Circular construction

Six key recommendations

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Commentary

Circular construction: Six key recommendations

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In terms of mass, construction materials and construction and demolition waste make up the largest part of humankind's material and waste footprints, particularly after an energy transition has largely phased out fossil energy. However, a circular use of building and construction materials is fraught with challenges.

Humans used almost 92.8 Gt of materials in 2015, of which 84.4 Gt were extracted from nature and only 8.4 Gt were recycled. Fifty percent of this so-called global "material footprint" consists of construction minerals: sand, gravel, clay, limestone, and other minerals, which are used to make bricks, cement, and other building materials.[1,2] But the use of materials in the building sector does not stop there. Large amounts of cement, steel, copper, and plastics are used in buildings and infrastructure too. The production of all these materials with, for example, cement kilns and blast furnaces creates significant environmental impacts; they are responsible, for instance, for around 20% of the global carbon emissions, while local resource extraction can have significant biodiversity impacts or create water stress.[2] And what goes in, at some moment must come out; construction and demolition waste (CDW) from the built environment is also the most important source of waste by volume. Its treatment only adds to the environmental burden.

All of these problems could largely be avoided if the world would turn to circular material use in general and the built environment specifically. A circular economy would use materials as efficiently as possible, and keep them in use for as long as possible via the so-called "R" strategies as outlined in Figure 1.[3,4,5] Since the built environment uses 50% of all global material extraction, it is obvious that any country with circular economy ambitions will fail if the built environment does not become circular. Potential strategies include efficient design and production (R1, R2; such as building the same housing space with less material), more intensive use (R1; such as living in the same space with more people), building lifetime extension (R2, R3, R4; such as ensuring that a building can be used for different purposes according to needs over its lifetime), material substitution (R2; such as using low-carbon alternatives for cement and steel), component reuse (R3, R4; such as reusing window frames), and enhanced material recycling (R5; such as ensuring bricks can be reused as bricks instead of being crushed and used as foundation material).[6,7]

Circularity challenges in the built environment

Unfortunately, a circular economy is still far out of reach. Even in the EU, which probably has the most advanced resource efficiency and recycling policies globally, only 12% of all the 4.3 Gt of materials used annually currently come from secondary (i.e., recycled) sources.[2] With regard to the build environment, such large gaps between total and secondary material use are driven by three main factors.

First, what we can use as secondary materials is dictated by what has been built decades ago, and historically, buildings have not been built using circular principles. Therefore, many existing buildings are not fit for reuse or upgrading. Particularly in the office market, this can lead to premature replacement by more modern units better aligned with further developed changing esthetical and representation demands of users, leading to significant waste generation in the process. Similarly, construction elements (e.g., façade panels) in buildings have historically not been designed for reuse of either the components themselves or the materials they are made from.

Second, even in countries with high CDW recovery, waste management is still not fit for high-value recycling or reuse. The current CDW recovery rate of the EU-27 stands at 88%, which seems like a good number[8] (see Figure 2). But it is related mainly to the stony CDW fraction such as concrete, ceramics, and bricks, which is crushed and downcycled for road foundation and backfill rather than being used as building bricks again, or for the production of new cement. Furthermore, even where recovery rates are high, several EU-27 countries still landfill a sizable part of their CDW rather than recycling.[3]

Third, in most countries, the built environment is still expanding, requiring additional primary raw materials, even if CDW could be fully recycled for new building construction. In previous work, Deetman et al.[9] found that the expected material stocks of residential and service buildings in Europe will grow to approximately 46 Gt by 2050, accounting for 10% of the global building sector material stocks (see Figures 3A and 3B). Inflows related to new buildings and renovation in Europe will have stabilized at 900 Mt/yr after 2010 (Figure 3C). But the secondary material outflows initially are much lower and will only reach in 2050 a volume of 700 Mt/yr (Figure 3D). So only from 2050 it will be theoretically possible to cover material needs in the European built environment largely by secondary materials. Before that time, there is simply not enough

