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Recyclable and Efficient Construction using Mineral Landfill Materials and Demolition Wastes

Michael Max Bühler [1,*], Pia Hollenbach [1], Alexander Michalski [1], Sonja Meyer [1], Emanuel Birle [2], Rebecca Off [1], Christina Lang [1], Wolfram Schmidt [3], Roberto Cudmani [2], Oliver Fritz [1], Guido Baltes [1] and Geraldine Kortmann [1]

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Abstract: An inter- and transdisciplinary concept has been developed, focusing on the scaling of industrial circular construction using innovative compacted mineral mixtures (CMM) derived from various soil types (sand, silt, clay) and recycled mineral waste. The concept aims to accelerate the systemic transformation of the construction industry towards carbon neutrality by promoting the large-scale adoption and automation of CMM-based construction materials, which incorporate natural mineral components and recycled aggregates or industrial by-products. In close collaboration with international and domestic stakeholders in the construction sector, the concept explores the integration of various CMM-based construction methods for producing wall elements in conventional building construction. Leveraging a digital urban mining platform, the concept aims to standardize the production process and enable mass-scale production. The ultimate goal is to fully harness the potential of automated CMM-based wall elements as a fast, competitive, emission-free, and recyclable alternative to traditional masonry and concrete construction techniques. To achieve this objective, the concept draws upon the latest advances in soil mechanics, rheology, and automation and incorporates open-source digital platform technologies to enhance data accessibility, processing, and knowledge acquisition. This will bolster confidence in CMM-based technologies and facilitate their widespread adoption. The extraordinary transfer potential of this approach necessitates both basic and applied research. As such, the proposed transformative, inter- and transdisciplinary concept will be conducted and synthesized using a comprehensive, holistic, and transfer-oriented methodology.

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

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1. Introduction

Before the advent of industrialization, traditional construction methods relied on locally available, renewable materials that had a minimal impact 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 sustainable forestry practices in Bavaria, Germany. In the early 18th century, Bavarian forester Hans Carl von Carlowitz [2–4] formulated the principle of sustainability in his book, "Sylvicultura Oeconomica." His work emphasized 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 the 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 utilized natural and locally sourced materials, such as timber, adobe, and stone. These materials were not only abundant but also had a low environmental impact. For instance, timber, a renewable resource, can be

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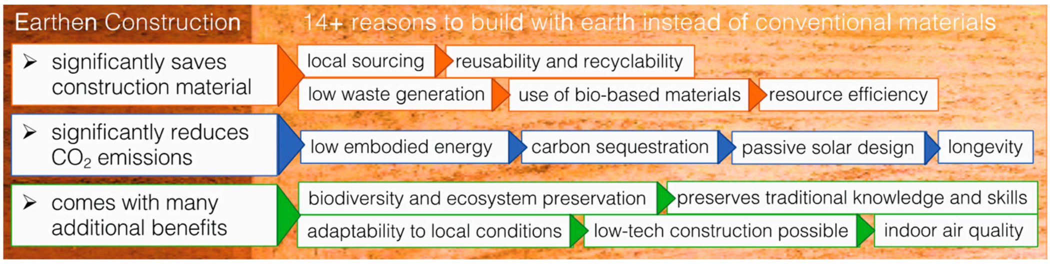
harvested sustainably by maintaining a balance between the growth and harvesting of trees. Adobe and stone, similarly, can be sourced and used with minimal processing, reducing their overall environmental footprint.

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 the current environmental challenges, there is an urgent need to return to sustainable construction methods and materials that characterized 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 a significant share 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. The proposal is grounded in interdisciplinary collaboration between academia, industry, and policy stakeholders, recognizing the importance of holistic approaches to addressing the complex challenges facing the construction sector.

The primary objectives of this proposed concept are to

(1) develop and test circular, low-carbon construction materials and methods (CMM);
(2) leverage digitalization, including Building Information Modelling (BIM) and Urban Mining Platform (UMP), to optimize material use, reduce waste, and enhance overall construction efficiency;
(3) promote the adoption of automation and robotics technologies in the construction sector; and
(4) foster knowledge dissemination and capacity-building through open-source educational programs, training opportunities, and transdisciplinary collaborations.

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

2. Research Objectives

The primary objective of this proposed research concept is to revolutionize 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, the 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, characterized by 100% circularity, CO_2-neutrality, and enhanced economic efficiency. The research's potential impact is significant, considering that walls for commercial and residential buildings represent a substantial market share, estimated at €95 billion per annum in the European Union and €10 billion per annum in Germany, based on 2021 estimates[1].

By transforming conventional construction methods, this research concept aims to contribute meaningfully to the broader goal of sustainable development within the construction industry. It seeks 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.

3.1. Motivation, scientific goals and scientific innovation potential

The **motivation** is to aim for a systemic transformation of the construction industry towards circular, emission-free, decarbonized, and competitive construction methods. The proposed concept is committed working towards the latest statements of the UN Global Status Report for Buildings and Construction (2022) [[5]: *"…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, the concept supports the ambitious amendments of the German Climate Protection act in 2021 [6], demanding a emission reduction of 65% compared to 1990, and anchoring climate neutrality by 2045. These higher ambitions directly influence the CO_2 reduction targets for individual sectors such as industry, buildings and agriculture [7]. On international and domestic level, this concept assists achieving the sustainable development goals (SDGs) and Agenda 2030, more specific: SDG 12, SDG 9, SDG 8.2, 8.4, SDG 4.3, 4.4, SDG 17, and SDG 11 [8] and is fully aligned with the European Green Deal (p.11) [9].

The **overall scientific goal** is to establish the 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 the tamped or compacted mineral material (CMM) to meet strength and durability requirements of structures, including weatherability and long-term stability.

Following **research questions** are operationalized through Work Packages (cf.3.1.1):

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 to digitally capture circular material flows and process strategies and facilitate sourcing, trading, production, quality control, standardization, 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, contemporary teaching methodologies (e.g., Massive Open Online Courses) be leveraged to enable and promote access

[1] 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 cost of walls can be estimated between about 30 to 40%, it can 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 at €10.6 billion (Germany), €95.4 billion (Europe), and €866.1 billion worldwide (with €66.5 billion, €596 billion, and €5.413 billion total construction market in 2021, respectively). Data sources: Eurostat, Hauptverband der Deutschen Bauindustrie, Statista, Statistisches Bundesamt

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 revolutionize the earthwork process and envisaging a breakthrough in the large-scale use of new innovative CMM made from natural, mineral soil components and recycled aggregates as an innovative building material. The **unique selling points** are: (a) **radical decarbonization** and **circular economy** approach starting from waste as feedstock, (b) **industrial scaling** of a niche product, (c) **digital urban mining platform** as dynamic matchmaking between disposers and buyers; and (d) **access for all** through a consistent open-source/open-innovation approach.

