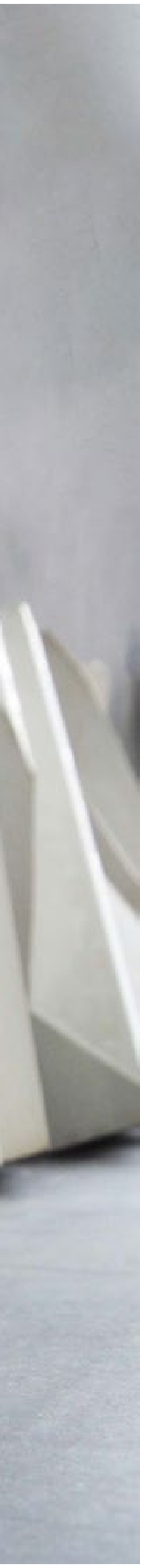
Fabio Amicarelli and Ena Lloret-Fritschi

Optimising Concrete Slabs with Paper Formworks



Fabrication and Material Aware Architecture (FMAA) group, Foldcast, Academy of Architecture, Università della Svizzera Italiana (USI), Mendrisio, Switzerland, 2022–4

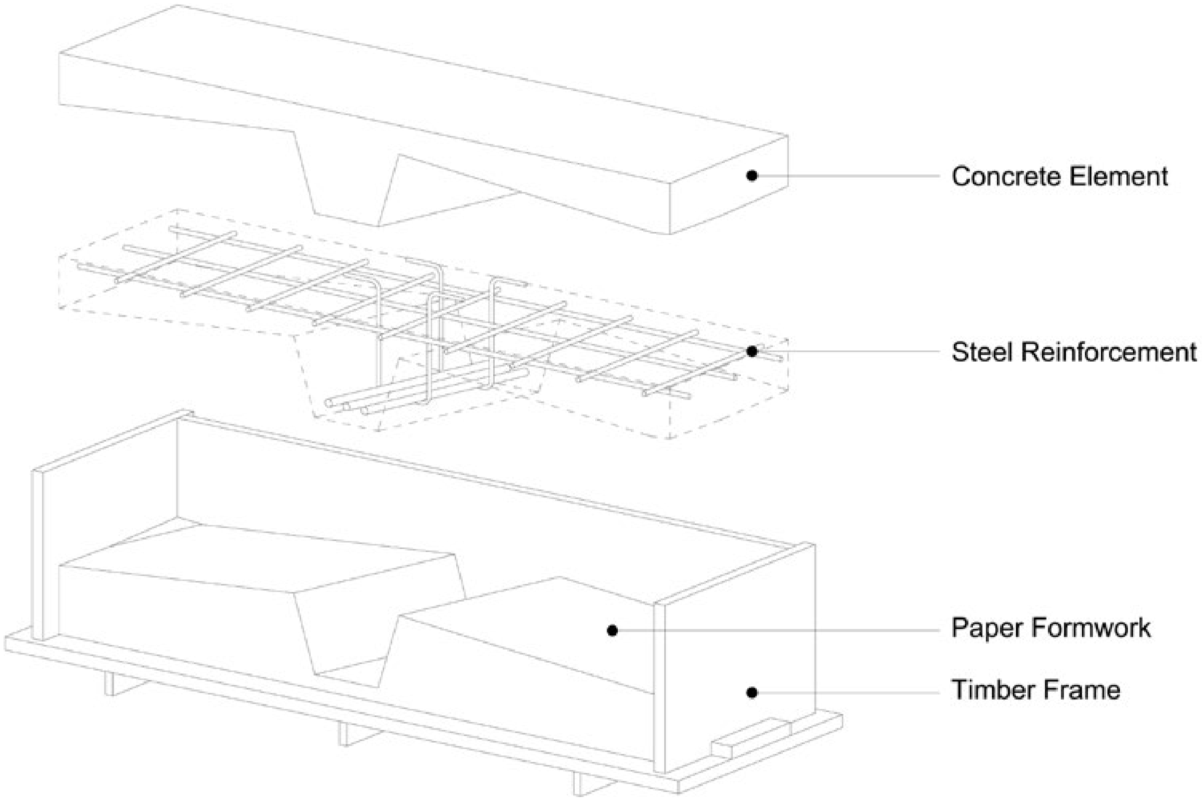
Design variations on scaled models. Paper is a low-cost and recyclable material, which can be three-dimensionally shaped according to predefined folding patterns. When used as material for formwork, this can enhance the design flexibility and variation of building elements, allowing the production of optimised structures with up to 50 per cent less concrete.

