. For all other possible transfer opportunities, see Figure 2. The university can draw on many years of experience in knowledge and technology transfer with its successful conclusion of over 450 long-term cooperation, transfer, and licensing agreements with companies since 2000. The spirit of entrepreneurship is anchored within teaching and research that provides support through the start-up initiative "Kilometer1". Transfer, exchange, co-creation, and an open innovative mindset will be cultivated and supported by the newly founded Lake Con-stance Arts & Sciences Association, successor of the International Lake Constance University (IBH), bringing together 25 universities and colleges from Germany, Austria, Switzerland, and Liechtenstein.

6.1. Social Relevance of the Proposed Project

Man-made global warming is endangering the lives of billions of people all over the world. To counteract the increasing loss of life, ambitious inter/national accelerated biodiversity and infrastructure adaptation measures have been set over the last few decades, aiming for a profound reduction in greenhouse gas emissions [65]. In the Paris declaration of 2015, the world community committed itself—under international law—to keep global warming below 2 °C compared to pre-industrial temperatures, and, if possible, not to exceed 1.5 °C. To achieve this goal, according to the latest scientific findings and CO_2 calculations [66–68], climate neutrality must be achieved by the mid-century. The efforts of the next few years will be particularly decisive. To act now, our proposed concept aims to transform the construction industry through (a) decarbonisation; (b) waste and carbon footprint reduction; and (c) material circularisation and lifespan expansion. The shift towards more sustainable construction practices and recyclable material benefits will mitigate climate change, disaster risk reduction, and environment pollution and preserve natural resources, ultimately contributing to the well-being of current and future generations.

Our proposed concept shows social relevance by addressing the following future global challenges as shown in Table 4:

Table 4. Social relevance in addressing future global challenges.

Global Social Challenge	Description
Affordable Housing	CMMs and innovative construction methods will provide cost-effective solutions that will ensure access to safe, decent, and affordable housing for all (UN 2021).
Community Resilience and Cultural Preservation	CMMs are locally sourced, reducing transportation costs and emissions as well as promoting local economies and community resilience. The use of traditional building techniques will preserve local cultural heritage and foster senses of community identity and pride.
Education and Knowledge Dissemination	The development of new open-source educational programs and training opportunities in sustainable construction and building practices will empower individuals and communities to make informed decisions to contribute towards more sustainable built-environment technology.
Health and Well-Being	CMMs contribute to healthier indoor environments with improved air quality, thermal comfort, and humidity regulation, reducing long-term respiratory health issues and other health problems associated with poor indoor air quality.

6.2. Economic Relevance of the Proposed Concept

A recent study analysing a BIM bill of quantity data from 243 commercial and residential projects with heights of three stories or less revealed that wall elements constitute 59% of the total element volume (in m^3). When a broader scope of 800 projects without height limitations was considered, this figure increased to 64%. Walls account for 12–20% of total building construction costs, indicating a significant market potential for innovative building materials, techniques, and technologies.

In Germany, the estimated market size for this sector is 10.6 billion EUR, while it has reached 95.4 billion EUR in Europe and 866.1 billion EUR worldwide. These figures are based on the assumption that 40–50% of the total construction costs for residential and commercial buildings are related to shell costs and that the total costs of walls fall within the range of 30–40%. Given the substantial market sizes of 66.5 billion EUR in Germany, 596 billion EUR in Europe, and 5.413 trillion EUR globally (based on 2021 total construction market data), the wall segment in residential and commercial buildings holds considerable potential for growth and innovation [6,7,9].

This shows that the proposed project holds considerable economic relevance, impacting the construction industry through a baseline construction volume, new technology applications, job creation, and additional digital service revenues. The adoption of digital services and automation technologies, such as BIM, the UMP, and robotics, is expected to expand construction volume and attract larger market shares across Europe, Africa, and Asia. In Europe, the construction industry employs approximately 15.7 million people (2022), with an expected increase due to the adoption of innovative practices [69].

7. Discussion

The proposed research project, focused on sustainable construction, decarbonisation, and circular economy, has significant implications for both the construction industry and society at large. As we have shown, this project aims to address global challenges such as climate change, affordable housing, community resilience, cultural preservation, education, and health and well-being. In this discussion, we will synthesise the key aspects of this project and elaborate on its potential long-term impacts on various stakeholders.