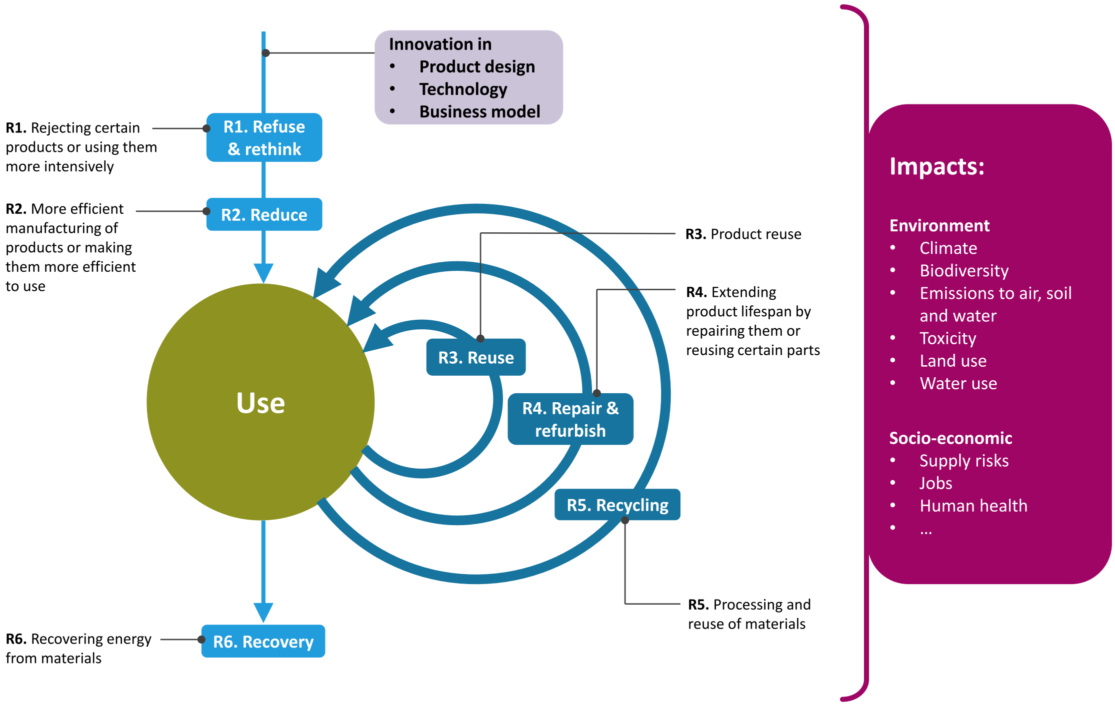

Figure 1. Circularity strategies and socio-environmental impacts

The left side of the figure shows so-called "R" strategies to reduce the inflow of primary raw materials in a product system, or the built environment, in our case. By this, the same primary materials are kept much longer in economic use. This is expected to have a beneficial effect on impacts mentioned at the right side of the figure, such as climate-related emissions, biodiversity loss, and reduction of supply risks. Combines Figures 1 and 3 from the summary of the Netherland Integral Circular Economy Report by PBL.[4]

secondary material available. Primary extraction is for quite some time still inevitable to cover the needs for new buildings and renovation.

Toward solutions for a circular built environment

Here, we propose six strategies to overcome the circularity challenges and facilitate a sustainable built environment.

Efficient design and production

This strategy implies using designs that limit material use, but more importantly, ensure that building components can easily be reused at the end of life of buildings. Lightweight design, such as using thinner interior walls or hollow bricks, can reduce the primary material requirements for building components.[3] At the end-of-life stage, designing to reduce waste, designing for dismantling, designing for deconstruction, and designing for recycling are expected to minimize waste production and enable easier material recycling. For instance, highway bridges are often constructed with concrete beams that support the road surface. If well designed, such beams can be re-used should the original bridge be decommissioned and replaced to accommodate an expanded highway.[3] A problem with this strategy can be that the upfront costs of such design for circularity improvements lead to higher construction costs for building companies. This usually is not in their interest; housing prices per m^2 of floor space in a specific neighborhood are often a given, and building as cheap as possible is the best strategy to give them the highest profit. In principle, buyers could pay a premium for a house with components that could be reused at the end of life; the value of such components is considerably higher as the rubble produced when a house is demolished in the traditional way at its end-of-life. But since these monetary benefits will only become tangible in decades, or even more than a century in future, it is unlikely the first buyer will be willing to pay for it. Addressing this split incentive will be vital to improving circularity in the building sector from a perspective of true life cycle costs.

