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Perspective

A Life Cycle Thinking Framework to Mitigate the Environmental Impact of Building Materials

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SUMMARY

Urbanization and population growth have contributed to a tripling of building material consumption from 2000 to 2017. Building materials have a range of environmental impacts throughout their life cycle, from extraction, processing, and transport of raw materials to building construction, use, and eventual demolition and waste. Mitigation measures that target specific materials or value chain stages may therefore have incremental or even adverse net environmental effects. In this perspective, we develop a framework for applying life cycle thinking to identify key impacts and corresponding mitigation approaches, inform building design and material selection, and ensure effective treatment and recycling of construction and demolition wastes. Life cycle evaluation can also be used to assess and avoid environmental trade-offs among life cycle stages. Challenges for implementing these life cycle principles include collecting and integrating inventory data for products, managing multiple stakeholders within the construction industry, and monitoring end-of-life impacts; measures for overcoming such challenges are discussed.

INTRODUCTION

Rapid urbanization and population growth has resulted in soaring consumption of building materials.[1,2] Global consumption of building materials tripled from 6.7 billion tons in 2000 to 17.5 billion tons in 2017; concrete, aggregates, and bricks are the most commonly used building materials (Figure 1A). The largest growth in building material use over this period was in China, which has experienced accelerated urbanization, accounting for more than half of the global use of building materials in 2017 (Figure 1B). Use of building materials in Europe and North America stabilized and even decreased during this same period.

Increased global consumption of building materials has resulted in equally extensive pollutant and waste emissions. The environmental costs of building materials occur along their value chain activities ranging from extraction to manufacture and treatment after demolition.[2,7–10] Cement, steel, and concrete have the most severe environmental burden during their manufacture.[11] At the disposal stage of the material life cycle, stone, metal, cement, and wood release leachate emissions containing organic acid, bacteria, heavy metal ions, and multiple air pollutants. Incineration processes discharge heavy metals and volatile organic acids into the environment.[12,13]

Multi-pronged strategies to reduce the environmental burdens of building materials have been proposed, beginning with building design.[14–16] During later value chain stages, such as construction and waste treatment, site monitoring with pollution and emissions controls have helped to mitigate environmental burdens.[17,18] Building material recycling efforts also occur throughout the value chain stages. These recycling efforts reduce usage of virgin materials while mitigating the environmental costs that are embedded in materials.[19–21]

Most state-of-the-art studies discussing mitigation measures have targeted specific materials or value chain stages. Without a holistic perspective, mitigation measures for one life cycle stage may result in incremental or even adverse environmental effects. Prefabricated and modular construction is one example of an intervention aimed at improving the sustainability of the construction industry. Although prefabricated and modular construction has the advantage of reducing the amount of waste produced in the construction and waste treatment stage,[22] the energy consumption of long-distance transportation of prefabricated building components may offset the benefits of greenhouse gas (GHG) mitigation generated from the treatment processes.[23] These efforts may therefore have an adverse net environmental impact when considering the whole life cycle of building materials.