3.1.1. Operationalization of the proposed concept

The overarching **transdisciplinary organization** (Figure 1) 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 above research questions.

Transdisciplinary organization and agile management[2]

The transdisciplinary organization focuses on the organisation, design & management of six (6) transdisciplinary co-creation workshops applying design thinking, a use-centred research approach including iterative and lean processes spanning across different technology readiness levels, supported by a co-creative approach and individual topic-related sprints.

[2] **Agile research**, a methodology of conducting research that is iterative and adaptive to changing circumstances, to respond to complex and rapidly evolving challenges anticipated in the context of the Our proposed concept project. 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 using CMM 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 at the HTWG. To support this agile research process, open-source digital platform technologies are used to f**acilitate data access, processing, and knowledge gain**. This enables all researchers and industrial partners to **quickly analyse data** and identify trends or issues and **adjust the research process** as needed. In addition, the holistic and transfer-oriented approach of the Our proposed concept project is also supported by agile research, as it would enable researchers to rapidly respond to new challenges and emerging opportunities as they arise and ensure that the research is continuously aligned with the overall goals and objectives of the project.

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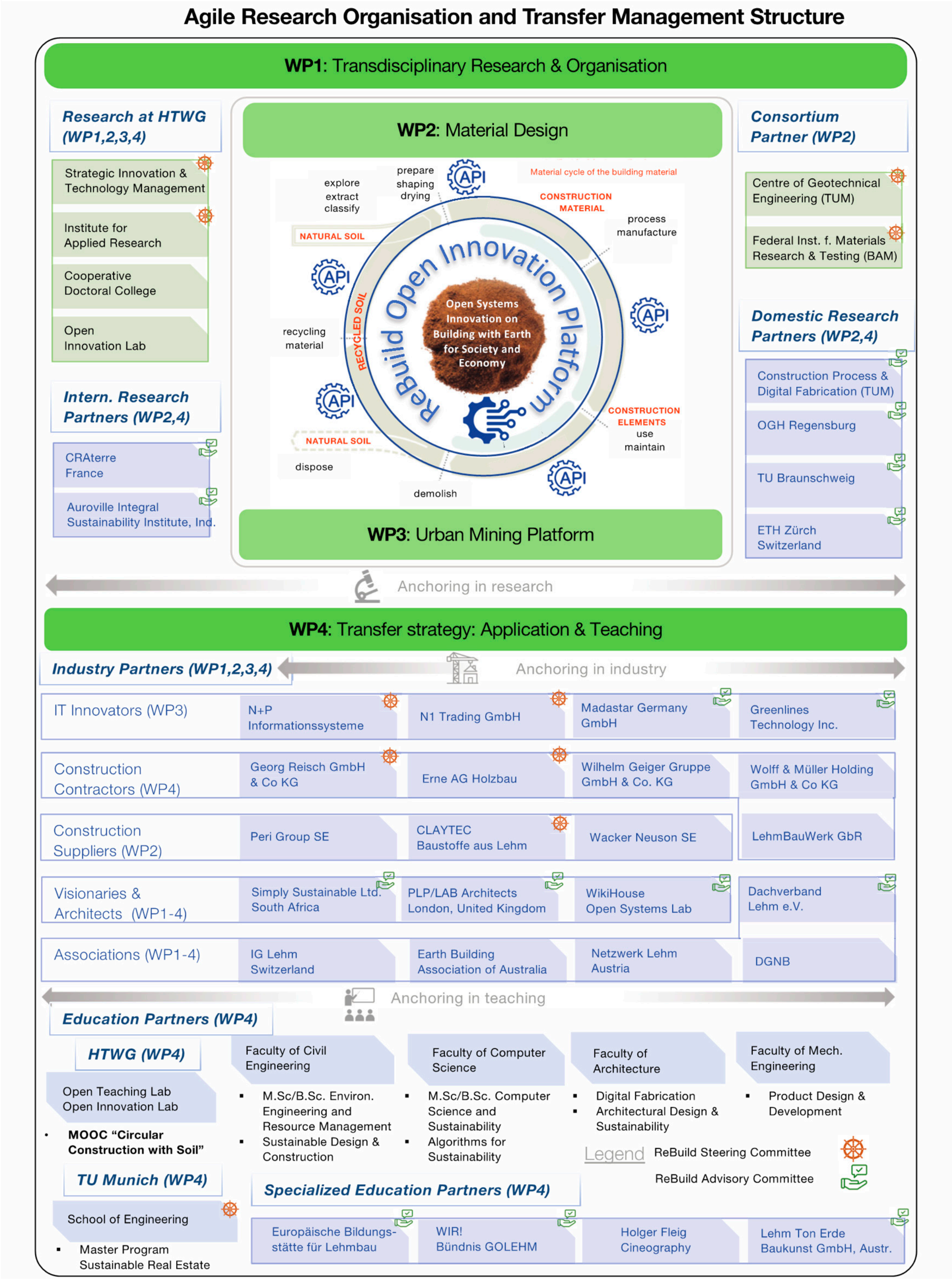

Figure 1. Agile Organisation and Transfer Management Structure.

The priority 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, are organized to secure exchanges, adjustments and co-creation. Hackathons and the definition of requirements and specifications for Technology Readiness Levels (TRL) are key aspects to adjust the research and to differentiate the technical core and validate the technical solution concept in the following step. Accompanied prototyping and user validations lead up to a complete first prototype. Testing the prototype with transfer partners ensures its efficacy in real-world situations and results 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 documenting, scientific open-access publications and production of online handbooks and guidelines. Results and activities will be continuously transferred.

Material selection, characterization, and quality control

This works will be conducted with a co-creative and participatory approach integrating relevant research and industry partners through online or in-person meetings as well as in material tests (in-situ and laboratory). This allows direct interventions, adjustments and co-learning with a high quality applied and implementation quality.

Material selection and Quality Control Methodology: to achieve standardized and competitive CMM-based building materials, as known from industrially produced materials such as steel, wood, concrete, mortar and bricks, evaluations and extensive testing will be conducted to develop a quality control methodology based on laboratory and in-situ material testing.

Material properties data base: to ensure design assumptions regarding material homogeneity, strength, deformability and durability, the quality control methodology will significantly improve the confidence of CMM building technique.

