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.

The need for a circular build environment

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 building too. The production of all these materials with e.g. cement kilns and blast furnaces creates significant environmental impacts – they are responsible for instance for around 20% of the global carbon emissions, while locally 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 and 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. [4,6,7] 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 re-using window frames), and enhanced material recycling (R5; such as ensuring bricks can be re-used as bricks instead of being crushed and used as foundation material).[8,9]

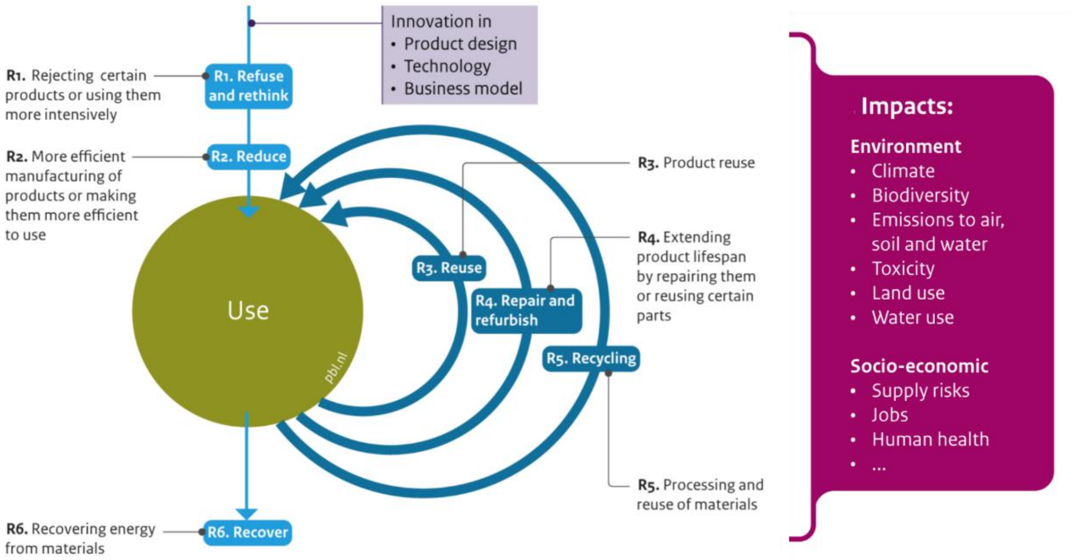

Figure 1 Circularity strategies and socio-environmental impacts. The left side of the figure shows so-called 'R' strategies to reduce the inflow of primary raw materials in a product system, in our case the built environment. By this, the same primary materials are kept much longer in economic use. This 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 Figure 1 and 3 from the summary of the Netherland Integral Circular Economy Report by PBL.[6]

Circularity challenges in the build environment

Unfortunately, a circular economy in the built environment 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 the 4.3 Gt of materials used annually currently come from secondary (i.e. recycled) sources. This large gap is 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 a good number[3] (see **Error! Reference source not found.**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 sizeable part of their CDW rather than recycling.[4]

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.[5] 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 **Error! Reference source not found.**3A–B). Inflows related to new buildings and renovation in Europe will have stabilised at 900 Mt/yr after 2010 (**Error! Reference source not found.**3C). But the outflows initially are much lower, and will only reach in 2050 a volume of 700 Mt/yr by 2050 (**Error! Reference source not found.**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 secondary material available and primary extraction is inevitable to cover the needs for new buildings and renovation.

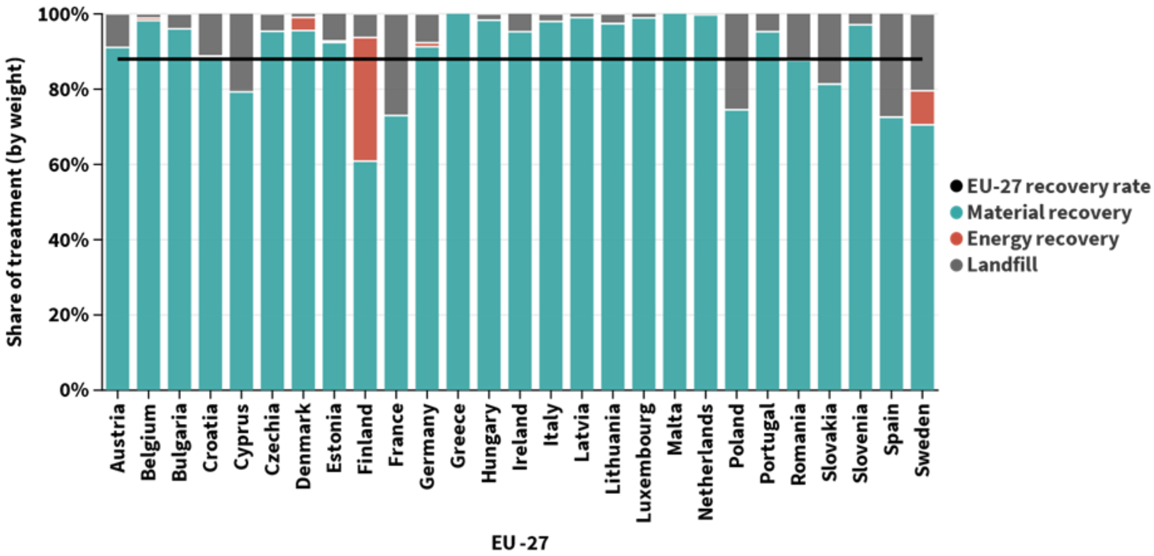

Figure 2 *Mineral construction and demolition waste management in the EU-27 in 2020. Data from Eurostat.*[3]