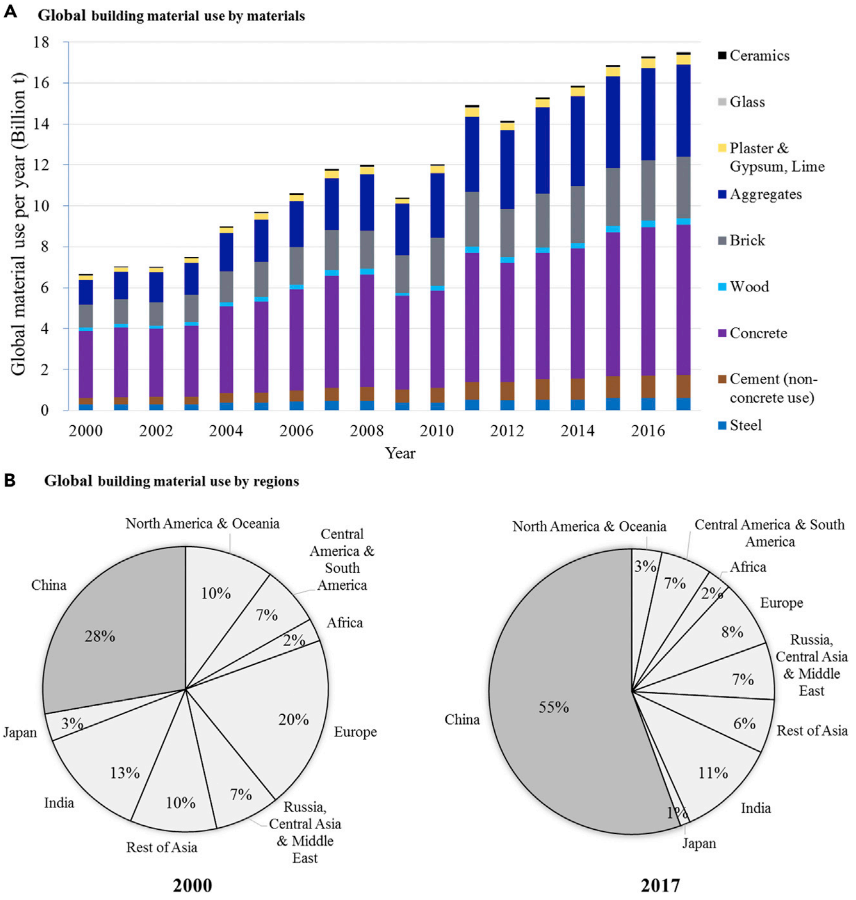


Figure 1. Annual Global Building Material Use during 2000–2017 by Material and Region

More details are available in Table S1. Data source of building material intensity: Heeren and Fishman (2019),[3] Huang et al. (2018)[4] Marinova et al. (2020);[5] data source of annual constructed building area: Deetman et al. (2020).[6]

Integrated analysis is also necessary to identify effective mitigation measures because the pollution impacts of building materials are also closely related between different life cycle stages. For instance, environmental impact assessment of the manufacturing stage could inform how the design of buildings can be modified to avoid or reduce the corresponding impacts.

In this perspective, we argue that environmental impacts of building materials and mitigation approaches must be evaluated through life cycle thinking to avoid strategies that can mitigate environmental impacts in one stage but may have more adverse impacts in other life stages. Initially, we generally describe life cycle thinking in a building materials context. Then we introduce various holistic and integrative strategies and tools for mitigating environmental impacts. We also identify challenges and provide insights on how to overcome these challenges.

LIFE CYCLE THINKING FOR BUILDING MATERIALS

The full life cycle stages—value chain or supply chain processes—of building materials include the extraction of raw materials, processing and manufacture of these raw materials, transportation, construction and retrofitting, use and maintenance, demolition and waste management, disposal and circular processing through reuse, recycling, and recovery[24] (Figure 2).

As a technique for assessing the potential environmental impacts associated with a product, life cycle assessment (LCA) can help assess the environmental impacts associated with all the stages of the life of building materials (Figure 3). Material, energy usage, and emissions inventory data from the various stages of building materials need to be captured, either from case investigations or through building material databases such as Ecointent,[25] ELCD (European Life Cycle Database),[26] and US LCI (US Life Cycle Inventory).[27] Impact assessment can be conducted through LCA software such as Gabi and Simapro.[28]

Thereafter, an interpretative analysis of desired changes can reveal impact mitigation approaches.[29–31] In the analysis in this paper, the energy consumption of facilities during the building operations process is not captured. We bounded our evaluation to focus on building materials instead of the operations of buildings or facilities.

Acquiring complete building life cycle inventory (LCI) data over the material lifespan is challenging, as it would require sustained data collection over a long period and from different stakeholders.[32] This challenge is especially true when integrating building material LCI of demolition and waste treatment with the manufacturing process stages. To address this challenge, we propose extending LCA to include life cycle thinking (LCT) to explore roadmaps for mitigating the environmental burdens of building materials.

LCT is a systemic framework that takes a holistic view of the production and consumption of one product or service.[33,34] In the case of building materials as a target product, LCT would incorporate environmental and socio-economic performance during the life cycle of building materials and seek approaches to reduce the usage of building materials and related emissions. LCA serves as the foundation enabling LCT by quantitatively evaluating the environmental impacts of one product or service through its entire life cycle.