Experimental Tests: to determine the suitability of the material (first stage) and to check the quality during the construction of CMM-structures (second stage).

The first stage will focus on determining the chemical and physical properties of the raw materials, assessing suitable mixtures of raw materials (e.g., natural clay, natural aggregates, recycled materials, industrial by-products) and the necessity of mechanical or chemical stabilization to fulfil requirements regarding strength and durability. In this stage, the material composition, the optimum water content, eventually the required dosage of additives, as well as the relevant mechanical and hydraulic properties of the compacted material including their statistical distribution will be specified. Further investigated in the CMM context will be the use of biopolymers as rheology modifiers. Tests comprise standard tests for the classification of the 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 behaviour. For the analysis of the durability the following laboratory tests are planned: cyclic wetting and drying tests, cyclic freezing-thawing tests, erosion tests and permeability tests.

Constitutive Model: to analyse the applicability of existing constitutive models for the numerical simulation of the thermo-hydraulic and the mechanical behaviour of unsaturated CMM. Thereafter, a suitable constitutive model will be adopted and implemented in a commercial Finite Element Code to create 2D- and 3D-digital twins of a CMM structure and predict the structural response to external actions.

Material processing: to control technical specifications laboratory and field tests during construction (second stage) (cf. 3.3). Laboratory tests are carried out with samples taken from CMM structures including rammed earth and/or compressed earth. In addition, destructive and non-destructive field tests are carried out. These experimental results 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.

Urban Mining Platform (UMP) and Digital Material Procurement

The UMP (Figure 2) on the one hand is scraping together knowledge, output and findings. In addition, UMP builds on BAM's digital material platform MaterialDigital [10,11], which includes the material optimization Artificial Intelligence algorithm "*Sequential Learning App for Materials Discovery SLAMD*" [12] applicable to soil materials and mineral aggregates. On the other hand, UMP streamlines the procurement, processing and distribution of earth-based building materials. It includes the following functionalities and the illustrated high-level architecture:

Material procurement: to increase construction supply chain efficiency, digital representation and automation of material procurement is essential. Persistent data storage and management of material information ensures transparency and traceability throughout the material lifecycle. Suitable algorithms that optimize material availability help to develop suitable sources, avoid waste, and

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reduce material needs. A test integration of suitable IoT sensors (e.g., GPS location determination) supports material extraction aiming for sustainable procurement processes.

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

Quality Measures: the digitization of quality determination through specialized sensors that measure, monitor and optimize enables precise assurance of material quality. Internet-connected technology supports measurements over long distances by sending the measuring devices to the place of examination. Collaboration and integration of specialized laboratories back up comprehensive analysis to assure high levels of quality. Open-source digital training supports to better understanding, interpreting and evaluating the quality of the material and its complex analyses.

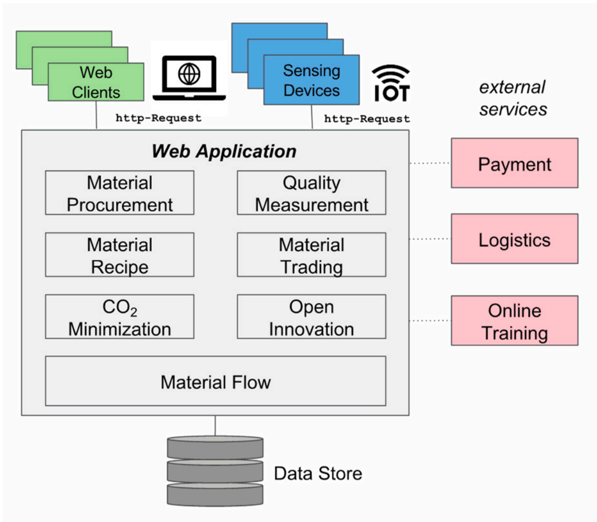

Figure 2. UMP Architecture; own illustration, 2023.

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

Material Trading: to optimize logistics and the supply chain a simple store functionality brings together material trading partners such as sellers, buyers, suppliers and processors. Suitable algorithms from the field of operations. A rating system provides transparency and increases trust, supported by the integration of information and communication tools enabling a smooth exchange. To ensure competitive prices, suitable algorithms for price optimization are used and adapted. Digital payment options are handled via external services to simplify and accelerate the process.

CO_2 emission determination and minimization: to digitally map, monitor, and analyse CO_2 emissions in the entire material flow and identify and minimize potential savings. Integrated functions will measure recycling and reuse capabilities as well as identify possible waste or contamination advancing to reduce final waste amounts and associated CO_2 emissions. In addition to the functional components, UMPs web-based client-server architecture applies 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 connect sensor devices (GPS, soil quality measurement) to the web. Figure 1 illustrates a possible architecture of UMP.

Transfer strategy, transfer activities, networking and utilization

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This concept aims to leverage recent advances in soil mechanics, rheology and automation to support the construction sector develop innovative construction methods for manufacturing of wall elements. This will enable a more efficient and cost-effective construction process increasing the competitiveness of earthen building materials over traditional materials such as concrete and masonry. Specifically, the construction industry will be enabled to have load-bearing walls and interior walls produced by machine that the construction method is not only emission-free, and circular compared to the conventional approach, but also economically competitive, i.e., faster and cheaper. Furthermore, it contributes 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 inducing soil from a niche building material to scalable and competitive mass product. The WP includes different steps to bring forth a user-friendly, needs-oriented and co-created open source that organically continues to grow and flourish internationally. Applying qualitative participatory methods WP4.1 will assess and analyse the needs of relevant transfer partners to develop a needs-based and stakeholder-oriented transfer and DACH networking strategy. Further, UMP will support the professionalization and transfer of knowledge into practice to secure continued education and knowledge production on CMM standardization, materiality, quality assurance, building techniques and architectural designs. WP4.2 encompasses the planning and creation of a collaborative massive open online course (MOOC) on "Circular Construction with Soil" promoting and fostering UMPs digital education component in close collaboration with existing and newly established international education, practice and policy networks (WP4.3) within the circular building with soil community (cf. Appendices A5, A6). Besides, theoretical and methodological educational WP4.4 contains an into action component. Together with different project cooperation partners and HTWG students the 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 automatization 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 (cf. Appendix A6). Our research group is active in African networks of standardization 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 foresees the organization and implementation of an international conference applying method that foster active exchanges, co-creation and attentive learning on "Circular Building with Soil" with the cooperation partner PLP Architecture and DGNB.

3.2. Rough estimate of potential CO_2 or raw materials 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, Table A-1 listing more materials).

