# New trends on design, fabrication, and materials for construction: CARBCOMN, an EIC Pathfinder Challenge project

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**Synopsis**: Greenhouse gas (GHG) emissions from material extraction, manufacturing construction products, and building or renovation activities account for 5-12% of global GHG emissions. Concrete is particularly high in emissions due to its popular use and carbon-intensive cement clinker production, which contributes about 8% of global CO2 emissions. To reduce its impact, concrete must be re-evaluated in terms of carbon footprint and design. In response to this challenge, the EIC-funded "CARBon-negative COMpression dominant structures for decarbonized and deconstructable CONcrete buildings" project (CARBCOMN, www.cordis.europa.eu/project/id/101161535) aims to realise an innovative decarbonized construction system for load-bearing concrete structures, which can revolutionize the current practice in the construction sector through a cross-scale innovation. The CARBCOMN construction system focuses on compression dominant stress states, so to utilize the concrete at its strongest stress resisting state, make it intrinsically more durable by being no longer susceptible to reinforcement corrosion, and to be more compatible with extrusion-based 3D concrete printing. It is worth highlighting that, in this context, compression dominant stress states can be either induced by geometry (e.g. curved members) or mechanics (e.g. post-tensioning). Carbonatable binders complement this vision by optimizing $CO_2$ sequestration for both hardening and emission reduction. A multi-scale material design enhances carbonation, developing a dense, durable binder matrix within the topology-optimized structure. Using industrial by-products like slags minimizes raw material use, supporting circular economy principles. Durability against freeze-thaw cycles, shrinkage, and corrosion-free performance will be assessed. Deconstructability of concrete structure enables reuse and recycling. A life cycle assessment will demonstrate CARBCOMN superiority over conventional concrete construction, highlighting its transformative potential. The paper will elaborate on the concepts of CARBCOMN and the first research results obtained.

**Keywords:** Sustainability; Carbon-negative material; Compression-dominant structures; Durability; Deconstructability

## INTRODUCTION

Greenhouse gas (GHG) emissions from material extraction, manufacturing of construction products, as well as construction and renovation of buildings are estimated at 5-12% of the global GHG emissions [1]. Huge amounts of GHG are emitted during concrete production mainly because of the high calcination temperatures needed to produce cement clinker (about 40%) and to decarbonize the limestone (about 60%), which in total accounts for about 8% of global $CO_2$ emissions. Also, 1 $m^3$ of concrete requires 2,6 tons of construction minerals, that vastly contributes to about 50% of all extracted material dedicated to the built environment [2]. This is why concrete, as we know it today, is one of the most relevant construction materials that needs to be reconsidered in terms of carbon footprint, raw materials usage, structural usage and architectural design, to lower its high impact and turn it into a sustainable and renewable commodity for the construction sector [3]. Currently, emerging climate-neutral concretes and applications are being scrutinized on a global scale but generally fail to have a full net-zero-carbon impact, because they bring partial and mostly fragmented solutions that cannot stand up to the technical demands of AEC. *CARBCOMN will drastically change this by pursuing a future vision for load-bearing concrete buildings and infrastructure, through an integrated digital pipeline enabling a new structural system (Fig. 1a) that has unprecedented circularity features*. The project will do this by combining (i) carbon-negative concrete through carbon mineralisation, (ii) zero primary raw materials for making the concrete, (iii) compression dominant structures that are immune to rebar corrosion and become intrinsically more durable, (iv) automated manufacturing of geometrical shapes that largely reduce material consumption, (v) discretised blocks that allow deconstruction and reuse of the entire structure, (vi) shape memory alloy to improve system redundancy, and (vii) life cycle assessment (LCA) integration in the form optimised structural design of this decarbonised and deconstructable concrete load-bearing elements. This combination of features *requires a new digital AEC design paradigm* as it cannot be achieved with the current design and fabrication methodologies for reinforced and prestressed concrete structures.

In fact, RC structures generally consist of moment-resisting frames, which implies that (i) concrete should be cracked to work and (ii) a significant amount of steel reinforcement is requested. This means that, from a conceptual design point of view, concrete is not employed in the most congenial and efficient way, which, among other things, results in a significant environmental impact for concrete structures. Measures currently under investigation to reduce the GHG emission associated to RC structures mainly act at the material level, as they either propose concrete mixture compositions with recycled constituents [4] and alternative binders (such as alkali-activated materials or geopolymers) [5] or figure out the possibility to replace the use of concrete with other supposedly more sustainable materials, such as timber or bamboo [6]. All these measures can certainly lead to an "incremental" innovation, which is limited by the actual availability of those alternative materials [7].