Here, we develop five major building material LCT principles. First, we propose steps for using LCA and LCT to identify key environmental impacts of building materials and corresponding mitigation approaches. Next, we emphasize LCT approaches to building design, material selection, and construction and demolition waste (CDW) treatment and recycling. We then discuss how LCT can be used to avoid environmental trade-offs in the building material life cycle. Coupling LCA with material flow analysis (MFA) and geographic information systems (GIS) is also discussed as a further principle that can incorporate spatial and temporal aspects of the impacts of building materials.

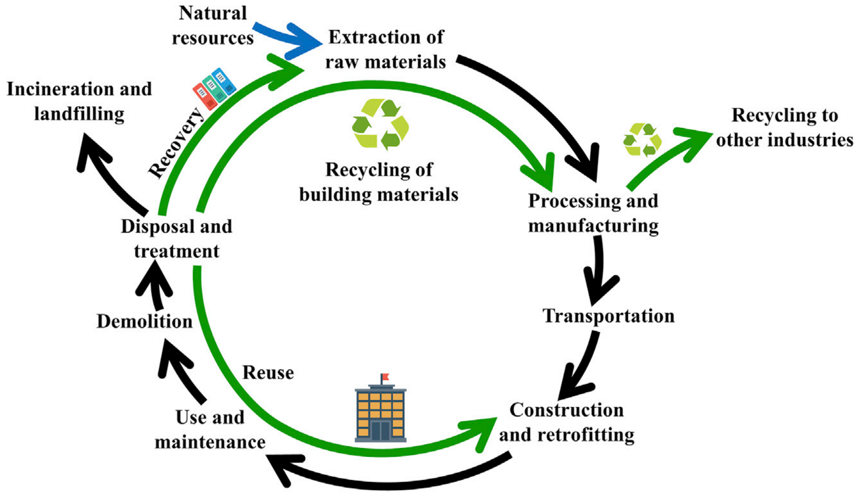


Figure 2. Conceptual Diagram of Building Material Life Cycle
Arrows represent building material sources (blue) and both general (black) and circular (green) material life cycle processes and value chains.

IDENTIFY KEY IMPACTS AND MITIGATION APPROACHES

One of the first principles of LCT is to help identify impacts and mitigation approaches for various materials and stages. Each building material life cycle process activity involves energy and resource consumption and pollutant emissions (see Figure 4), which vary on both input and output dimensions. Extraction and manufacturing of building material activities result in almost 90% of the life cycle environmental pollutants, not including the treatment process.[4] Environmental impacts during transportation and construction include nitrogen oxides (NOx) and carbon dioxide (CO_2) emissions resulting from fossil fuel consumption.[19,35] Building waste treatment includes waste plaster and wood, which are key contributors of organic acid in landfills.[36,37] Incineration of wood, plastic, and paper generates pollutants such as ammonia (NH_3), heavy metal ions, and volatile organic compounds (VOCs);[38–40] each has human and ecological toxicity impacts.

We have evaluated environmental impacts in the extraction and manufacturing stages of key building materials with the LCA methodology known as ReCiPe.[4] Through normalizing[41,42] to global indicators in 2000, our results show that human toxicity, fossil fuel consumption, global warming, and metal consumption are key environmental impacts, as summarized in Figure 5. Tracing the sources of these impacts shows that human toxicity is caused by heavy metals emitted from the raw material mining and manufacturing process of cement and concrete. Fossil fuel consumption due to coal, oil, electricity, and natural gas demand occurs in the manufacture of iron, brick, gravel, and cement. The impact of global warming arises from energy consumption in the production of steel, cement, and concrete. Chemical reactions in the production of clinker used in cement production also contributes to global warming.[4]

Determining the environmental impact of building materials is only the beginning of this process. LCT should incorporate strategies to mitigate environmental impacts. To reduce the impact on global warming, reducing energy consumption and using less CO_2-intensive energy sources in steel and lime production have been identified as effective approaches. Global warming pressures can be reduced through reducing consumption or using substitute materials with lower GHG emissions, such as shifting from traditional blocks to hollow concrete blocks or stabilized soil blocks.[24]

The impact on human toxicity can be reduced by preventing discharge of heavy metals in the extraction and manufacture of concrete, bricks, and cement. Renewable bio-materials, such as wood and bamboo, can reduce environmental impacts and depletion of fossil fuel and metal resources.[43] Recycling of concrete, steel, and wood are effective measures to mitigate environmental burdens by reducing the requirement for virgin material resources and alleviating the environmental burden of waste treatment.