Table 1. CO2 footprint rammed earth compared to conventional building methods.

Global Warming Potential by Life Cycle Stage (in kg CO2 equivalents)

Material	Unit	Production (A1 - A3)	Demolition (C1)	Transport (C2)	Disposal (C3)	Recycling Potential (D)	Total Global Warming Potential
Rammed Earth	kg CO2 / m³	9,3	1,6	6,0	6,8	-2,9	20,8
Concrete Brick	kg CO2 / m³	242,4	1,3	5,1	13,5	-4,1	258,2

data source: OEKOBAU.DAT

These estimates may vary depending on factors such as regional conditions, construction techniques, and the specific materials used in both conventional and CEB. The reduction of carbon emissions (CO_{2e}) and embodied energy (EE) in the life cycle by replacing individual components with the proposed CMM is significant. Potential savings vary between 86% and 95% [13]. In case of stabilized compressed earth (using 4% hydraulic lime) more conservative assumptions claim that CEB can lead to CO_2 savings of about 73% and 57%, respectively, compared to conventional construction methods using traditional cavity brickwork or brick veneer [14,15]. For a typical building, 86.7% of CO_{2e} (i.e., 10.1t CO_{2e}) was found to be attributable to structural components made of concrete, aluminium, structural steel, and steel [16].

By replacing structural elements (e.g., non-load-bearing walls, interior walls, flooring, etc.) with CMM 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 11.8t CO_{2e} to 9.0 t CO_{2e}). A figure that can drastically be increased if rammed earth or CEB is used as load-bearing material.

3.3. Aspired application possibilities

The applications proposed by this concept are diverse with a high potential to revolutionize the global construction industry supporting to achieve the international set goal of Zero Built Environment System3 by 2050. In the following, we suggest two application possibilities in more detail:

Standardization and mass production:

In the project process, our proposed concept will make use and apply the UMP components-procurement of material, quality control methodology, open-source design and planning, to produce a prototype at the HTWG Campus. Close by available material will be identified and mixed with local earth and tested for their usability and quality (proof of WP2). With support of an industrial robot with an electric vibratory end effector4 students together with project partners will produce in-situ prefabricated building modules that fulfil the standardization requirements and prove the concept of automatized CMM production. Co-created architectural designs for a prototype are downloaded through the open-source UMP and various tutorials support the actual built implementation. The integration of innovative CMM into mass production techniques such automated processes with 3D printing or robotics, elevates the production volume of prefabricated wall elements and bricks enabling the construction industry to build more sustainable and faster. This way, CMM becomes competitive as it is highly predicable in construction material availability, economic costs, construction planning, temporal implementation and calculability of emission-consumption.

International usage of 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, UMP will test its applicability in a twofold approach:

Education: in a first step, students and volunteers from practice will be trained and educated by attending an online course on innovative CMM building approaches. Further, co-creative and human-centred methods are 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 material 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 aggregate from recycled mineral waste will be identified and an innovative locally adapted CMM will be created. Mass production technology such as additive manufacturing [17,18] will be identified and used to begin in-situ production of prefabricated CMM modules that will be assembled into the proposed prototype.

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3 https://globalabc.org/news/building-momentum-cop26-historic-engagement-and-visibility-built-environment

4 Kuka KR 240 and linar unit KL 1500 provided by craftwise GmbH and electric vibrators provided by Wacker Neuson. The suitability of the vibrators and/or tampers is tested at TU Munich before shipped to HTWG

3.4. Structural and strategic goals, integration in the strategic profiling of the university

The HTWG Structure and Development Plan 2022-2026 (StEP) prioritizes the following five strategic fields of action: (1) sustainability, (2) networking, internationalization and flexibilization, (3) digital transformation, (4) collaboration and identification, (5) diversity and inclusion. These strategic and operative fields of action are pursued in all HTWG faculties and areas of responsibility: teaching, scientific continued education, research, transfer of knowledge, and junior researchers.

The concept is turning HTWG into a "real laboratory for applied, sustainable action" (4.1.2b), contributing specifically to the following strategic fields of action:

Sustainability: as a transformative research project focusing on sustainable building materials and methods, this concept directly supports the strategic goal of strengthening the anchoring of sustainability issues within the university (4.1.1). By developing earth-bound building materials and circular construction methods, the project contributes to university-wide, inter- and transdisciplinary projects in the field of sustainable development supporting the goal of anchoring sustainable development more firmly in HTWG's diverse research and transfer areas.

Networking, internationalization and flexibilization: using open-source platform technologies and thus the networking and cooperation of inter/national stakeholders from science, practice and application, this concept promotes international collaboration and knowledge exchange (4.2.1). The yet established strong international, inter- and transdisciplinary cooperation and collaboration network (cf. A6) continues to grow intensifying cross-regional partnerships (4.2.2) positioning HTWG as a global leader in the research and development of sustainable building materials and methods.

Digital transformation: UPM education component supports "Future Skills education and practice" (4.3) consciously adjusting to current inter/national challenges, needs and trendsetting transformative thematic foci (4.3.1c). The close intern/national collaboration with the practice and industry further strengthens the anchoring and sensitization for social just and sustainable entrepreneurial thinking (4.3.1b).

Collaboration and identification: This concept works with a mindset of collaborative leadership creating and using thematic, methodological and operational synergies university-wide aiming for operational excellency (4.4.1) and stronger research output, broader exploitation and dissemination opportunities (4.4.1a).

Diversity and Inclusion: This concept promotes diversity acting as a role model with a female Professor in a MINT-academic subject. Similarly, with female Postdocs supporting the promotion of equal rights and access to education for all (cf. WP3) regardless of nationality, sexual orientation, gender and religion. This concept commits itself to the HTWG equality and diversity plan (2022-2026) GLEICH. Relating to HTWG's relevant areas of activity, significant contributions are made to:

Research: This concept advances the state of the art in sustainable building materials, soil mechanics, rheology and automation. Its interdisciplinary approach fosters collaboration between researchers from different fields and creates synergies that drive innovation.

Teaching: The proposed concept provides a platform for integrating sustainability topics in HTWG curricula and introduces students to cutting-edge research. The project equips students with knowledge, skills and capabilities providing the foundation to develop new courses, workshops, and seminars aiming to create a more sustainable future. The Faculty of Civil Engineering in particular has stipulated the integration of sustainable construction in its curricula in the StEP.

Transfer: This concept leverages open-source technologies and collaborates with public, private and industry stakeholders promoting knowledge and technology transfer between academia, industry, and society. This strengthens HTWG's reputation as a partner for businesses and communities seeking for sustainable applied solutions.