More intensive use

This implies using the same space more intensively and, in doing so, reducing the demand for floor area per capita. Examples include shared office desks, buildings with smart and flexible layouts, creative storage solutions, shared common spaces, peer-to-peer lodging, trendy smaller homes, and replacing single-family homes with multi-family homes. But this strategy is not without challenges. Consumers may value having their own spaces and hence oppose solutions for shared use. Furthermore, the housing and office space per capita in the Global South is already significantly lower compared to wealthy regions, which limits the opportunity for more intensive use without compromising the standards of decent living. Indeed, expansion of floor space per capita and improving the quality of buildings in the Global South seems still needed to realize a good quality of life.[10] From the strategies we list here, research has shown it is one of the most effective strategies for reduction of material use and related GHG emissions in the build environment.[6]

Lifetime extension

Longer-lasting designs prolong the operational stage of buildings, leading to less

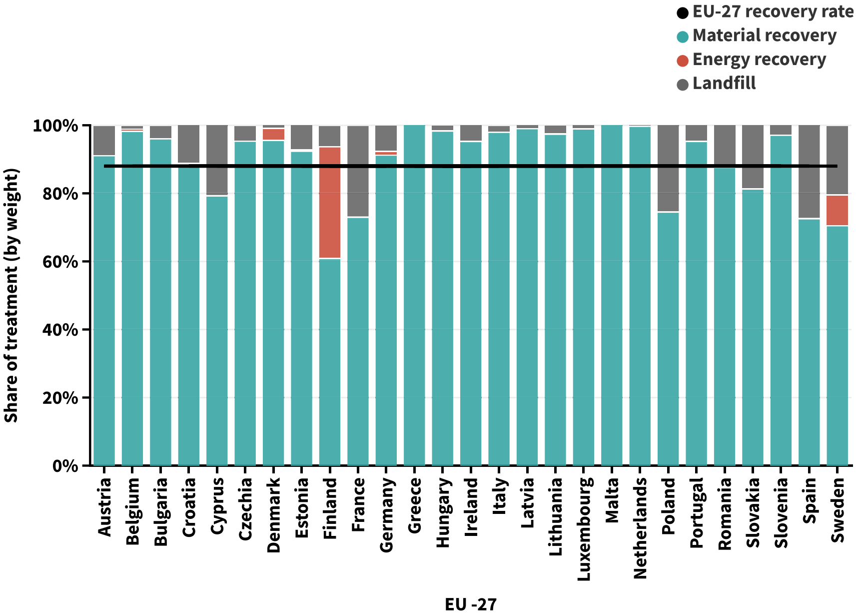

Figure 2. Mineral construction and demolition waste management in the EU-27 in 2020
Data from Eurostat.[8]

frequent replacements and disposal. Similarly, extending the lifespan of existing buildings through refurbishment reduces the need for new construction. For instance, renewing the façade and renewing the interior of a worn-out looking office, or refurbishing an old office to apartments, avoids demolishing the supporting structure of a building, which is often made from carbon-intensive concrete or steel.