The constant demand for new buildings means concrete continues to contribute to a large proportion of global greenhouse gas emissions. Italian architect and researcher **Fabio Amicarelli**, and Assistant Professor in Architecture and Guest-Editor of this AD **Ena Lloret-Fritschi**, discuss the Foldcast project being developed by the Fabrication and Material Aware Architecture (FMAA) group at the Università della Svizzera Italiana in Mendrisio. Foldcast combines software and digital machines to produce non-standard, recyclable, paper-based moulds for casting structurally efficient concrete elements.

Concrete is by far the most commonly used material in construction, making the cement industry responsible for around 6 per cent of CO_2 emissions worldwide.[1] With the global population predicted to rise to nearly 10 billion by 2050,[2] the demand for buildings is expected to double over the next 40 years.[3] Concrete being the most durable construction material, we can assume that it will continue to contribute to a significant proportion of the world's greenhouse gas emissions.[4] A reduction in the material's use is urgently needed across the planet, and there are new structural optimisation methods that could notably reduce its consumption and enhance construction efficiency. These methods are, however, often prohibitively expensive to implement, particularly because traditional construction systems lack adaptability and struggle to accommodate variation.

In the early 1990s, the introduction of digitally controlled machines in architecture promised to produce countless design variations of the same object at no extra cost.[5] However, this potential has not been fully realised in the construction industry. Currently, digital technologies are continuing to push its boundaries, aiming to bridge the gap between standardised building processes and customised design. Still, even after 30 years of digital construction, the fundamental question remains: can digital fabrication processes enhance how we create non-standard building elements, enabling design flexibility and fostering more sustainable construction processes?

Foldcast is a research project started in 2022 as part of the Fabrication and Material Aware Architecture (FMAA) group at the Academy of Architecture in Mendrisio, within the Università della Svizzera Italiana (USI). It combines computational tools and digital machines to produce non-standard formworks made of paper-based materials. This approach enables the production of structurally optimised building elements, using significantly less concrete while adopting low-cost and fully recyclable formworks. Foldcast thus illustrates that it is possible to significantly reduce the carbon footprint of concrete structural elements and make construction processes more efficient and sustainable.



The Return of Structural Optimisation

Concrete is a resilient and versatile material that complies with nearly any desired shape when poured into a formwork. Formworks are typically constructed using wooden or metal panels and are essential for shaping uncured concrete and withstanding its pressure. Yet, to facilitate the use of such standard timber or metal formworks, slabs are often built with a uniform depth (flat slabs), using far more material than structurally necessary. Through such excessive use of concrete in structural elements, the construction sector has over the past decades favoured cost and time reduction over sustainability.

Posing an alternative, optimised systems like ribbed slabs employ about half the typical concrete volume by placing material only where strategically needed to ensure structural integrity. Ribbed slabs are flooring systems which consist of thin profiles and typically parallel reinforced concrete T-beams, and are usually produced by placing voids inside the formwork to reduce the bulk material of the slab and thus its weight. An early example is the

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Traditional construction systems use timber or metal panels to produce formworks. This results in expensive and labour-intensive processes when applied to optimised concrete elements. Foldcast employs digital technologies to design and manufacture custom formworks from fully recyclable paper, facilitating the creation of structurally optimised concrete structures. Shown here, an axonometry of paper formwork components.

Digital fabrication has the potential to produce flexible, non-standard formwork without notable additional costs, allowing customised concrete elements to be realised through industrial processes

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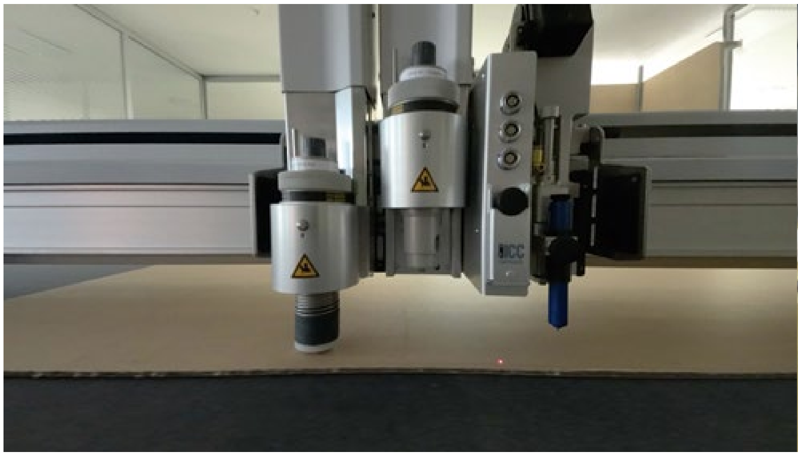
below and opposite bottom: The paper formworks are designed with custom software, pre-cut using digital machines, and manually assembled into a formwork for concrete casting. This technology reduces production time and costs of custom formwork, optimises the use of materials and resources and allows an easy implementation in existing building processes.