The CARBCOMN overall objective is to formulate on the one hand a digital twin composed of a digital pipeline (further described in WP5), and at the other hand its physical counterpart involving the above-described alternative design-to-fabrication technique based on employing carbon-negative concrete in innovative structural concepts intended for unleashing their potential for building and construction. More specifically, this disruptive innovation for the construction sector is targeted by combining a comprehensive research effort and innovation activity addressed by specific objectives (OB1-7):

- OB1. Optimising the LCA-based *$CO_2$ sequestration capability of a carbon-negative concrete* that is manufactured with carbonatable by-products (slags and ashes, excluding over-utilized secondary cementitious materials such as blast furnace slag and coal fired fly ash) and recycled/secondary concrete aggregates: the target is to i) use 0% primary raw materials and raise the current level of 5 $kgCO_2$/ton [8] to 10 $kgCO_2$/ton of concrete;
- OB2. Optimising the reactivity-based *mix design and pore structure of the carbon-negative concrete,* with the aim to achieve complex forms manufactured by extrusion-based 3D printing that remain suited for carbon mineralisation;
- OB3. Adapting *advanced computational structural design methods* (limit analysis, 3D graphic statics, Discrete Element Modelling, Finite Element Analysis, topology optimisation, joint design) for discrete structural geometries that are particularly fit for the aforementioned materials and use [9];
- OB4. Exploiting digital design and fabrication methodology (e.g. through extrusion-based 3D printing) to realise discrete blocks according to OB1-2, with the aim of assembling structures designed as in OB3 establishing a *robust and replicable computational pipeline from design-to-fabrication*;
- OB5. Evaluate the *structural safety* under static and seismic actions of the CARBCOMN load-bearing carbon-neutral concrete structures and understanding how *self-prestressing with shape memory alloy* (SMA) can enhance the capacity;

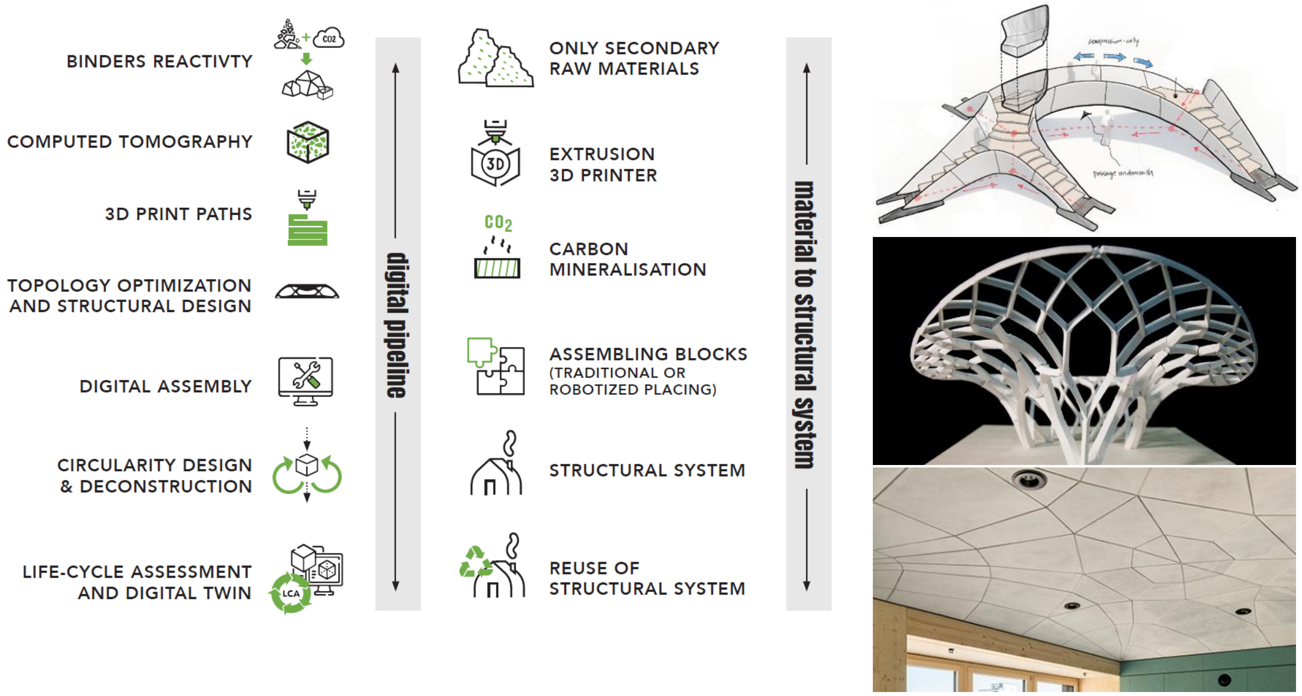



**Fig. 1–Envisioning decarbonized and deconstructable compression dominant structures through robust design-to-fabrication digital pipeline (left), scale model examples and example of funicular floor system (right).**

