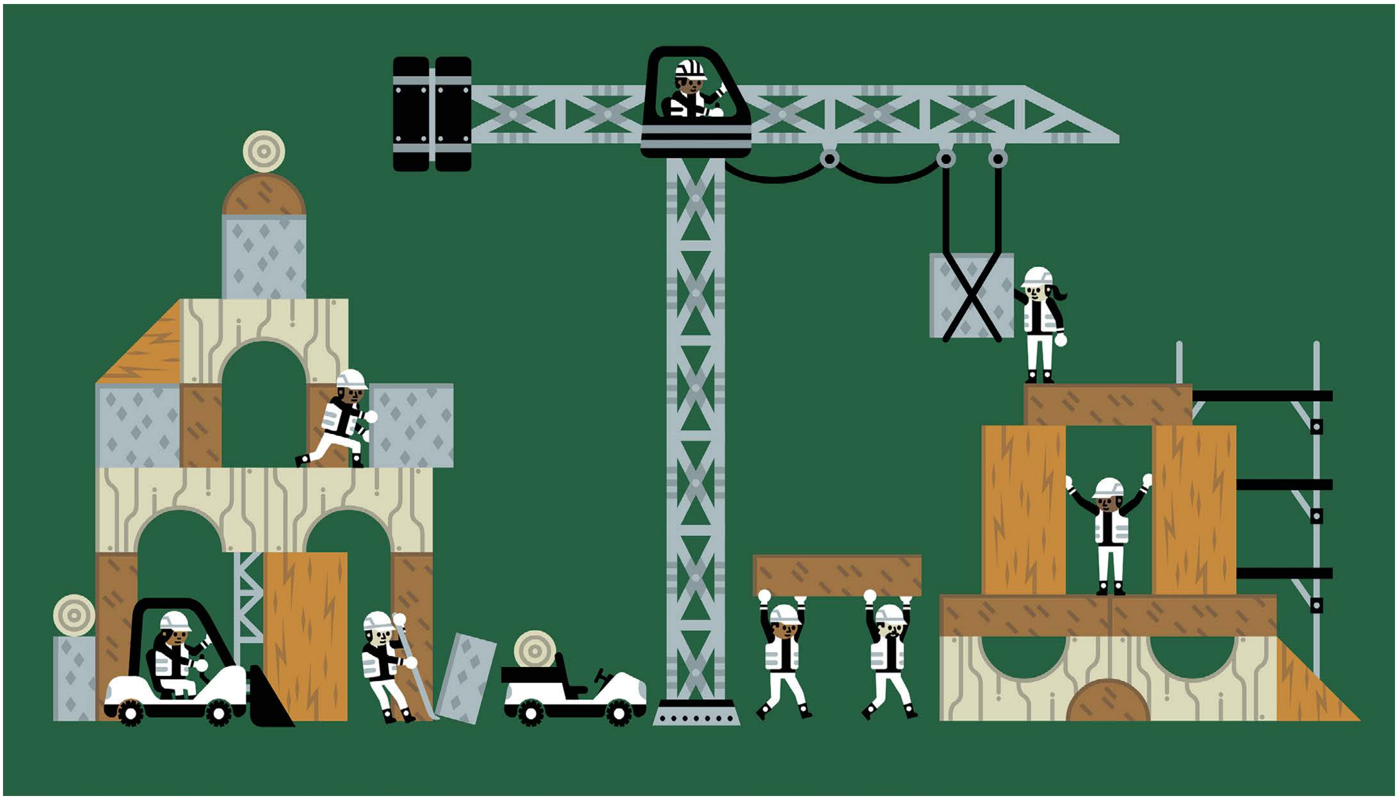

ILLUSTRATION BY JAN KALLWEJT

Greener buildings

The built environment provides a huge opportunity to move to a circular economy. Standardization, along with smart design and implementation, will be key to enabling the shift. **By Katharine Sanderson**

Our built environment – from houses to offices, schools and shops – is not environmentally benign. Buildings and the construction industry are, in fact, the world's biggest consumer of raw materials and contribute 25–40% of global carbon dioxide emissions (F. Pomponi & A. J. Moncaster *Clean. Prod.* **143**, 710–718; 2017). Making buildings part of a circular economy that minimizes the waste of materials could therefore yield huge environmental rewards. Conversely, failure on this front could have dire consequences.

