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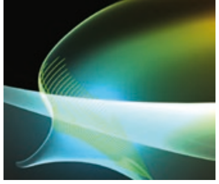

REVIEW

Think circular—Reducing embodied carbon through materials selection

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ABSTRACT

Material choices can affect both the environmental conditions and the human health impacts of buildings. Decision making can be improved through greater transparency and a broader view of materials impact.

With more architects and engineers recognising the impacts of global climate change, a renewed focus on carbon emissions from buildings is underway. Material choices in the built environment have significant impacts on both the building's carbon emissions and the health of building occupants. As the operational carbon in buildings falls through improved efficiencies and design, the amount of embodied carbon released from the extraction, manufacturing, and transportation of materials and products is becoming relatively more significant. Through the selection of materials, designers can reduce the overall carbon emissions of buildings while maintaining high standards for occupant health.

Keywords: carbon dioxide; efficiency; material availability; society; sustainability

DISCUSSION POINTS

- What new tools are needed to generate and collate better data for materials selection? What do we need to know?
- How can circular economy principles help architects and engineers embed environmental and health impacts in decisions about materials selection for construction?

Materials matter

As architects and engineers, how do we decide on which materials and products to specify? Materials affect the form, function, and feel of a space. They often intimate what activities take place or with what level of seriousness they occur. They can also affect both the health of the environment at large and ourselves. When choosing materials, we base our decisions on three primary criteria: aesthetics, performance, and cost. Material performance has many factors and the health and environmental aspects have long been hard to quantify and communicate.

Material impacts can be thought of in a number of ways. We examine the effect of a material by its ability to perform its core function, its influence on the built and natural environment, and its impact on public and individual health. Potential harm to the environment and people caused by buildings and building materials has been a growing area of concern for designers and occupants alike.

Building operations are responsible for 41.7% of U.S. energy consumption, with building construction and materials accounting for an additional 5.9% of consumption, as shown in Fig. 1. Over the past decades, designers have become more aware of the need to conserve natural resources, reduce energy use, and minimise carbon pollution. The strategies have primarily focused on reducing energy use from carbon emitting sources during the operation of buildings, but this is only part of the carbon emissions story.

Carbon emissions are separated into two categories: embodied carbon and operational carbon. Embodied carbon (eCO_2) is the total CO_2 emitted during the extraction, manufacture, transportation, construction, and demolition of a building. Operational carbon (oCO_2) is the carbon emitted during the life of the building (heating, cooling, lighting, etc.). In new highly energy efficient buildings and net zero energy buildings, the role of embodied carbon in building emissions is typically greater than that of operational carbon[2] and the industry needs to refocus its priorities accordingly.

More typically, by the time a new building is built, and before it is fully occupied, 30–70% of the carbon emissions that the building will be responsible for over the course of its lifetime will have already been expended.[7] The percentage varies depending on the building program and composition.[3] As buildings become more efficient and less carbon intensive, operational emissions

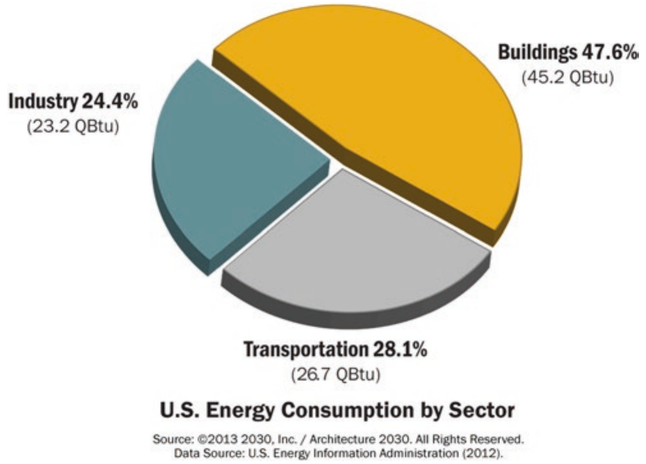

Figure 1. U.S. energy consumption by sector.

will continue to decrease. In an energy-efficient, mid-rise commercial office building with a 30-year lifespan, for example, the embodied carbon can be as much as 65% of the building's total carbon emissions.[2] However, with global temperature quickly approaching a 2 °C increase over pre-industrial times, which climatologists believe will cause irreversible and potentially catastrophic environmental damage, we can no longer afford to release such vast amounts of carbon in the extraction, manufacture, and transportation of building materials.