OB6. Defining scenarios and demonstration cases for the *proof-of-concept* of the CARBCOMN technological solution;

OB7. Exploring the future exploitation potential of the results in collaboration with other portfolio projects and disseminate information on the project result.

Fig. 1 proposes an overview of the main steps included both in the digital pipeline and CARBCOMN system, and it also depicts three relevant application of compression dominant structures realised or figured out for a pedestrian bridge, an outdoor canopy and an indoor floor system where the combination of curved geometry and post-tensioning ensure equilibrium and stability.

CARBCOMN is a collaborative project financed by the EU as part of the EIC-Pathfinder-Challenge 2023 call. The partnership consists of eleven beneficiaries, each one represented by one co-coauthor of this paper; the project started in October 2024 and is based on a 4-year work programme intended at achieving the objectives listed above.
The present paper aims at pointing out the general ideas behind the CARBCOMN project initiative

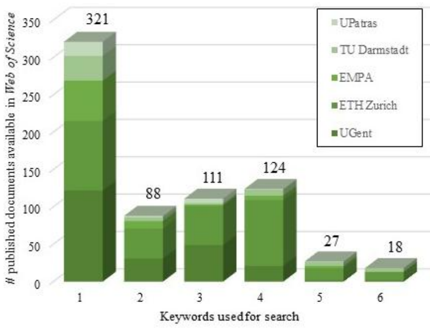
## RESEARCH SIGNIFICANCE

CARBCOMN aims at realising an innovative decarbonized construction system for load-bearing concrete structures, which can revolutionize the current practice in the construction sector through a cross-scale innovation (carbon-negative materials avoiding natural resources, topology optimized structures composed of discrete geometries, design-to-fabrication digital pipeline, adapted for circularity through reuse, etc.). The construction system focuses on compression dominant stress states, so to utilize the concrete at its strongest stress resisting state, make it intrinsically more durable by being no longer susceptible to reinforcement corrosion (which is the main cause of deterioration of concrete structures), and to be more compatible with extrusion-based 3D concrete printing (that cannot easily integrate embedded tensile reinforcement).

## CONSORTIUM COMPOSITION AND ROLE IN THE PROJECT IMPLEMENTATION

The CARBCOMN consortium partners have the background knowledge and starting expertise to realize these technical breakthroughs. The academic partners are very active in research and development activities about subjects of relevance for the present project proposal. This can be demonstrated by looking at the current scientific literature. More specifically, a search on Web of Science using the search terms as listed in Fig. 2 shows that previously the

CARBCOMN consortium has published over 700 journal papers. These relate to sustainable concrete formulations, life cycle analysis, additive manufacturing and digital fabrication, compression dominant structure, SMA and digital pipeline construction. Although the absolute number varies between these search terms, the consortium has already produced a significant number of papers published on the prior art that will be at the basis of the novel CARBCOMN system. Moreover, the industrial partners are frontrunners and experts in key aspects of the required background knowledge, such as related to carbon-negative concrete (Orbix), SMA (re-fer), additive manufacturing (in3d), structural safety and sustainability of concrete construction and deconstructable systems (TESIS), digital pipeline (ZHA) and sustainable design including compression dominant structures (MCA).




| Keyword n° | Used Keywords in Web of Science | # hits |
|---|---|---|
| 1 | Sustainable Concrete OR Alkali-activated Concrete OR Alternative Binder Concrete OR Supplementary Cementitious Materials Concrete OR Geopolymer Concrete | 20445 |
| 2 | Life Cycle Analysis AND Concrete | 3707 |
| 3 | Additive Manufacturing Concrete OR 3D Printed Concrete OR 3D Printing Concrete | 2229 |
| 4 | Digital Fabrication Concrete OR Digital Design Concrete OR Digital Design and Fabrication Concrete | 1819 |
| 5 | Compression Dominant Structures | 1285 |
| 6 | Digital Pipeline Construction OR Digital Twin Construction | 1071 |