Junior Researcher(s): The proposed concept targets the active involvement and promotion of doctoral students. Two PhD students will be integrated in the HTWG cooperative doctoral college which promotes further qualification and networking as well as an interdisciplinary discourse across faculties. Furthermore, they will be involved in the project on an equal footing, work together with relevant stakeholders and ideally be part and get access to the TUM doctoral process to further benefit from strong established exchange and knowledge networks.

4. State of research and technology

4.1. 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) standardization, (3) open source as innovation driver for digitization, and (4) transformative knowledge production and innovation management. Through its research, our proposed concept addresses the research gaps identified in the field of building with CMM: (a) standardization of material mixtures, (b) low-threshold methods for quality control of CMM, (c) urban mining platform and lifecycle tracking of CO_2 savings and circularity in earthen construction, and (d) automation and digitalization of material flows throughout the lifecycle and optimization of the production process (scalability and prefabrication).

4.1.1. Sustainable construction material

From the geotechnical point of view, mineral material for rammed earth (RE) constructions consists of compacted partially saturated aggregates with particle sizes in the range of gravel, sand, silt and clay [19]. 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 material (jute, hemp, sisal etc. [20]) 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 [21,22]. Especially, reinforced concrete building materials and industrial by-products, which have a post-hardening potential due to the formation of carbonate phases, appear to be particularly attractive for the use as RE materials. Since RE constructions are usually designed without hydraulic binders ("non-stabilized"), the water content of the construction materials is of particular importance [23] showed that materials exhibit significantly different strengths and stiffness as a function of CMM moisture content. Similarly, structures made of non-stabilized RE building materials exhibit great water sensitivity and frost sensitivity [24]. As with the mechanical properties, the water and frost sensitivity depend largely on the water content. Various studies [25,26] show that stabilization with binder has a very positive effect on mechanical properties and resistance to water and frost stress.

For the design of RE constructions the thermo-hydro-mechanical behaviour of the material, which is governed by the physical and chemical properties of the aggregates and so-called "state variables", must be described. 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 describe the behaviour of RE materials are based on the principles of soil mechanics on unsaturated soils [27,28]. 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 were developed to describe the properties at comparatively high saturation levels and not for very dry soils or building materials such as those found in rammed earth structures [29]. Thus, there is still a significant need for establishing appropriate constitutive models for RE-materials.

4.1.2. Standardization

The most important national developments in earthen construction in Germany include the publication of DIN 18945 and DIN 18948 in 2018. This second generation of standards in earthen construction covers, 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. The earthen building materials not yet covered by DIN standards are regulated in the Lehmbau Regeln [30]. At the international level, similar standards are under development [31–36]. However, although structures made of CMM are built worldwide [37], there is still a considerable lack of uniform specifications and regulations both for the suitability testing of the materials used and for quality monitoring [38,39]. The consortium and cooperation partners are working with international associations and researchers in the field of international standardization efforts and processes (see partner list), on the following aspects: Material selection, manufacturing techniques, extent and type of suitability testing, field tests and quality control, durability to mechanical, thermal and hydraulic actions.

4.1.3. Digitalization and Open Source

The digital transformation as well as open-source technologies significantly impact the construction industry [40,41]. They 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 revolutionized the construction industry [42]. BIM enables the virtual design, construction, and management of buildings and optimizes processes and communication between stakeholders. This technology has also been applied to earth-based construction projects [43] to enable better decision-making and coordination during the construction process.

The development of digital platforms for urban mining [44] has enabled more efficient procurement, processing, and distribution of sustainable building materials. By cataloguing and mapping available resources, these platforms help construction professionals identify and make locally available materials accessible, reducing transportation costs and associated environmental impacts.

Automation technologies such as robotics [45] and sensors, partly connected to the Internet [46], 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 a powerful tool for promoting knowledge exchange and collaboration among stakeholders in the construction industry [47]. 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.

4.1.4. 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 [48,49]. 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 [50–52] 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 impact. 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 requires 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 practice are integrated emphatically into the research process from the outset [53].

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 [54,55].

4.2. 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 material are emphasising the urgency of the proposed research project. With an inclusive mindset the proposed concept cooperates with numerous partners from business and academia listed in Appendix A6 (Letter of Intent) A12 (Additional Tables).

5. Quality of the project group

5.1. Research performance and scientific visibility of participating scientists and/or research groups

The project team comprises a diverse group of experts from various disciplines, ensuring a well-rounded and comprehensive approach to the research. The main applicant and coordinator (WP1,2, Civil Engineering, HTWG) and the two lead researchers (WP4, Civil Engineering, HTWG) and (WP3, Computer Science, HTWG) will be responsible for overseeing research (WP2,3) and transfer (WP4) activities. Collaborators from the Open Innovation Lab (WP4, Architecture, HTWG), the Institute for Strategic Innovation and Technology Management (WP1, Mechanical Engineering, HTWG), TUM research group from the Center for Geotechnical Engineering (WP2.2, TU Munich), and the Federal Institute for Materials Testing (WP2.3, BAM) will contribute their expertise to the various work programs.

With extensive experience in construction, infrastructure, and urban development, the project group's research expertise covers areas such as geotechnical engineering, earthquake engineering [56], soil dynamics [57], climate research [58,59], and education/management research [60]. The team's professional experience spans geotechnical design/construction management, infrastructure advisory/finance, and global initiatives, research, strategy, and business development through involvement with organizations like the World Economic Forum, T20/G20 Task Forces [61–63], G20 Infrastructure Hub [64], and OECD Executive Consultation Group.

Team members possess a wide range of skills and achievements [58,65–71], including expertise in lightweight structures, algorithmic foundations of digitalized business processes [72–76], software-driven optimization, parametric modeling, CNC manufacturing methods, rheology and chemical admixtures for cement and concrete, and corporate venturing. Additionally, the team has experience in researching and implementing sustainable urban construction technologies using local, environmentally friendly resources in Africa and is engaged with international organizations focused on construction materials and structures.