Sustainable construction materials (CMMs) and innovative construction methods are at the heart of this project, aimed at reducing waste and emissions while promoting material circularity and lifespan expansion. The use of CMMs not only contributes to climate change mitigation but also has the potential to improve the overall health and well-being of building occupants. This is particularly relevant in the context of affordable housing, where access to safe, decent, and healthy living spaces is crucial.

In addition, this project's focus on locally sourced materials and traditional building techniques holds promise for fostering community resilience and preserving cultural heritages. By promoting local economies, reducing transportation costs, and maintaining cultural identities, this project can have a positive impact on both the economic and social aspects of communities around the world.

The integration of digital technologies, such as Building Information Modelling (BIM), the Urban Mining Platform (UMP), and robotics, is another critical aspect of this project. These technologies have the potential to increase efficiency, reduce costs, and improve the overall quality of construction projects. Furthermore, their adoption is expected to drive market growth and job creation in the construction industry, particularly in Europe, Africa, and Asia.

Education and knowledge dissemination are also central to this project's long-term impact. The development of open-source educational programs and training opportunities in sustainable construction will empower individuals and communities to make informed decisions and contribute to a more sustainable built environment. This aligns with this project's commitment to workforce development and lifelong learning, ultimately benefiting the research profile and strategy of the universities involved.

The economic relevance of this project is evident in the potential market size for innovative building materials, techniques, and technologies. With the construction industry's significant contribution to global greenhouse gas emissions, the shift towards sustainable practices is not only a moral imperative but also a substantial economic opportunity. This project's success in promoting sustainable construction could lead to job creation, additional digital service revenues, and an increase in market shares for innovative construction solutions.

Finally, the proposed research project holds significant potential for transforming the construction industry and addressing pressing global challenges. By focusing on sustainable materials, innovative construction methods, digital technologies, and education, this project can contribute to a more sustainable, healthy, and resilient built environment. As this project moves forward, it is essential to monitor and evaluate its progress, engage with diverse stakeholders, and remain adaptable to changing circumstances in order to maximise its long-term impact and success.

8. Validity and Limitations of the Proposed Framework in Developing Countries

One significant aspect of the proposed framework relates to its adaptability in various socio-economic settings, particularly in developing countries where resources, both financial and managerial, can be restricted. We understand that implementing such an advanced framework in these contexts can pose unique challenges, but we also believe that its potential for promoting sustainability and resource efficiency makes it a compelling solution worth considering.

8.1. Economic Constraints

In developing countries, financial limitations can significantly restrict the adoption of innovative construction techniques and sustainable practices. The initial costs associated with acquiring new technologies, training labour forces, and securing sustainable construction materials may be prohibitive for many local construction firms. It is important to note, however, that the long-term economic benefits of adopting sustainable construction practices can outweigh the upfront costs.

Cost efficiency is a central aspect of the Compacted Mineral Mixture (CMM)-based construction approach. Our framework leverages the use of local, abundant, and often underutilised resources, potentially reducing material procurement costs. Moreover, the longer lifespans and lower maintenance requirements of structures built with CMM materials can provide further financial advantages in the long run.

8.2. Managerial Constraints

The managerial resources of developing countries can also be a limiting factor, as the successful implementation of our proposed framework requires certain levels of technical expertise and organisational capacity. However, it is important to view this challenge as an opportunity for capacity building and local knowledge development. The proposed framework places a strong emphasis on education and knowledge dissemination, aiming to empower local communities and enhance local capacities.

Training programs and workshops designed to equip local construction workers and managers with necessary skills and knowledge can be an effective way to address these managerial constraints. Furthermore, partnering with local educational institutions, NGOs, and government agencies can help build a supportive ecosystem for knowledge sharing and capacity building.

8.3. Addressing the Limitations

To address these financial and managerial constraints, several strategies can be adopted. For instance, developing partnerships with international organisations, foundations, and private sector entities can help secure necessary funding and technical support. Tailoring the implementation of the framework to match local contexts is also vital. This might include adapting the proposed techniques to work with available materials and technologies and modifying the training programs to accommodate the local workforce's skill levels.

It is important to note that these limitations are not insurmountable. With strategic planning, cooperation, and a commitment to sustainability and local empowerment, our proposed framework can bring about significant benefits in developing countries. While the road to sustainable construction might be challenging, the journey is essential for the creation of a more resilient and sustainable built environment in all corners of the world.

In conclusion, the limitations of implementing the proposed framework in developing countries, while real, can be effectively addressed through thoughtful strategies and collaborative efforts. The validity of our framework in such contexts hinges not only on its intrinsic merits but also on the collective will and commitment of various stakeholders to drive the transition towards sustainable construction practices.