**Fig. 2–Research output of CARBCOMN academic partners for specific search terms used in Web of Science.**

## NOVELTY WITH RESPOCT TO RELEVANT STATE-OF-THE-ART

The CARBCOMN approach goes far beyond this state-of-the-art and will have a *disruptive effect on this current practice in construction*, with significant reduction in GHG emissions for the whole sector [10]. In fact, the majority of buildings are made of reinforced concrete, with a marked prevalence of cast-in-situ structures with respect to precast ones [11]. The CARBCOMN concept implies a radical change in how constructions are built. Recollecting shapes and experiences from the past architectural knowledge, it relies on the use of modern digital fabrication tools and computational design platforms to realise structures which are made (i) of a carbon-negative material, (ii) employing the minimal quantity of materials and (iii) are constructed by using dry-joint unreinforced blocks assembled into deconstructable compression dominant structures.

Given its environmental impact, the scale of demand for sustainably sourced, produced and exploited concrete structures [12]. Making the concrete construction sector more durable will require more drive and courage, as becomes clear from various non-binding initiatives that emerge, such as the Alliance for Low-Carbon Cement & Concrete (alliancelccc.com).

Moreover, based on the taxonomy proposed by the 2023 AEC Challenge of the EIC Pathfinder Programme, the CARBCOMN project is broadly transversal with respect to the proposed triad of computational design, digital fabrication and materials. As already highlighted above, it falls in multiple of subcategories of the AEC triad, of which the 3 main ones are as follows:

- Topology optimisation (category “Computational design”) is needed to select the optimal configuration of the compression dominant structures in view of meeting the safety/functionality requirements, utilising as less material as possible while being deconstructable.
- AM: extrusion-based printing (category “digitalized fabrication”) that is of key importance to tailor the shape of the carbon-negative blocks and to match performance-based material design.
- Discrete blocks made of LCA-driven carbon-negative concrete (category “Materials”) that are architectured in geometry and material properties to be fit for durable and sustainable load-bearing concrete structures composed of deconstructable compression dominant elements.

## BACKGROUND AND PRELIMINARY RESULTS

Several studies (among which by partners UGent and Orbix) have been recently proposed with the aim to formulate *carbon-neutral (net-zero) or even carbon-negative concrete* [13]. These studies, which are quite often in a germinal stage, are based on exploiting various chemical reactions or physical phenomena (e.g. concrete with seawater-derived magnesium feedstocks[14], silane-modified recycled powders[15], washout water and biochar[16] or even natural enzymes[17]) with the aim to unleash the carbon capture process. The carbon-negative concrete solution *through carbon mineralisation* is obtained by applying a Portland cement free mixture of carbonatable secondary raw materials, such as fine powder of stainless-steel slags, that is cured through exposure to $CO_2$ in a carbonation curing chamber[18][19]. Although these materials are nowadays introduced on the market[20], this is only the case for simple applications, such as paver blocks[21] or hollow bricks in artificial masonry constructions[22], and produced through relatively traditional processes (e.g. moulding and pressing). Although sufficiently high in compressive strength, this carbon-negative concrete is regarded not suitable for load-bearing concrete structures, because of not being compatible with traditional steel reinforcement that is susceptible to carbonation-induced corrosion. This will be tackled by CARBCOMN through digitalisation in design-to-fabrication, (i) to make the internal material structure more receptive to the carbonation process, (ii) to avoid massive elements that are hard to carbonate, (iii) to avoid internal steel rebars that are the main cause of deterioration through carbonation-induced or other forms of corrosion, and (iv) to use extrusion-based 3D printing to realise structural geometries with high surface-to-volume ratio (for further improvement of the carbonation process) and increased complexity (to suit as building block within the assembled compression dominant structure).

Combining a negative-emission material with *extrusion-based printing of 3D building blocks* will allow to bridge the "gaps" affecting the current practice. The carbon-negative building blocks consisting of multiple extruded layers will be aimed at increasing the surface-to-volume ratio to maximize the surface available for the $CO_2$ sequestration process. Moreover, as for common extrusion-based 3D printed cementitious materials[23] (as previously research by partners UGent and in3d), the inclusion of reinforcement faces a serious production issue that is hard to overcome. In contrast, for *compression dominant structures*, the need to place reinforcement does not exist and will lead to a real breakthrough in this field. Project partners (ETH, EMPA, re-fer) have already explored the potential of compression dominant structures:

(i) funicular discretised compression-only structures characterised by superior structural efficiency with respect to the widely adopted moment-resisting frame systems mainstream in today's practice, because of the geometry-induced compression-dominant stress state[24], and

(ii) (ii) post-tensioned segmental members with mechanics-induced compression-dominant stress state, especially realised by adopting an innovative post-tensioning system based on the use of iron-based shape-memory alloys (Fe-SMA) [25]. To handle these complex systems[26], CARBCOMN will employ *digital design-to-fabrication techniques*, among which computed tomography, topology optimisation and discretisation, extrusion-based 3D printing. Experiences, by partners ETH and ZHA, with such a digital pipeline have been made open source.