The diverse expertise of the project team, combined with their extensive experience in research, industry, and international collaboration, ensures a comprehensive and robust approach to tackling the challenges of sustainable construction and innovative building techniques [77,78]. With this strong foundation, the project is well-positioned to deliver valuable insights and contribute meaningfully to the advancement of sustainable practices in the construction industry [79–88]. Recognized articles proof excellency on hydraulic-mechanical coupled processes in compacted fine- and mixed grained soils [89–91], recycled construction materials [92] and industrial by-products for the use in earthworks [93,94]. Published in geotechnical engineering [95–103], including works on the time-dependent behaviour of sands under oedometric compression [100], predicting soil water characteristic curves [102,103], and rate- and time-dependent mechanical behaviour of foam-grouted coarse-grained soils [98]. Additionally, excellent knowledge in numerical modelling of saturated and unsaturated soils [97,102,103] lead to successful inter/national research projects and cooperation. The centre works in close collaboration with cooperation partner BAM (Institute for Material Research and Testing) and engages geotechnical engineering efforts, such as DIN Standardization, European Committee for standardization, TC 221 “Tailing Storage Facilities” of the International Society of Soil Mechanics and Geotechnical Engineering, and several external reviewer positions.

5.2. Integration of the project group into existing structures

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All participating researchers and their respective working groups are integrated and well established in the research structures of the HTWG and as members of the Institute for Applied Research (IAF), all work with a mindset of co-creation, inter- and transdisciplinary and collaborative leadership. Explicitly our concept will integrate and collaborate with following HTWG institutes: (1) Open Innovation Lab (Prof. Fritz) for transdisciplinary activities (e.g., co-creation sprints), (2) Open Teaching Lab (Prof. Birkhölzer, HTWG Vice President for Teaching) for knowledge and teaching transfer (e.g., MOOC production), and (3) Strategic Innovation and Technology Management (Prof. Baltes) for training, capacity building, and transfer activities.

5.3. Planned networking of the project group with external partners

Based on the proposed concept, we will strongly collaborate with existing and newly established inter/national networks and partners to secure successful scientific and practice implementation (cf. 4.2). 30 collaboration partners (cf. Appendix A6) bring in large expertise in theory, methodology and practice from various backgrounds belonging to research institutions, industry practitioners, and construction companies. The following introduces the network strategizing:

The project aims to innovate scalable, sustainable, and circular construction materials by establishing strong relationships and transparent communication with construction companies, suppliers, and transfer partners. Through regular meetings, workshops, consultations, and feedback rounds, the project ensures that industry expectations and demands are integrated thematically, strategically, and methodically.

In collaboration with materials and materials technology companies, the project conducts joint activities such as materials testing, prototyping, and performance analysis to ensure that the envisioned outputs meet industry standards. As the project progresses, additional transfer companies will be identified and integrated into the process.

The project also works closely with IT industry partners to support the development of a user-friendly and intuitive open-source platform. Requirements and idea sprints are organized to gather insights and feedback from industry experts, ensuring efficient and effective platform development. The platform will serve as a central hub for knowledge exchange and collaboration among all partners.

To design and build prototypes based on industry requirements and goals, the project integrates external knowledge partners, facilitating professionalization and capacity building among practitioners, small craft businesses, the interested public, and university students. This also includes the development of a Massive Open Online Course (MOOC) focused on circular construction with soil.

6. Organizational and management structures

6.1. Description of organizational and management structures

Our proposed concept is organized in four interlocking Work Packages (WP), the already described thematic WP2 and 3 (cf. 3.1.1 and Figure 1) and the overarching organisation and cooperation **WP1.**

6.2. Project planning (milestone plan)

The overall project management lies in the responsibility of the principal investigator and the main researchers and the external research partner at TU Munich. As described in section 3.1 and illustrated in A1, our proposed concept is divided into four Work Packages that collaboratively identified the following four Milestones (MS):

MS1 – Architecture Definition: The overall concept of a holistic architecture has been defined and evaluated by means of a discover sprint, numerous stakeholder interviews (pain points, interests and needs) and a requirements analysis.

MS2 – Proof of Concept: Concept requirements/specifications have been validated, ideation hackathon(s) have been successfully carried out, the technical core/solution concept has been differentiated and validated by various user groups/stakeholders.

MS3 – Prototype Completed: Prototyping workshop(s) have been carried out; users/stakeholders have validated the prototype.

MS4 – Minimal Viable Product: Filed tests with the prototype have been carried out with practice/transfer partners, prototype improvements have been carried out, lessons learned have been compiled and exchanged in implement sprint(s). Final evaluation with partners with agreed MVP validation points has been carried out.

6.3. Description of internal quality assurance and project management measures

Our proposed concept applies a comprehensive project management and quality assurance strategy combining traditional and agile elements to ensure successful implementation. Measures include:

Table 2. Internal quality assurance and project management measures.

Measure	Description
Project management structure	Clearly outline the roles and responsibilities of project leader, team members, and supporting personnel to facilitate effective communication, decision-making, and resource allocation
Progress meetings	Review project milestones, discuss challenges or obstacles (on all levels), and identify potential solutions to ensure transparent information and status quo sharing, a collaborative and problem-solving mindset
Track progress	WPs regularly conduct iterative sprints, report on work progress, deadlines and achieved deliverables. MS will be tracked, and progress reported to ensure timely completion and adherence to project goals
Internal review(s)	Internal peer-review and constructive feedback sessions assess (a) the quality of research outputs, such as data, reports, and publications, and (b) open opportunities for revision, ensuring all outputs meet the project's quality standards.
Risk mitigation strategy	Identification of potential internal and external risk(s) will proactively minimize disruptions and maintain momentum towards achieving set project objectives
Finances and budget control	Regular budget reviews and financial reports help to ensure resource efficiency, transparency and a prompt identification of potential cost overruns. Close control allows adjustments of resource allocation as needed
Support committees	Steering committee: senior project partners, transfer partners from industry give direction and jointly define research targets, define expectations ensuring valuable transfer results (Steering committee members see Figure 1, symbol ⎈) Advisory committee inter/national experts from academia, associations and other relevant stakeholders will actively provide body of knowledge, guidance, and feedback on progress and scientific output to refine research approach

	and ensure alignment with set goals and objectives (Advisory committee members see Figure 1, symbol)
Documentation	Documentation and record-keeping practices maintain accurate recording of all project activities, decisions, and outputs to enable transparent communication, open monitoring and well-informed retrospect sessions
Improvement mindset	Regularly evaluating processes, methodologies, and outputs allow direct intervention and adjustments related to changing circumstances. Agility and adaptiveness assure quality, overall resilience and maximizing success

6.4. Measures for the integration and promotion of young researchers

Our proposed concept has committed to create an inclusive and supportive work environment and to foster the next researcher generation in the field of sustainable construction. Our proposed concept will create opportunities for integration, promotion, scientific qualification, and professional growth. Following measures will be implemented to support development and career progression:

(1) Active involved in various research activities, such as experimental work, data analysis, dissemination activities, and publications. (2) Mentorship and supervision through experienced researchers and practice partners offering guidance, feedback, and support throughout their project involvement helping to grow professionally, to gain scientific confidence and personality, and enhancing long-term career prospects. (3) Training sessions and workshops in relevant topics, such as research methodologies, data analysis techniques, and scientific communication help to expand knowledge and skills increasing research competence and employability. (4) Inter/national conference and seminar participation facilitate connections with peers, experts, and potential collaborators building up strong professional networks that promote career development. (5) Further education opportunities, such as enrolling in advanced courses, obtaining certifications, or pursuing higher degrees are desired and supported, include financial assistance and time allowances. (6) Collaborative leadership enables young researchers to develop leadership and management skills by taking on leadership roles, such as managing specific tasks or coordinating activities.