Material substitution

Concrete and steel are among the most carbon-intensive materials and contribute highly to the carbon emissions from building materials production. Also, brick production requires significant energy input. Replacing such materials with, for instance, timber, is one of the most effective strategies for mitigating embodied GHG emissions of the building stock. Engineered timber (in the form of glulam and cross-laminated timber) offers vast opportunities for substitution of structural concrete and steel. A global uptake of timber in hybrid structures could reduce, on average, 50Mt CO_2-eq by 2050.[11] Steps have been taken to decarbonize concrete and steel production. But, these are dependent on the large scale application of relatively new technologies based on hydrogen, large-scale electrification, and carbon capture and storage, introducing uncertainty about their possible contribution.[12] Moreover, compared to primary materials used to produce cement and steel, timber is a renewable resource, as trees can be replanted and grown, ensuring a sustainable supply of building materials. Having said this, at this point it is still challenging to completely substitute concrete and steel with timber. Problems with load-bearing capacity have hindered the use of timber in high-rise buildings, with a handful of wooden buildings globally reaching a maximum height of 80–90 m.[13] Next to this, emissions and biodiversity loss related to land use from timber production needs to be avoided.

Component reuse

This strategy refers to salvaging, refurbishing, and reusing individual building components (e.g., concrete panels, timber doors, and window glass) from one construction project to another. Component reuse is often favored over material recycling, as it requires only re-installation or refurbishing instead of manufacturing of a new component. This strategy usually needs to be enabled by the aforementioned strategy of efficient design, as the example of concrete beams from highway bridges illustrates. This strategy also needs to be supported by a further standardization of building and construction components. If, for instance, the loading capacity of a specific component is unknown, or was custom designed, it is impossible to use it in a new project that poses different demands on the component. The growing prevalence of prefabricated constructions in Europe underscores the future potential for component reuse, as prefabricated construction often adopts standardized components and modules that streamline integration and reuse.

Enhanced material recycling

The last option, if all the strategies above are exhausted, is to recycle materials. On the surface, the EU-27 does reasonably well; thanks to landfill taxes and bans in its member states, it realizes a high CDW recovery rate.[3] But, as stated, it mainly concerns crushing stone, concrete, and other solid materials to rubble, which is then used for road foundation and backfill. Only the metals in CDW, such as steel, copper, and aluminum, are truly recycled because of their higher economic value and ease of sorting. It would be obviously much better, for instance, to reuse bricks as bricks and use several fractions of end-of-waste cement in cement production. This, however, requires that CDW is efficiently pretreated. Residues and contaminants in waste should be removed before being sent for recycling. Mandating the implementation of on-site dismantling, sorting, and selective demolition ensures the quality of waste and increases the likelihood of recycling.[3] The drawbacks are also clear: such additional pretreatment could make recycling more costly than landfilling and backfilling. New technologies hence play an important role in cost-effective waste treatment, since they can enable higher revenues because of the higher-quality material produced in the recycling process. For example, in concrete recycling, innovative technologies, such as advanced dry recovery and heating air classification systems, can reduce costs of concrete waste treatment and generate materials that substitute primary inputs into concrete and cement production.[3] However, due to the energy-intensive nature of the diesel-based thermal treatment process, this technological system also generates significant GHG emissions.

Final reflections

Realizing a circular built environment is crucial to reduce global material use and can be an important contributor to climate