Even though extraction, manufacturing, and disposal stages are identified as having a significant environmental burden,[2,8–10] more complete determination of the impacts throughout the life cycle activities of building materials requires further study. Additional studies are needed due to lack of integrated inventory data. Case studies to track data on the inputs and outputs of specific buildings, from material extraction to final disposal stage, are needed to develop more reliable estimates. Tracing these data and analyzing the environmental performance of building materials over the full life cycle can provide more accurate estimates of the impacts and additional mitigation strategies.

BUILDING DESIGN AND MATERIAL SELECTION

The second major LCT principle is emphasizing building design and material selection to reduce environmental burdens. The design process is essential for avoiding or reducing environmental impacts; it also sets the stage for enhancing life cycle sustainability of building materials and building operations. Design and material selection can reduce environmental burdens during manufacturing, construction, application, deconstruction, and recycling.

Interventions such as eco-labeling[44–46] can support the process of matching building materials and products to specific functions while minimizing associated environmental impacts. Environmental product declaration schemes have been used in some countries to assess the environmental burden of building materials,[47–49] and can be applied to other materials as well.

Green building certification systems—a form of eco-label certification—including BREEAM (Building Research Establishment Environmental Assessment Method), CASBEE (Comprehensive Assessment System for Built Environment Efficiency), and LEED (Leadership in Energy and Environmental Design) use LCA for building evaluation and certification.[50–53] For example, builders receive certification points for using recycled building

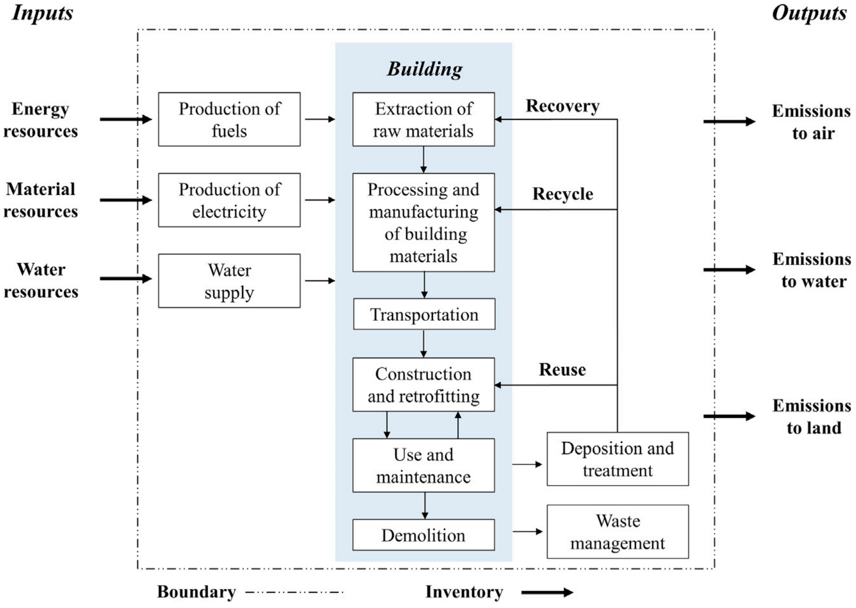


Figure 3. Life Cycle Assessment Application Framework for Building Materials
Blue shading represents the life cycle of building materials. LCA boundary (dashed line) includes input resources, building materials, and output emissions in different life stages. Inventory data include energy and water usage, building materials, and polluting emissions.

materials in these certification systems.[54] LEED also offers credits for life cycle impact reduction by encouraging building and material reuse, renovation of abandoned or blighted buildings, and GHG reduction through LCA. CASBEE requires life cycle information for recycled building materials to ensure the alleviation of environmental impacts. BREEAM evaluates the resources of building materials and offers credits for projects with green supply chain management. Integrating LCA into green building certification tools promotes the greening of buildings in the whole life cycle.