6.5. Measures to actively promote diversity

Our proposed concept lives and promotes diversity establishing a clear commitment to equity and inclusion (cf. 3.4) throughout its organisational, implementation and transfer processes. It further recognizes and lives up to the HTWG's internal equality plan 2022-2026 GLEICH (cf. 3.4) communicating core principals to all project members and involved cooperation partners. The project will establish an inclusive work environment where all individuals feel respected, valued, and abled to openly communicate and address any instances of discrimination or bias and encouraging team members to share their diverse perspectives and experiences. More specific, the project: (a) adopts fair and transparent recruitment practices actively encouraging applications from individuals of diverse backgrounds, including but not limited to gender, ethnicity, age, socioeconomic background, and disability status; (b) supports all members, regardless of their background, to have equal access to opportunities for professional development, mentorship, and career progression; (c) raises awareness of decolonizing research measures and communication; and (d) actively engages with an inter/national diverse range of stakeholders, including industry partners, policymakers, and community representatives, to ensure that the research remains relevant and responsive to the needs of diverse groups and diverse socio-economic backgrounds. Regular monitoring and evaluation sessions using relevant metrics and feedback methods, critically assess progress and identify areas for improvement in the set diversity and inclusion strategy.

7. Research data concept

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The research data concept aims to establish a systematic and transparent approach to managing, storing, and sharing research data generated throughout the project. The 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 achieving advancement of knowledge creation in the field of sustainable construction and related areas.

7.1. Concept for handling the research data

A comprehensive data management plan (DMP) will be developed at the beginning with regular review sessions and updating to accommodate any changes in the research data landscape or project requirements. Following aspects and specific procedures will be outlined:

Table 3. Concept for handling the 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 standardized metadata formats, ensuring consistency, comparability, and rigor analysis
storage and security	data is securely stored on the university's centralized data storage system or a trusted external data repository in accordance with the DFG Code of Good Scientific Practice 2019. Access be controlled through user authentication and authorization mechanisms, ensuring confidentiality
backup and preservation	regular backups prevent data loss, and long-term data preservation strategies ensure the availability of research data beyond the project's duration. Data repository or storage solution adhere to established data preservation standards and best practices
sharing and access	research data will be shared with project members and, where appropriate, external collaborators throughout the project. Upon completion of the project, data will be made publicly available through trusted data repository or open-access platform(s)
licensing and reuse	research data will be 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	with ethical guidelines and legal requirements: The handling of research data will adhere 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 will consult with the university's ethics committee or legal department as needed to ensure compliance with these guidelines and requirements

8. Long-term perspective

8.1. Concrete measures for continuity

The open innovation platform UMP (WP2, WP3) secures easy transferability into different systems such as research, practice and industry. Inter/national research and cooperation partners

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form long-term strategic alliances with construction and IT industry stakeholders, academic institutions, and associations specialized in earth construction to ensure a continuous exchange and growth of knowledge and the sustainability of UMP as recognized and highly accepted resource and practice application. The active engagement of earth construction industry and association partners on the hone hand emphasises the practical relevance of the topic, on the other hand it ensures the optimization of UMP leading to economically viable processes. The development and production of an inter-and transdisciplinary MOOC (WP4) lays the foundation for long-term continued education programs and training workshops accessible for various stakeholders inter/nationally, from science and practice. Research findings are integrated in curricula at HTWG, TUM, academic partner institutions, and in training and workshop plans of transfer partners/professional associations.

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

8.2. 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 HTWG (cf. 3.4, 6.5) by aligning to its current StEP and contributing to enhance the reputation of involved faculties and institutes as leaders in sustainable circular construction, automatization, digitalization, and scaling of building with earth. Specific added values include:

Table 4. Added value for the strategy and research profile.

Area	Description
Real-world impact and social responsibility	Focusing on transferable, applied, circular, and sustainable solutions to decarbonize and minimize emissions in the construction industry, our proposed concept supports the university commitment to address real-world challenges co-creating knowledge and solutions achieving social and environmental sustainability
Research excellence	Conducting inter/national cutting-edge research in sustainable construction materials, digitalization, and transformative knowledge production, our proposed concept contributes to enhance the university's research profile, reputation for research excellence, and visibility in academia and industry. This leads to attract top-tier researchers, students, and funding opportunities, further bolstering HTWGs status as leading applied research institution
Educational opportunities and workforce development	Creating open-source access for knowledge sharing, continued knowledge creation and learning, and professionalization, our proposed concept creates 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, strengthens the university's

	relationships with industry partners contributing to regional economic development. This enhances the university's reputation as a valuable partner in promoting sustainable economic growth

9. Transfer

HTWG[5] (WP4) 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 (e.g. Wolff & Müller) to early adopters (e.g. Erne), will find their role to expand their knowledge base or identify business opportunities for collaboration. In this regard, the research community will benefit from the expertise of industry, and in turn, industry will benefit from Our proposed concept's research findings. The main focus of the multi-directional and multilateral transfer activities and opportunities are (A) materials, e.g. between experts in mineral recycled materials (e.g. Geiger, TUM, BAM, etc.) and (B) digital urban mining, e.g. with transfer between academia and IT innovators. For all other possible transfer opportunities, see Figure 1.

9.1. Social relevance of the proposed project

Man-made global warming is endangering the lives of billions from people all over the world. To counteract the increasing loss of life, biodiversity and infrastructure inter/national ambitious accelerated adaptation measures have been set over the last decades aiming for a profound reduction of greenhouse gas emission [104]. In the Paris declaration 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 CO2 calculations [105–107], climate neutrality must be achieved by mid of the century. The efforts of the next few years are particularly decisive. To act now, our proposed concept is aiming to transform the construction industry (cf. 3) through (a) decarbonization; (b) waste and carbon footprint reduction; and (c) material circularisation and lifespan expansion. The shift towards more sustainable construction practices and recyclable material benefits climate change mitigates, disaster risk reduction, environment pollution, and preserves natural resources ultimately contributing to the well-being of current and future generations.