For Arup's projects, we advise designers to select materials based on their physical performance and to prioritize those that have low eCO_2, emissions, help minimize oCO_2 emissions, and do not negatively impact occupant health. We also advocate for the integration of circular economy thinking, a regenerative approach to keeping materials in their highest use for the longest period of time, to help meet these goals.

Applying circular economy material strategies to reduce embodied carbon emissions

With buildings, the typical approach to production and consumption of natural resources is linear. The approach can be described as a "take, make, use, and dispose" practice (Fig. 2). Often the extraction, production, and transportation of buildings materials is very carbon-intensive (i.e., steel, glass, aluminum, and concrete). At the end of a building's use, we often demolish it without much thought toward minimising carbon emissions or maintaining the highest economic value of the material.

Unlike linear resource consumption, a circular economy that follows a "take, make, use, and remake" practice is restorative and low-carbon by design. Products and assets are designed and built to be reused, repaired, refurbished, remanufactured, and recycled, keeping them at their highest possible economic value for as long as possible. By moving away from linear resource consumption, resources are preserved, waste is minimized, and negative externalities are designed out so that economic growth is decoupled from resource consumption.

One of these negative externalities is carbon pollution. Designers and engineers can help minimise eCO_2 in buildings by focusing on material value and material volume and by embracing circular economy principles. In a circular economy, designers can prioritize low-carbon materials that minimize negative health impacts while maintaining economic value in building assets. Doing so requires adopting the following strategies which align with circular economy principles:

Capitalize on existing buildings and materials

Renovating or reusing an existing building typically reduces the building's embodied carbon by 50–70% compared to new construction.[6] Construction materials are often down-cycled into less valuable products instead of recycled into similar or upcycled into more valuable products because they cannot be easily separated from other components.

Materials can serve several buildings during their lifetime if we design and build for disassembly and reuse. By designing a building to achieve net zero or net positive carbon emissions, the renovated building can start paying off its previous carbon debt.

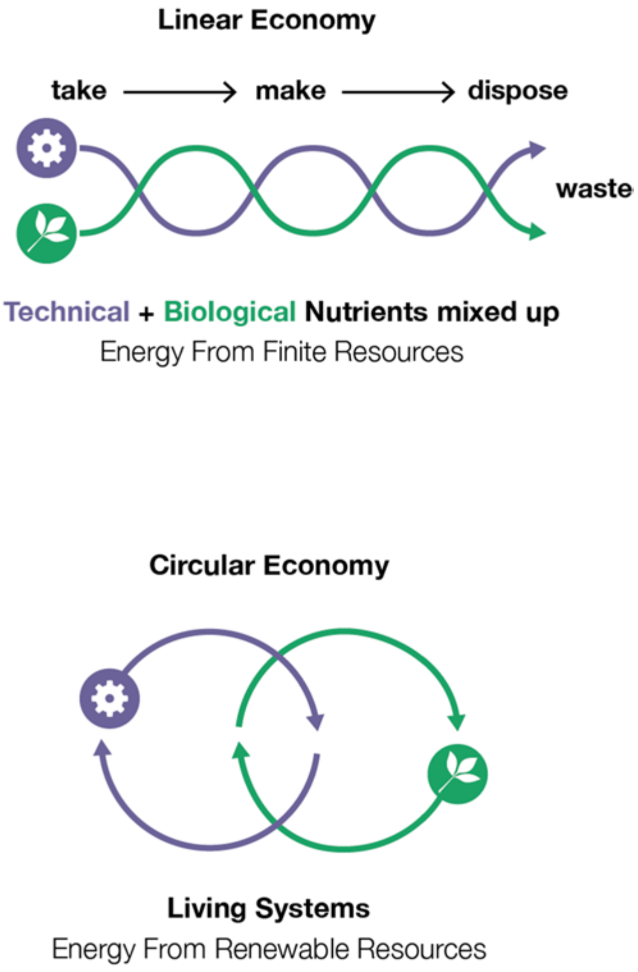

Figure 2. Linear and circular economy approach to consumption (adapted from original graphic by the Ellen MacArthur Foundation).