"Buildings can, and must, work in a circular way," says Francesco Pomponi, who studies the built environment at Edinburgh Napier University, UK. "Otherwise, there's no way out of the climate crisis."

Take concrete, made by mixing gravel, cement and water. It is the world's most widely used building material, yet it is also a huge carbon source, accounting for up to 8% of global human-made carbon emissions. Cement, more than four billion tonnes of which are made each year, is the biggest contributor. Its production requires limestone (primarily composed of calcium carbonate) to be heated to yield lime (calcium oxide). The reaction releases CO_2, and yet more CO_2 is produced by fuel combustion to generate the heat.

Buildings as a positive force

Across the globe, engineers, construction companies and architects are beginning to embrace and apply the circular model. There are ample opportunities to improve the materials that are used in construction, to introduce circular design principles so that those materials can be properly repurposed, and – even more ambitiously – to create buildings that make a positive contribution to climate and biodiversity. But much work needs to be done if those huge contributions to emissions are going to come down. And come down they must – fast.

Innovations in materials could help to make concrete a more sustainable option. Adding graphene – a 2D form of carbon – into the mix, for example, might improve the environmental footprint by strengthening concrete and thus reducing the amount needed for a particular application. Sprinkling it into concrete could bring enormous benefits, according to Nationwide Engineering, a company based in Amesbury, UK, that developed this mixture, called Concretene, in collaboration with researchers at the University of Manchester, UK. The first building to benefit from Concretene was a gym in Amesbury in May 2021, which had a new floor laid using the material.

Concrete could even become a carbon sink. CarbonCure, a company based in Halifax, Canada, has developed a technology that adds captured CO_2 into concrete. The CO_2 reacts with the calcium in the mixture to form calcium carbonate, a mineral that the company says adds strength to the concrete as well as locking in carbon.

Concrete is already commonly repurposed — waste concrete is crushed up to form recycled concrete aggregate (RCA), which can then be used to make new aggregate. But RCA tends to be used in low-tech applications, such as filling in roads. This reduction in the quality and value of concrete doesn't fit well with a fully circular economy.

CarbonCure is developing a new type of RCA that can be used in buildings. Sean Monkman, who heads technology development at the company, says that the same CO_2-injecting technology, and subsequent mineralization, can be applied to RCA as well as freshly made concrete. Another company, Blue Planet Systems, based in Los Gatos, California, has developed an RCA made from recycled waste concrete and incorporating captured CO_2.

At the Georgia Institute of Technology in Atlanta, the Kendeda Building for Innovative Sustainable Design uses CO_2-storing concrete as one of a suite of sustainable innovations. The Kendeda project was built as part of the Living Building Challenge (LBC), a programme that allows the designation 'living building' to be applied to construction projects that meet a range of criteria, from responsible water use to sourcing materials that eliminate waste. The programme aims to provide an incentive for buildings to generate energy, produce their own water and give back to nature more than they take, says Kendeda Building director Shan Arora. There are 83 certified Living Building projects globally, with another 241 projects registered to pursue certification.

In trying to meet the LBC criteria, the Kendeda construction team salvaged materials by using local labour to intercept them as they were about to reach landfill sites, and then turned them into suitable feedstock. "During the construction process, the Kendeda Building diverted more waste from the landfill than it sent to the landfill," says Arora.

The LBC project is hugely ambitious. "I view the LBC as a sort of holy grail for regenerative building design," says Nick Jeffries, who specializes in building innovations at the Ellen MacArthur Foundation, a charity based in Cowes, UK, devoted to furthering the circular economy.