Besides Our proposed concept shows social relevance addressing following future global challenges:

Table 5. Social relevance in addressing future global challenges.

Global social challenge	Description
Affordable housing	CMM and innovative construction methods provide cost-effective solutions that ensure access to safe, decent, and affordable housing for all. (UN 2021)
Community resilience and cultural preservation	Community resilience and cultural preservation: CMM is locally sourced reducing transportation costs and

[5] HTWG can draw on many years of experience in knowledge and technology transfer with successfully concluding over 450 long-term cooperation, transfer and licensing agreements with companies since 2000. The spirit of entrepreneurship is anchored within teaching and research providing support through the start-up initiative "Kilometer1". Transfer, exchange, co-creation and an open innovative mindset is cultivated and supported by the newly founded Lake Constance Arts & Sciences Association, successor of the International Lake Constance University (IBH), bringing together 25 universities and colleges from Germany, Austria, Switzerland and Liechtenstein.

	emissions, as well promoting local economies and community resilience. Use of traditional building techniques preserve local cultural heritage and foster a sense of community identity and pride
Education and knowledge dissemination	development of new open-source educational programs and training opportunities in sustainable construction and building practices empower individuals and communities taking informed decisions to contribute towards a more sustainable built environment technology
Health and well-being	CMM contribute to healthier indoor environment with improved air quality, thermal comfort, and humidity regulation reducing long-term health of respiratory issues and other health problems associated with poor indoor air quality [101]

9.2. Economic relevance of the proposed concept

A recent study on BIM bill of quantity data conducted on 243 commercial and residential projects with heights of three stories and less shows that 59% of total element volume (in m^3) consists of wall elements. Without limiting the height of the building (evaluation of a total of 800 projects), this figure rises even to 64%. As walls represent 12-20% of total building construction costs, the proposed project signifies a potential market size of €10.6 billion in Germany, €95.4 billion in Europe, and €866.1 billion worldwide for innovative building materials, techniques, and technologies[6]. This shows that the proposed project holds considerable economic relevance, impacting the construction industry through baseline construction volume, new technology applications, job creation, and additional digital service revenues. The adoption of digital services and automation technologies, such as BIM, UMP, and robotics, is expected to expand construction volume and attract a larger market share 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 [108].

10. Discussion

The proposed research project, focused on sustainable construction, decarbonization, and circular economy, has significant implications for both the construction industry and society at large. As we have seen, the 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 synthesize the key aspects of the project and elaborate on its potential long-term impact on various stakeholders.

Sustainable construction materials (CMM) and innovative construction methods are at the heart of the project, aimed at reducing waste and emissions while promoting material circularity and

[6] 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 cost of walls can be estimated between about 30 to 40%, it can 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 at €10.6 billion (Germany), €95.4 billion (Europe), and €866.1 billion worldwide (with €66.5 billion, €596 billion, and €5.413 billion total construction market in 2021, respectively). Data sources: Eurostat, Hauptverband der Deutschen Bauindustrie, Statista, Statistisches Bundesamt

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lifespan expansion. The use of CMM 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, the project's focus on locally sourced materials and traditional building techniques holds promise for fostering community resilience and preserving cultural heritage. By promoting local economies, reducing transportation costs, and maintaining cultural identity, the project can have a positive impact on both economic and social aspects of communities around the world.

The integration of digital technologies, such as Building Information Modelling (BIM), Urban Mining Platform (UMP), and robotics, is another critical aspect of the 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 the 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 the project's commitment to workforce development and lifelong learning, ultimately benefiting the research profile and strategy of the universities involved.

The economic relevance of the 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. The project's success in promoting sustainable construction could lead to job creation, additional digital service revenues, and an increase in market share 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, the project can contribute to a more sustainable, healthy, and resilient built environment. As the project moves forward, it will be essential to monitor and evaluate its progress, engage with diverse stakeholders, and remain adaptable to changing circumstances in order to maximize its long-term impact and success.

11. 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. The project's focus on sustainable construction, circular economy, and innovative building materials and methods is consistent with the growing body of literature emphasizing the importance of addressing environmental and social challenges in the construction industry. This discussion will explore the implications of the project's findings in the broader context, as well as highlight potential future research directions.

The use of sustainable construction materials (CMM) and innovative construction methods in the 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, the project's findings support the working hypothesis that sustainable construction practices can contribute significantly to mitigating climate change and promoting a circular economy.

Moreover, the 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. The findings suggest 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, UMP, and robotics, represents another critical aspect of the project that is consistent with the growing trend of digitalization 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. The 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 the 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 highlighting 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. Investigate the long-term performance and durability of sustainable construction materials and innovative building techniques in different climatic conditions and contexts.
2. Explore the social, cultural, and psychological factors influencing the adoption of sustainable construction practices and materials in various communities.
3. Assess the effectiveness of educational and training programs in driving the adoption of sustainable construction practices among diverse stakeholders.
4. Investigate the potential barriers to the widespread adoption of digital technologies in the construction industry and develop strategies for overcoming these challenges.
5. Examine the policy and regulatory frameworks that can support and incentivize 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 serves 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 A-1. Global warming potential by life cycle stage (in kg CO2 equivalents).

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Material	Unit	Production (A1 - A3)	Demolition (C1)	Transport (C2)	Disposal (C3)	Recycling Potential (D)	Total Global Warming Potential
Rammed Earth	kg CO2 / m³	9,3	1,6	6,0	6,8	-2,9	20,8
Clay Plaster	kg CO2 / m³	93,2	no data	2,5	2,8	-3,9	94,6
Compressed Earth Brick	kg CO2 / m³	93,6	no data	3,6	4,1	-1,8	99,6
Gypsum Plaster	kg CO2 / m³	119,4	no data	2,9	13,5	no data	122,8
Burnt Clay Brick	kg CO2 / m³	138,3	0,3	3,2	0,3	-7,0	135,2
Sand-Lime Brick	kg CO2 / m³	136,0	no data	no data	no data	no data	no data
Concrete	kg CO2 / m³	197,0	3,1	12,0	6,0	-21,4	196,7
Concrete Brick	kg CO2 / m³	242,4	1,3	5,1	13,5	-4,1	258,2
Lime-Cement Plaster	kg CO2 / m³	356,6	no data	5,8	27,0	no data	389,4

data source: OEKOBAU.DAT

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