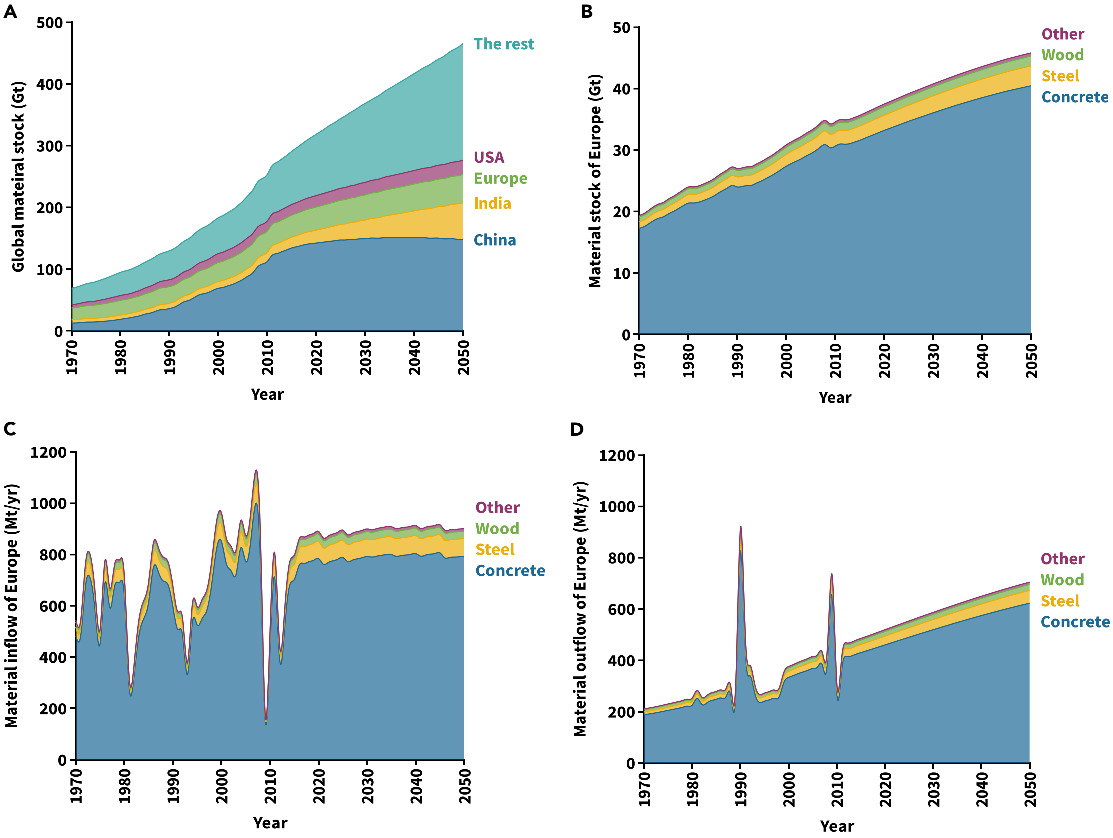

Figure 3. Material stock, inflow, and outflow for the built environment (residential and service buildings included only) in Europe for the period 1970–2050

(A) Material stock for the built environment in different regions of the world.
(B) Material stock for the built environment in Europe.
(C) Material inflows for the built environment in Europe.
(D) Material outflows for the built environment in Europe. Data from Deetman et al.[9].

mitigation. We propose a number of strategies to make this happen. Design is the connecting factor between virtually all these strategies. Design determines how efficiently materials are used to create a specific floor space. Design determines if a more intensively used building with, for example, shared office space, feels pleasant and inviting or not and if buildings can be used for a long period or not. Design further helps to find ways for material substitution and can make component reuse and high-quality material recycling possible.

It is, however, clear that a circular built environment will not be realized without changes in business practices, user practices, and policy incentives. Certain strategies, such as more intensive use, clearly require a change in user practices; not everyone will be happy with shared office space let alone shared desks. The already-crowded space per capita in the Global South requires more tailor-made inclusive strategies. The building and construction industry may embark on the required further standardization of building components as an enabler for circularity, since this will likely bring benefits; using used components in a new project obviously will reduce costs. However, businesses also have an incentive to build as cheaply as possible. That determines their profit margin given the market price for a square meter housing or office space in a specific market. This may imply that they are not interested in designing or constructing for easy refurbishing and lifetime extension, component reuse, or material reuse, should such approaches prove more expensive. An interesting way to overcome such split incentives is, for instance, "design-build-operate" (DBO) contracts, where the user pays an annual fee for the use of the building, and the builder takes responsibility for the building over its full life cycle. At the same time, potential disadvantages deserve early attention; a builder may not have control over how a user behaves, and hence takes all kind of new unfamiliar risks and essentially has to embark on a new unknown business model.

Policy cannot sit idle. It is illustrative that while many countries still landfill their CDW, landfill bans and taxes and similar incentives led to significant CDW recycling in the EU-27. We need similar policies, but now focused on stimulating the circularity solutions, to make a true circular-built environment a reality.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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