Anti-pollution and anti-corrosion elements in construction design protect buildings from being polluted with heavy metals and reduce the production of heavy metal-imbued buildings.[55] These anti-pollution approaches apply to industrial buildings, especially chemical plants. It is also crucial to recycle construction materials through "design for deconstruction" with easier disassembly and recyclable construction materials.[56] Design for deconstruction brings us to our next LCT for building materials principle: CDW treatment and recycling to reduce environmental impacts.

CONSTRUCTION AND DEMOLITION WASTE TREATMENT AND RECYCLING

CDW represents building materials after the end of life of buildings.[57] We introduce a separate LCT principle for CDW because the potential to reduce the environmental burden from activities can be substantial at this stage. The first two LCT principles align mostly with activities earlier in the value chain. We now turn our attention to building materials at building end of life.

CDW materials include concrete, steel, wood products, asphalt shingles, and bricks.[58,59] CDW treatment can release significant environmental pollutants and threaten land use.[60] Usage of recycled materials reduces the use of virgin materials and energy consumption, leading to mitigation of embodied environmental impacts.[61,62]

Efficient CDW recycling treatment requires sorting at the deconstruction source where the building or facility is dismantled.[58] Reusable and recyclable materials, including wood, concrete, metals, and brick, need to be collected at the source. Materials that are environmentally damaging in landfill, such as scrap metal and contaminated wood,[63] need to be separated and stored in separate protected landfills. Harmful materials such as asbestos need to be carefully treated.[64] These approaches have been well practiced in countries such as the US and Japan,[58,65] but need to be reinforced in most developing countries, including China.

Figure 6 graphically summarizes key CDW treatment and recycling process flows. Waste concrete, brick, ceramic tiles, and gravel may be used for aggregate road pavement or as building materials. Steel, glass, plastic board, and plastic can be recycled after proper processing and manufacturing.

LCT requires special attention to be given to recycling high environmental burden materials, especially concrete and steel. Concrete waste typically comprises the largest fraction of CDW and is heavy. On-site crushing and recycling can help avoid energy consumption from transportation of this waste. The environmental burdens and benefits of steel waste include collection, sorting, processing, melting, purification, solidifying, and transportation—all activities that need careful LCT evaluation.[66] Economically viable recycling technologies are key for enhancing the environmental performance of building materials throughout their life cycle.[4]

LIFE CYCLE THINKING TO AVOID PITFALLS

Use of LCT to avoid pitfalls—especially those associated with trade-offs among environmental concerns—is the fourth principle of LCT in a building materials value chain. Since LCA results cover various kinds of environmental impacts among life cycle stages, trade-offs may exist when balancing environmental and socio-economic priorities.[67] LCA needs to elucidate environmental costs and benefits to help identify optimal environmental outcomes.

For example, double-glazed windows may have greater environmental burdens than standard windows during their manufacture. Yet, during building usage, double-glazed windows are more environmentally beneficial from an energy-saving perspective.[68] It would be necessary to evaluate the life cycle cost-benefit of alternative materials in a specific region before