As the CARBCOMN carbon-negative material is intrinsically used to manufacture *discrete blocks*, they could be conveniently handled by industrialised automation tools, whose main features will be unravelled as part of this research project. In this regard, the possibility to come up with *deconstructable building systems*[27] whose members can be reused is a further frontier for the structural system under consideration. In this respect it is important to use 'dry joints' (no mortar connection between the joints), such as e.g. Fig 3. Partners Re-fer and TESIS have already cooperated in developing a deconstructable flat-slab concept[28]. TESIS is working further on deconstructable recycled aggregate concrete systems as part of a recently granted EU-project[29]. Such discretised and deconstructable structural systems remain yet unexplored from a decarbonized building perspective and faces the challenge of a *shift in engineering thinking from material induced structural ductility to system redundancy*.

**Fig. 3–Dry joint between blocks.**

In this respect, the use of *SMA post-tensioning* represents a highly innovative solution to realise structural systems by assembling discrete elements. Their suitability for real engineering structures was recently proven[30] by partner EMPA and their spin-out company Re-fer. Industrial production of a low-cost iron-based SMA (Fe-SMA) was scaled up to more than 50 tons. Leading material suppliers in Europe (such as Sika and Hilti) have also shown interest in these alloys and have participated in the execution of real demonstrative retrofitting projects[31]. Recently, the SMA technology was also explored (ETH, EMPA, Re-fer) for discrete helicoidal stair steps (Fig. 4). In CARBCOMN, Fe-SMA bars will be used for the first time to join and prestress the discretised carbon-negative blocks. This is particularly suited in those cases where compression dominant conditions cannot be fully achieved by finding a proper geometric form. The SMA post-tensioning will allow for a post installation after the assembly of the parts. The tensioning is achieved by 'resistive heating', also referred to as 'self-prestressing' given this easy prestressing method. Furthermore, thanks to their high level of ductility (owing failure strain above 30 %), they will bring ductility (and increased robustness) to the system, e.g. when horizontal actions are significant like in the case of earthquake-prone areas[32] (partner UPAT).
A comprehensive strictly verifiable and quantitatively measurable *life-cycle analysis (LCA)* of the newly developed construction system as a whole, applied to decarbonized and deconstructable concrete buildings, and with emphasis on different construction systems[33], is cutting-edge research employed by various partners of this project (among which TUDMS, MCA).

**Fig. 4–Steps assembled with SMA (Empa, CH).**

## CONCLUSIONS

Enduring and beneficial impacts will be established by CARBCOMN that cover various trans-disciplinary aspects in science and society, as described in the following set of wider impacts.
The novel CARBCOMN structural system essentially starts from both the structural and constructional principles of masonry structures. Instead of using traditional engineering designs (based on simple brickwork and/or based on the combined function of rebars and concrete) and associated labor-intensive construction processes, CARBCOMN aims to make a disruptive use of modern and novel digital fabrication tools (such as extrusion-based printing of the 3D building blocks) and computational design platforms (such as discrete shape forming combined with topology optimization at system level) to realise concrete load bearing structures that are made of a carbon-negative material, possibly SMAs as reinforcement, employ minimal quantity of materials, avoid primary raw materials in concrete making, and facilitate circularity through deconstructablilty.
Moreover, the outputs of CARBCOMN align well with and allow for further development strategies in Design for Manufacturing and Assembly (DFMA) and Design for Disassembling (DFD), which addresses the urgent need for productivity improvement in the construction industry needed to improve competitiveness and to provide adequate housing in the next decades due to the increase of the population. Thus, prefabrication and smarter and faster-controlled delivery of on-site of building components becomes highly relevant.
Finally, CARBCOMN is not just an academic endeavour, but it will serve as a catalyst for the transformation of the AEC industry with several key impacts:

1. Socio-economic and skills advancement, by introducing digital prefabrication processes not only enhances skills levels within the construction industry but also redefines the role of humans in construction.
2. Integration, collaboration and competitiveness, by fostering collaboration, efficiency, and integration, leading to a more competitive and profitable business model;
3. Structural paradigms evolution and building codes, by playing a pivotal role in advancing engineering tools and paradigms, with the potential to shape future building codes and industry practices.

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