9. Conclusions

In light of the results and objectives of the proposed research project, it is essential to consider how these findings can be interpreted in the context of previous studies and working hypotheses. This project's focus on sustainable construction, a circular economy, and innovative building materials and methods is consistent with the growing body of the literature emphasising the importance of addressing environmental and social challenges in the construction industry. This discussion explores the implications of this project's findings in the broader context, as well as highlighting potential future research directions.

The use of sustainable construction materials (CMMs) and innovative construction methods in this project aligns with prior research that has demonstrated the benefits of such approaches in terms of reduced emissions, waste reduction, and improved building performance. In this regard, this project's findings support the working hypothesis that sustainable construction practices can contribute significantly to mitigating climate change and promoting a circular economy.

Moreover, this project's emphasis on locally sourced materials and traditional building techniques complements previous studies that have highlighted the importance of community resilience and cultural preservation in sustainable development. These findings have suggested that integrating these elements into construction projects can have far-reaching social and economic benefits for communities worldwide while also supporting the global commitment to climate change mitigation and adaptation.

The integration of digital technologies, such as BIM, the UMP, and robotics, represents another critical aspect of this project that is consistent with the growing trend of digitalisation and automation in the construction industry. Prior research has demonstrated the potential of these technologies to improve efficiency, reduce costs, and enhance the overall quality of construction projects. This project's findings further support this hypothesis and suggest that the adoption of such technologies can drive growth and job creation in the industry.

Regarding this project's focus on education and knowledge dissemination, the findings underscore the importance of empowering individuals and communities through open-source educational programs and training opportunities. This approach aligns with previous studies that have highlighted the value of informed decision making and community engagement in promoting sustainable development.

In terms of future research directions, several avenues can be explored:

1. Investigating the long-term performance and durability of sustainable construction materials and innovative building techniques in different climatic conditions and contexts;
2. Exploring the social, cultural, and psychological factors that influence the adoption of sustainable construction practices and materials in various communities;
3. Assessing the effectiveness of educational and training programs in driving the adoption of sustainable construction practices among diverse stakeholders;
4. Investigating the potential barriers to the widespread adoption of digital technologies in the construction industry and developing strategies for overcoming these challenges;
5. Examining policy and regulatory frameworks that can support and incentivise the adoption of sustainable construction practices and circular economy principles in the construction sector.

In conclusion, the proposed research project's findings and implications contribute significantly to the existing body of knowledge on sustainable construction and offer valuable insights for future research. By continuing to explore the potential of sustainable materials, innovative construction methods, digital technologies, and education, researchers can help shape a more sustainable, healthy, and resilient built environment for generations to come. Ultimately, the proposed research project will serve as a valuable stepping stone in the journey towards a more sustainable, resilient, and healthy built environment. By embracing the principles of sustainability, innovation, and collaboration, the construction industry can play a pivotal role in addressing some of the most pressing global challenges and paving the way for a brighter, more equitable future for all.

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Appendix A

Table A1. Global warming potential based on life cycle stage (in kg CO_2 equivalents). Data retrieved from ÖKOBAU.DAT [1]. Global warming potential by life cycle stage (in kg CO_2 equivalents).

Material	Unit	Production (A1–A3)	Demolition (C1)	Transport (C2)	Disposal (C3)	Recycling Potential (D)	Total Global Warming Potential
Rammed Earth	kg CO_2/m^3	9.3	1.6	6.0	6.8	−2.9	20.8
Clay Plaster	kg CO_2/m^3	93.2	no data	2.5	2.8	−3.9	94.6
Compressed Earth Brick	kg CO_2/m^3	93.6	no data	3.6	4.1	−1.8	99.6
Gypsum Plaster	kg CO_2/m^3	119.4	no data	2.9	13.5	no data	122.8
Burnt Clay Brick	kg CO_2/m^3	138.3	0.3	3.2	0.3	−7.0	135.2
Sand-Lime Brick	kg CO_2/m^3	136.0	no data	no data	no data	no data	no data
Concrete	kg CO_2/m^3	197.0	3.1	12.0	6.0	−21.4	196.7
Concrete Brick	kg CO_2/m^3	242.4	1.3	5.1	13.5	4.1	258.2
Lime-Cement Plaster	kg CO_2/m^3	356.6	no data	5.8	27.0	no data	389.4

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