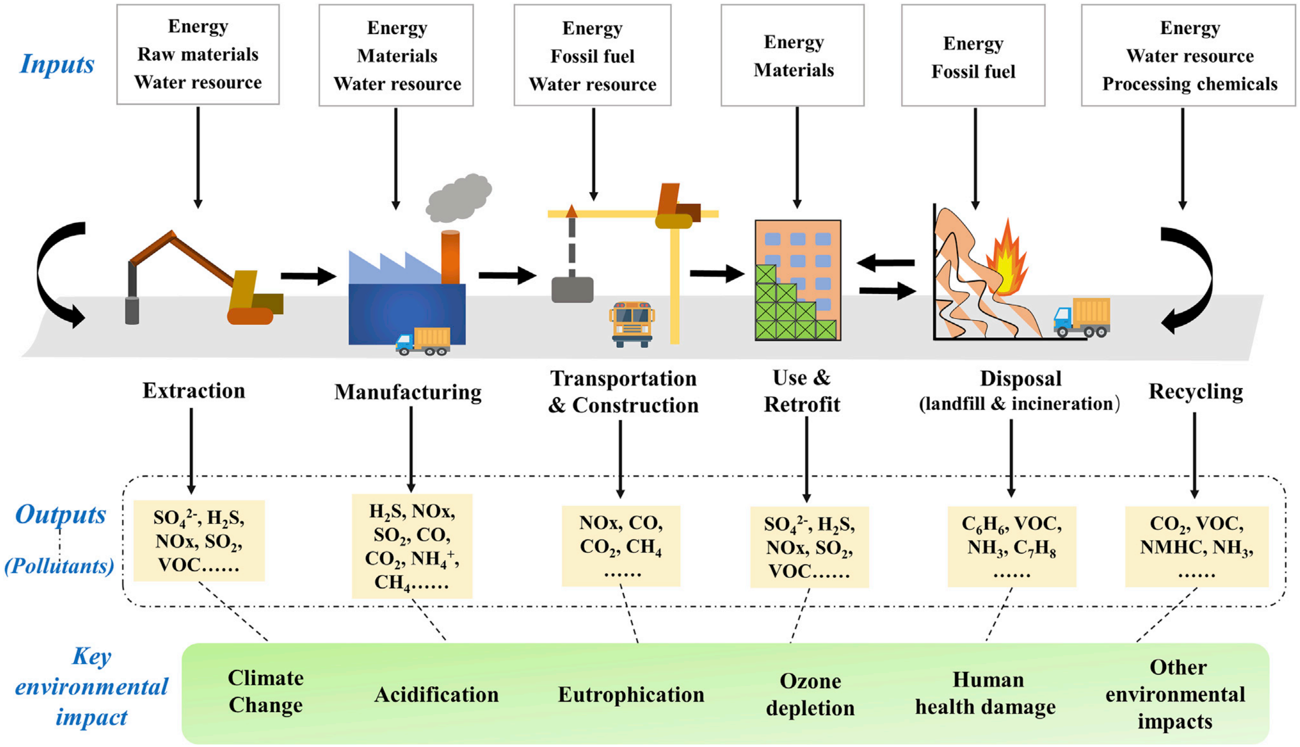


Figure 4. Key Environmental Impacts during the Life Cycle of Building Materials

selecting materials and making environmentally optimal decisions.

Retrofitting is an example of using LCT in trade-off situations. A building LCA program in Japan conducted a scenario analysis comparing buildings with 35- and 100-year lifespans. Their case study results revealed that although 100-year-old buildings consume more building materials from additional retrofitting rounds, their annual environmental pollution is largely reduced. For these longer-life buildings, GHG emissions may be reduced by 14%, acidification reduced by 11%, human health concerns reduced by 11%, and fossil fuel depletion reduced by 11%.[69] If building retrofits or reconstruction are planned, life cycle environmental evaluation balanced with economic and social benefits should be considered.

Another area influencing building materials LCT and trade-offs are prefabricated buildings.[70–72] Their environmental burdens and benefits during the material manufacturing and building construction processes are difficult to separate. The building components of prefabricated housing are built offsite and then assembled or installed after transport to the construction site.[73] Prefabricated construction needs much less on-site energy and labor and discharges less environmental pollutants than traditional construction methods.[74,75] However, during the manufacturing process of assembling components, prefabricated components would need additional processes such as steam curing to strengthen sub-assemblies.[75,76] Further, prefabricated components are oversized with heavy loads, therefore the additional energy consumed during transportation might offset the benefits of GHG mitigation during the construction phase. Their intensive use of roadways also increases roadway maintenance, which results in additional environmental impacts.[23]

Conflicts and trade-offs across different value chain stages for prefabricated buildings require evaluation of environmental costs and benefits across the whole life cycle and value chain stages. Geographic and socio-economic factors may also come into play. For example, some locations may encounter extra environmental costs in manufacturing and transportation, leading to loss of energy savings benefits during the construction process of prefabricated buildings. Thus, prefabricated building choices may not be a rational option for achieving environmental mitigation goals. Some additional spatial and temporal issues are discussed in the next section.