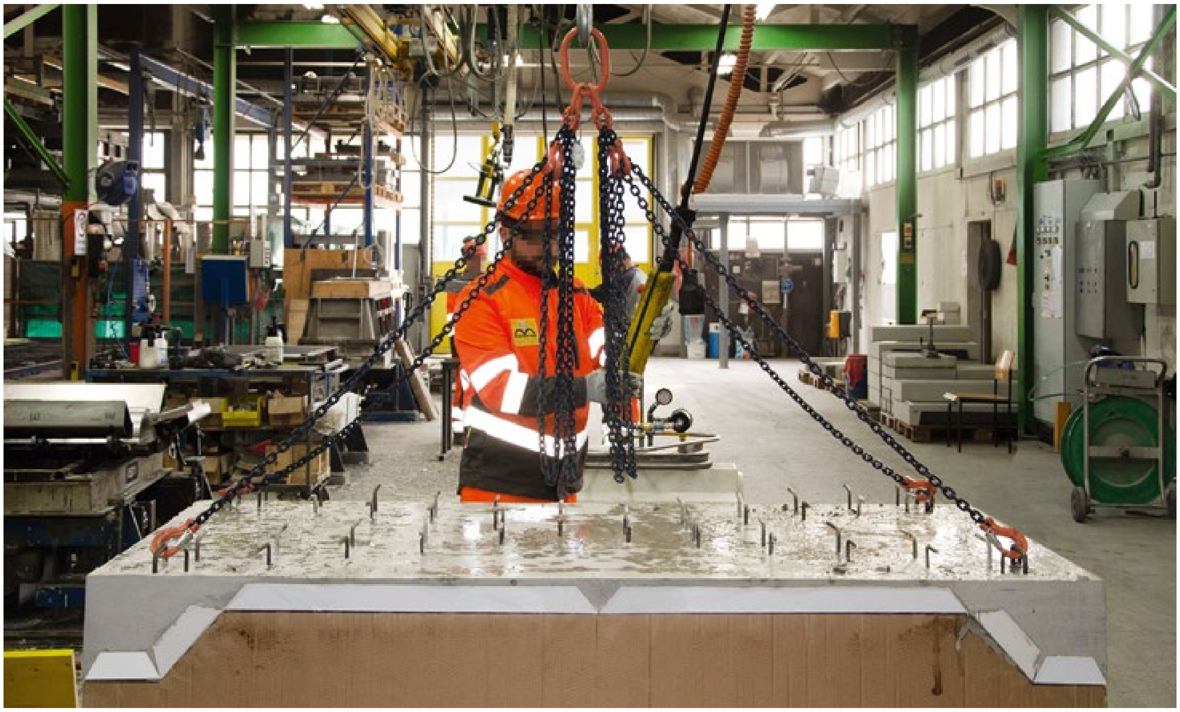


flooring system designed by Pier Luigi Nervi for the Gatti Wool Factory in Rome (1953), in which the curved ribs follow the principal bending moments of the floor.[6] Despite such benefits, ribbed slabs have still been sidelined, due to concerns about construction time and the cost of non-standard formwork made with timber or metal panels.[7]

Recently, digital design and fabrication processes have enabled the development of new methods to produce structural concrete elements with non-standard geometries, customised for individual requirements, without any notable influence on construction cost and time. These methods have thus made such structurally optimised concrete elements economically viable as a sustainable solution.

Improving Non-standard Concrete Formworks

Prefabrication involves the manufacturing of building components off site in an industrial setting. These elements are then transported to the construction site and assembled. Prefabricated building components have served as an alternative to on-site construction, improving efficiency, reducing waste, and ensuring higher-quality results in a safer environment. However, the modern-day paradigm of prefabrication is most suitable for the mass-production of standardised elements and is often associated with uniform and repetitive architecture. In this context, it is challenging to incorporate more complex, custom shapes such as those that are typically necessary for optimised structures. In the case of prefabricated concrete elements, the lack of flexibility



above: After the concrete hardening time, the wax-coated paper can be easily removed and fully recycled. A reusable paper-based supporting structure ensures that the formwork withstands the weight of the concrete.

is due to the high cost and time necessary to produce traditional formworks, which only become economically viable when reused several times. The inefficiency of producing variable structures often prevents designers from adopting non-standard systems.