Design to eliminate waste and maintain value

In a circular economy, the concept of waste is replaced by renewable and reusable products, goods, and services. Designers should seek out durable/low-maintenance materials and design for disassembly so that materials and finishes can be changed easily without significant retrofit. Using accessible mechanical connections facilitates design for disassembly. Leasing of services instead of purchasing of products such as light bulbs, ceiling tiles, and carpet allows manufacturers to take back products and reuse or recycle them. In a circular model, it is also imperative to only circulate healthy materials so we do not repeat negative health effects.

"Circular" materials maintain their value through their life cycle and can be easily adaptable, adjustable, removable, and renewable. If building components retain their value beyond a building's lifespan, capital can be invested early to buy high-quality products and systems that still have a dollar value at the end of their original useful life. This changes how we think about capital expenditure and demolition. It is not enough however to only design according to circular principles; the circular markets must also be in place to accept these materials for reuse at the end of the building lifespan to maintain their value.

By minimizing the total amount of material in a project consistent with other material requirements, we inherently reduce the carbon emissions from those buildings. This may take many forms: reducing the project size, exposing systems and structure, using natural finishes (stone, wood, etc.), or reducing the need for mechanical equipment through passive design.

Designing with standard material sizes and modular components also reduces offcuts and waste on the job site. Optimising structural shapes or using digitally printed bespoke components provides an opportunity to use just the amount of material needed. This optimization must take account of the material used for additional prototyping or testing of nonstandard components.

Use building information modeling and material passports

Building information modeling (BIM) and other innovative project-management processes provide new opportunities to optimize material value, minimize waste, and to index a building's parts for future disassembly or reuse. BIM and prefabrication allow comparison of design schemes early in the design process to reduce eCO_2 and oCO_2 in addition to supporting health and wellness goals. Although data on construction waste are difficult to obtain as it is considered commercially sensitive, construction managers we work with suggest that precoordinating trade work through BIM can result in as much as a 10% reduction in rework and wasted materials from field corrections.

We can use BIM to create a database of "material passports," a unique, data-filled ID tagged to the physical building products, components, or materials. By creating a building-specific material database, building owners can catalog and track performance, service, and potential next use of all pieces in a building. It also allows existing buildings to be "mined" for construction materials through a searchable database. The challenge is maintaining an accurate BIM database throughout the project. Programs such as Buildings as Material Banks (BAMB), funded by the European Union, are beginning to emerge with a focus on retaining the value of building materials in part through the use of material passports.[a]

Challenges to selecting low-embodied carbon emission materials

Even with the knowledge required and desire to design low eCO_2 buildings, barriers do exist. Previous versions of the Leadership in Energy and Environmental Design standard (LEED), a leading green building certification program, included strategies that reduce eCO_2. The strategies included purchasing local materials, selecting materials with recycled content, and choosing reuse materials. While these credits helped guide the market, they did not lead to a significant uptick in building renovation projects or salvaged material use. Only 3% of LEED-NC 2009 projects achieved the Materials Reuse credit and 17% of projects received points for Building Reuse.[5]

Additional data are needed to compare products and materials. We need more embodied carbon data that are accurate, local, and standardized. Currently, there are challenges to assess the eCO_2 of a material accurately and quickly enough to impact design decisions. It requires an agreed-upon system for measuring carbon emissions that takes into account all components of material production and local conditions. Early benchmarking would allow decision making and optimization of a project "carbon budget" during the design phases.

Massachusetts Institute of Technology is working on centralizing and publicizing embodied carbon data for thousands of buildings. The Database for Embodied Quantity Outputs (DeQo) combines data from a variety of sources and is able to provide accurate embodied carbon values for hundreds of buildings of different typologies around the world. While location-specific factors still need to be taken into account, collecting and standardizing this information can help spur the industry to embrace better reporting and influence decisions to decrease embodied carbon. To be more effective, databases like DeQo must grow to include materials that represent the full breadth of options within the building industry.