There are less ambitious, but still useful, steps that can be taken alongside more holistic and demanding projects. In a rapidly warming climate, even windows can make a difference. In 2010, the iconic Empire State building in New York City underwent a radical refit, including an upgrade to all of the skyscraper's 6,514 windows. The existing panes, rather than being ditched, were each taken out, and the gap in the double glazing was filled with an insulating gas — a mixture of argon and krypton. In addition, each pane was coated with a light-filtering clear film. These films, developed by scientists at the Massachusetts Institute of Technology's Lincoln Laboratory in Lexington in the 1970s (J. C. C. Fan *et al. Appl. Phys Lett.* **25**, 693; 1974), and now sold by the Eastman Chemical Company, headquartered in Kingsport, Tennessee, use nanometre-sized metal particles to reflect heat. The refurbished windows resulted in the Empire State Building consuming 40% less energy. Similar refits in other buildings will be crucial in a transition to circular construction, says Jeffries.

Dismantling the problem

In a circular economy, Jeffries says, "Buildings should be built like Lego. You should be able to disassemble them and reuse the structural elements."

Pomponi agrees that design is key, and that applying existing techniques thoughtfully can allow for buildings to incorporate such flexibility. For example, rather than welding steel frames together to form the skeleton of a building, bolts can be used instead. "This enables much easier disassembly when the useful life comes to an end, and much easier reuse of the structural section," Pomponi says.

"Even when materials with a low environmental impact are used, a building can be designed in a non-circular way," says Caroline Henrotay, a former coordinator of the Buildings as Materials Banks project (BAMB), a Horizon 2020 innovation project funded by the European Union. If materials are, for example, glued together, Henrotay explains, "it will be more difficult to create clean fractions for high quality recycling at the end of life".

Such mechanical construction approaches are key to Wikihouse, a BAMB-supported UK project that provides the open-source design for blocks that can be cut locally from birch plywood, allowing buildings to be assembled by slotting the pieces in place as in a jigsaw puzzle, and to be taken apart again easily. The approach has been used to build places such as libraries across the globe and houses in Almere, the Netherlands.

This kind of reuse has an ancient legacy, says Jeffries. "The theatre of Marcellus [in Rome] is still going after 2,000 years," he says. "It was used even as a quarry to build local bridges and roads. It was really a material bank for future buildings."

One modern-day tool to keep track of the components of a building — and ensure that they can be reused in a meaningful way — is a 'materials passport'. This document contains a detailed inventory of what materials were used, plus any data to do with safety or the origin of the material. With all this data collated, the components become a useful commodity at the end of that building's life. A materials passport makes it easy to design a follow-up building, because the component specifications are known exactly in advance. The passport, Jeffries says, "acknowledges that the material exists in a particular structure, and then identifies the most useful future destination". He points to an example of a building with such a passport that has already been dismantled for reuse: the Temporary Courthouse Amsterdam, which was moved to a business park outside the city of Enschede in early 2022 to become an office building.

Coordinated material tracing

A number of start-ups are emerging to offer materials-passport services, but this could lead to confusion in future. The LBC has a vision that is broader than simply having a materials passport, says Arora. The LBC also has a growing list of unsafe materials, the Red List, that must be avoided, such as asbestos, formaldehyde and chlorinated polymers, because they are damaging to human and environmental health. To be permitted in an LBC building, materials need to be listed and accounted for and also meet specific criteria. Given the range of ongoing projects, ambitions and definitions around the circular economy for buildings, its global adoption will take time. "I'm still figuring out who owns the circular-economy transition," says Pomponi.

Wholesale take-up of circular-economy practices will require enough decision makers to think not only that such measures will help the planet, but that they will be economically feasible. "We need everyone. We need the Apples, the Googles, the Microsofts of the world to prove that this can be done," Jeffries says. With more than 200 companies in the Ellen MacArthur Foundation's network, Jeffries wants to see them move beyond the shorter-term goals. "We can go beyond doing less harm," he says, and progress to the more affirmative goal of "reducing the materials we use, reducing emissions, reducing the waste generated, to buildings actively cleaning the air, providing habitats for wildlife".

Such ambitious advances in building design and construction will be essential to a sustainable global economy. Ultimately, the buildings that shelter and protect humanity will need to do more than offer a roof over our heads: by embracing innovative methods and materials, buildings could become a solution to the climate catastrophe that humans have invited.

Katharine Sanderson is a science journalist based in Cornwall, UK.