Today, the most common method of creating non-standard formwork is to produce voids or inlays – usually made of expanded polystyrene (EPS) foam – that are then placed into standard scaffold systems and used for concrete casting. Although this method allows a wide range of forms to be created, the manufacturing process used to shape EPS generates substantial waste, as large quantities of material must be removed to produce the formwork.[8] Over the last two decades, academic researchers and industry have thus investigated how to improve non-standard formwork, using emerging technologies and testing new fabrication methods and materials. Digital fabrication has the potential to produce flexible, non-standard formwork without notable additional costs, allowing customised concrete elements to be realised through industrial processes. This paradigm shift opens up new design possibilities that embrace variation and differentiation over standardisation and repetition, while still taking advantage of the efficiency of industrial processes typical of prefabrication. In the bigger picture, the combination of non-standard formwork with off-site construction can thus reduce building costs and time, offer a wider range of architectural design options, and promote sustainable construction by saving materials and resources.

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right: The flexibility of paper formworks creates new design opportunities that value variation and uniqueness over standardisation. Supported by custom computational tools, architects and engineers can investigate a large variety of structural forms previously hard and expensive to build – such as this ceiling.

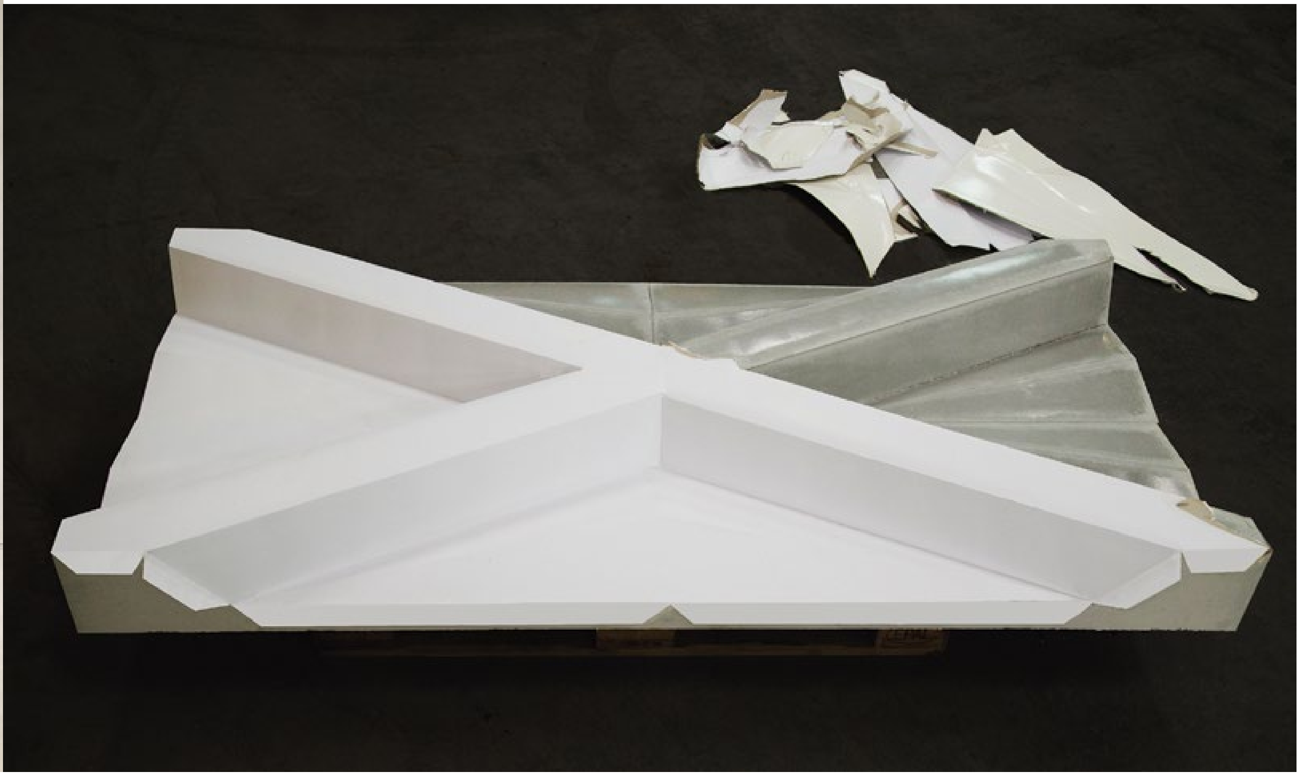
opposite: A 1:1-scale concrete slab element was produced in a research project involving researchers at the USI, University of Applied Sciences and Arts of Southern Switzerland (SUPSI) and Eastern Switzerland University of Applied Sciences (OST Rapperswil) along with industry partners Müller-Steinag Gruppe. From subsequent analysis and testing, it emerged that the prototype reduced the carbon footprint by 40 per cent overall compared to standard flat slabs made with timber formwork.