Designers can also look to Environmental Product Declarations (EPDs) to learn more about the full environmental performance of materials. EPDs are similar to food nutrition labels for building materials, including information on carbon emissions, acidification, ozone depletion, waste production, and standardized, third-party-reviewed life-cycle assessment (LCA). EPDs can help simplify complicated information and help architects and engineers make educated decisions.

LEED v4[b] has helped increase the demand for EPDs through a new Materials and Resources Building Product Disclosure and Optimization credit. Points are achieved by either selecting a minimum of 20 products with EPDs available or by demonstrating various environmental impact reductions for at least 50% of all products by cost. The EPD credit and separate LCA credit requirements are an improvement upon previous versions of LEED because they set out specific requirements–local, nontoxic, recycled content, recyclable–but that did not provide enough guidance to accurately compare products.

As mechanisms for measuring the comprehensive environmental impact of materials become more prevalent, architects and engineers will be increasingly armed with the information necessary to reduce embodied carbon in their buildings. Linking that information to BIM models will allow comparative analysis of various building schemes throughout design (e.g., steel may have a higher embodied carbon value by volume than timber but may require less material to support a given structure). Building simulations will reveal more comprehensive environmental metrics, not just energy use.

Even when materials with low-embodied carbon are sought out by designers and written into specifications, additional measures may be required to ensure building construction meet sustainability objectives. On a project proposed to be constructed with mass timber, Arup used LCAs to inform decision-making throughout the design process. Since Arup's role was limited in late-design phases, we used LCA to guide supplier selection on the project. We developed a supplier questionnaire for inclusion in the RFP process. This questionnaire requested information on transportation distances and methods, and biogenic carbon sequestration accounting–the amount of carbon stored in timber. The results brought more specificity to what would otherwise have been very general LCA data and helped ensure that sustainability was quantified alongside other criteria considered during the bid review process.

Health performance—from sick buildings to health and wellness

As we develop materials that are friendlier to the environment, we should also ensure that they do no harm to the occupants using the buildings. If we can create robust, durable materials that can be repurposed and reused in multiple buildings, it is important that those products provide a healthy environment and do not negatively impact the occupants or those who produce or disassemble the components.

Beyond "do no harm," we look to specify materials that enhance the natural and indoor environment and improve the health of people and planet. The importance of material choice on building occupants is most clearly shown in the cognitive function study conducted by the Harvard T.H. Chan School of Public Health's Center for Health and the Global Environment in 2014.[1] This study tested the effects of VOC and CO_2 air concentrations on 24 participants in a simulated office environment. The results showed that better air quality had a positive effect on participants. Cognitive function increased by 61% on "Green days" (low VOC concentrations and 50% outdoor air) and by 101% on "Green+ days" (100% outdoor air with controlled VOCs) over "Conventional days" (high VOC and 50% outdoor air). In addition, on Green+ days, crisis response was measured to be 131% higher, information usage 299% higher, and strategy 288% higher.

The use of Health Product Declarations (HPDs) as a reporting standard for material ingredients has grown significantly, more than doubling from 2014 to 2015 and continuing to grow according to HPD Collaborative.[4] Long standing certification standards such as LEED, as well as newer health and wellness focused standards including WELL and Fitwel have continued to promote the use of HPDs in the built environment. The combination of HPDs and EPDs helps architects, engineers, and contractors make more informed decisions when it comes to material choices.

Conclusion

Minimising eCO_2 and oCO_2 while maintaining occupant health should be top priorities for designers. Material selection is a key factor in the total carbon emissions of a building and its impact on wellbeing. eCO_2 emissions are responsible for an increasing percentage of a building's environmental impact. To be a factor in design and construction processes, eCO_2 data will need to be more standardized and accessible than it is now. Emerging tools and information databases that index the carbon consumed in the production, processing, and shipping of materials will allow architects and engineers to be more aware of the comprehensive environmental impact of their designs. Embodied carbon can then be embedded in building models and simulation tools as part of the complex matrix of factors–aesthetic, budgetary, environmental, and health–that inform decision-making during the design process.

End notes

[a] Buildings as Material Banks http://www.bamb2020.eu/.

[b] United States Green Building Council, https://new.usgbc.org/.

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