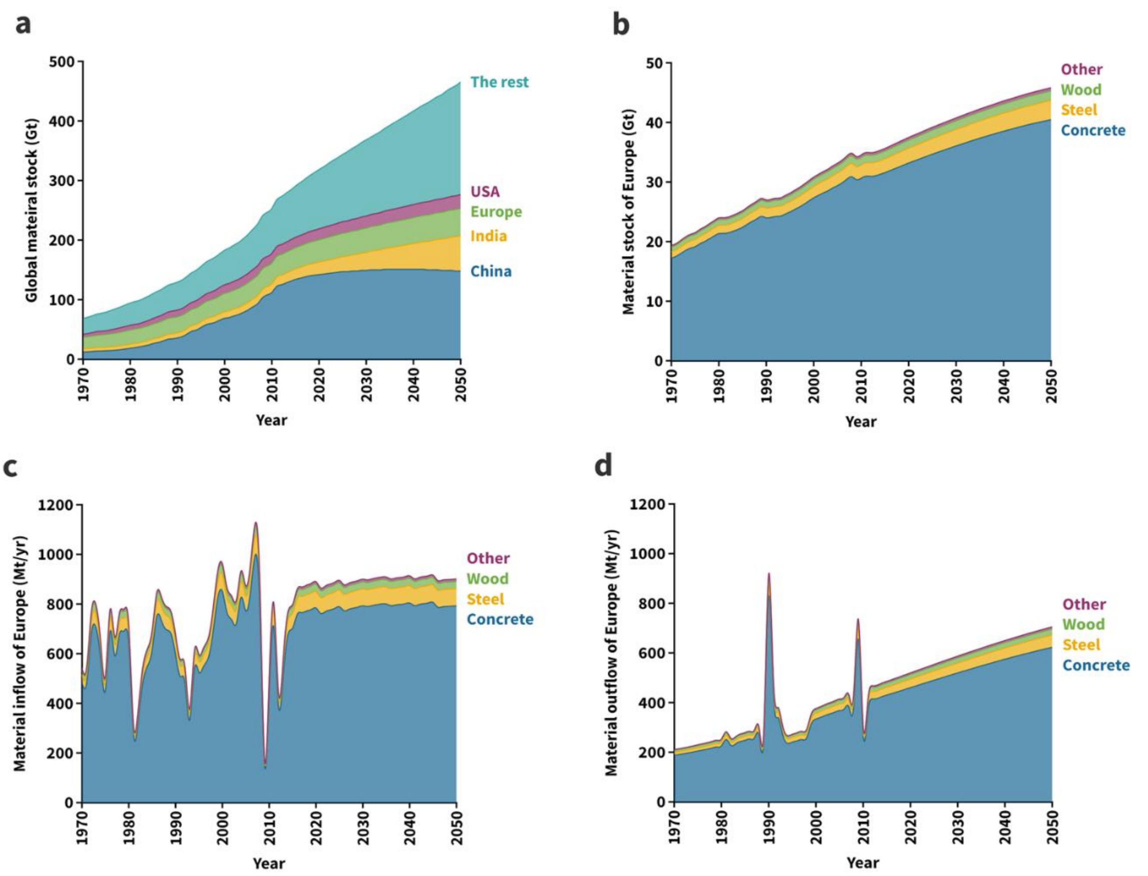

Figure 3 *Material stock, inflow and outflow for the built environment (residential and service buildings included only) in Europe for the period 1970–2050. (a) Material stock for the built environment in different regions of the world. (b) Material stock for the built environment in Europe. (c) Material inflows for the built environment in Europe. (d) Material outflows for the built environment in Europe. Data from Deetman et al.*[5]

Towards solutions for a circular build 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 re-used 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.[4] At the end-of-life stage, designing to reduce waste, designing for dismantling, designing for deconstruction, and designing for recycling are expected to minimise 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.[4] A problem with this strategy can be that the upfront costs of such improvements are for building companies leading to higher construction costs. This usually is not in their interest: housing prices per m^2 floor space in a specific neighbourhood 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 of which components could be re-used at the end of life, the value of such components is considerably higher as the rubble that would remain if at its end of life a house would be demolished in a traditional way. But since these monetary benefits only will become tangible 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 own their 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 with wealthy regions, which limits the opportunity for more intensive use without compromising the standards of decent living.[10] From the strategies we list here, research has shown it is one of the most effective strategies reduction of material use and related GHG emissions in the build environment.[8]

Life time extension. Longer-lasting designs prolong the operational stage of buildings, leading to less 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 for 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 CO2-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 e.g. 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 meters.[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 favoured over material recycling as it requires only re-installation or refurbishing instead of manufacturing 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 needs also 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 pre-fabricated constructions in Europe underscores the future potential for component reuse as prefabricated construction often adopts standardised components and modules that streamlines 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 realises a high CDW recovery rate [4] But as stated, it mainly concerns crushing stone, concrete and other solid materials to rubble, which then is used for road foundation and backfill. Only the metals in CDW, such as steel, copper, and aluminium, are truly recycled because of their higher economic value and ease of sorting. It would be obviously much better to substitute like for i.e. re-use 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.[4] The drawbacks are also clear: such additional pre-treatment could make recycling more costly than landfilling and backfilling. New technologies hence play an important role in cost-effective waste treatment, this is not only to prevent incentives to directly dump CDW, but also to 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.[4] 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 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 material are used to create a specific floor space. Design determines if a more intensively used building with e.g. 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 re-use 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 or even shared desks and 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 standardisation 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 that construct buildings usually pass such cost on to those who own the building, implying that businesses have an incentive to build as cheaply as possible. This may imply that they are not interested in designing or constructing for easy refurbishing and life time extension, component re-use or material re-use should such approaches prove more expensive. An interesting way to overcome such split incentives are 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 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.

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