Paper Formworks for Concrete Elements

The Foldcast research project employs digital technologies to produce paper-based formworks, enhancing the structural optimisation of concrete elements. Leveraging paper, an affordable and widely available material with inherent ductility, the project emphasises sustainability by offering a fully recyclable solution. Through the precise folding of paper sheets based on designated patterns, intricate three-dimensional optimised geometries can be achieved with remarkable simplicity. The integration of custom computational tools and digital cutting machines is a key aspect of this approach, promising to significantly reduce fabrication time and costs associated with non-standard concrete formworks. In comparison to traditional custom timber or metal formwork, the paper-based alternative stands out for its sustainability – being lightweight, easily shaped, fully recyclable and effortlessly transportable. This innovation seeks to redefine construction practices by providing a more efficient and eco-friendly solution.

The fabrication process starts with the digital design of optimised concrete structural elements using custom computational tools that automatically generate a folding pattern to produce the corresponding paper formwork. The folding pattern, as a file format, is used to pre-cut flat sheets of paper with a digital machine. The pre-cut paper is then shipped to the prefabrication plant, where it is manually folded into a three-dimensional formwork inlay, placed into reusable scaffold systems and used for concrete casting. A waterproof coating and a paper-based supporting structure make the formwork resistant to the concrete pressure and humidity. After the curing, the formwork can be removed, and the paper can be reused or fully recycled. The final concrete elements produced with this method are designed to use up to 50 per cent less concrete than standard flat slabs, while fulfilling the same structural requirements. To ensure that the elements are code compliant, standard reinforcement steel and concrete mixes can be used.

The paper formwork technology has been developed through several preliminary tests that were intended to provide information to the custom computational tool that designs the paper components. A large-scale prototype of a structurally optimised concrete slab has been built as a collaboration between academic researchers at the USI, University of Applied Sciences



and Arts of Southern Switzerland (SUPSI) and Eastern Switzerland University of Applied Sciences (OST Rapperswil) and industry partners Müller-Steinag Gruppe. To further reduce the embodied carbon of the slab, the paper formwork was used in combination with a recycled concrete mix. Subsequent analysis showed that the prototype reduced the carbon footprint by 40 per cent overall compared to standard flat slabs made with timber formwork.

Design Variation and Sustainable Construction

Foldcast represents a material- and cost-effective strategy that significantly reduces the carbon footprint of concrete structures while allowing design flexibility and customisation. Enabled by custom computational tools, architects and engineers can explore a wide range of structural shapes that have until now been difficult to conceive and produce. Such tools empower designers with early-stage decisions that enhance structural and fabrication data, while making the production of non-standard formwork more efficient. The technology integrates innovative approaches into existing construction processes, aiming for easy implementation within the industry. Considering the number of buildings to be constructed in the near future, it is essential to pursue solutions that can streamline the construction processes, elevate the quality of architectural design, and contribute to moving the building industry towards a more sustainable future. AD

Notes

1. UN Climate Change, 'Bigger Climate Action Emerging in Cement Industry', 26 October 2010: https://unfccc.int/news/bigger-climate-action-emerging-in-cement-industry.
2. UN Department of Economic and Social Affairs, *World Population Prospects: The 2017 Revision*, United Nations (New York), 2017: https://population.un.org/wpp/publications/files/wpp2017_keyfindings.pdf.
3. International Energy Agency, 'Global Building Sector CO_2 Emissions and Floor Area on the Net Zero Scenario, 2020–2050': www.iea.org/data-and-statistics/charts/global-buildings-sector-co2-emissions-and-floor-area-in-the-net-zero-scenario-2020-2050.
4. Architecture 2030, 'Why the Built Environment?': www.architecture2030.org/why-the-built-environment/.
5. Mario Carpo, *The Alphabet and the Algorithm*, MIT Press (Cambridge, MA), 2011, pp 98–9.
6. See Pier Luigi Nervi, *Costruire Correttamente*, 2nd edn, Ulrico Hoepli (Milan), 1965, pp 41–4.
7. Jaime Mata-Falcón *et al*, 'Digital Fabricated Ribbed Concrete Floor Slabs: A Sustainable Solution for Construction', *RILEM Technical Letters* 7, 2022, p 71.
8. Ena Lloret-Fritschi, 'Smart Dynamic Casting: A Digital Fabrication Method for Non-standard Concrete Structures', doctoral thesis, ETH Zurich, 2016, pp 33–4: www.research-collection.ethz.ch/handle/20.500.11850/123830.