There are also trade-offs in CDW recycling. For example, when incinerating CDW and recycling fly ash into alternative cement products, the process itself is energy intensive and discharges multiple air pollutants.[77,78] While some material recycling processes can reduce specific environmental impacts, some recycling treatments cause significant environmental burdens.[79] For instance, concrete recycling may reduce acidification outputs, but this activity has significant land consumption requirements. Another example is brick and mortar recycling, which has greater environmental costs than benefits.[79]

Recycling rates are still low in developing countries, mainly due to technology shortages and market failures.[80] There are substantial opportunities for improvement in the global recycling rates of building materials. If this additional recycling is to be pursued, environmental costs and benefits during the entire life cycle need to be carefully evaluated to avoid adverse outcomes.

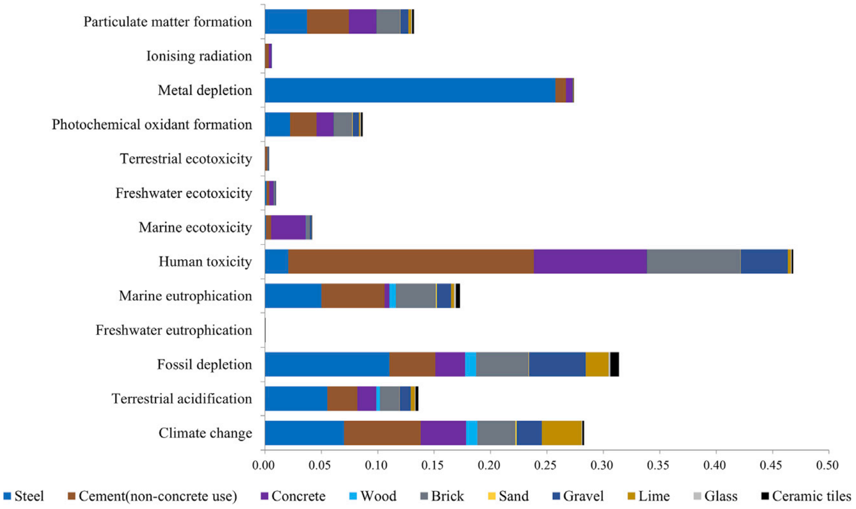


Figure 5. Environmental Impact Indicators Associated with the Production of Building Materials Used in China in 2015

Impact indicators were determined using the ReCiPe method, and normalized into equivalent value with global impact indicators in 2000. Source: Huang et al. (2018).[4]

SPATIAL AND TEMPORAL INTEGRATION

The final major LCT principle in a building materials value chain is the evaluation of spatial and temporal aspects. This evaluation can help further support identification of potential environmental burdens and remedies. LCA has the potential to provide insights based on geographic region. To be able to do this effectively, LCA requires integration with tools such as MFA, which can help track building material inflow and outflow by region. MFA can quantitatively anticipate the environmental burdens for regions, helping to support LCT. MFA can also inform categories and quantities for demolishing building waste in specific time periods.[81,82]

MFA can estimate the metabolism of building materials using models that use floor space, material intensity, and building lifetime parameters.[83] Life cycle information includes buildings, categories, and quantities of demolition waste generated in a given time period for a specified region.[84] This information assists in CDW treatment or recycling.

Using steel and concrete waste as an example, our calculations predict that the amount of CDW will reach 440 million tons and 7,750 million tons in 2050 for steel and concrete, respectively. This prediction is three to four times the amount of CDW in 2000 (Figure 7). Recycled steel has the potential to be a major construction material.[85] A supply-demand analysis is needed to avoid capacity surplus for steel production. Concrete CDW requires more recycling options in addition to common practices such as pavement and aggregate.[32,86,87] Reuse options such as recycling the concrete structure directly from deconstruction could be another viable approach. As shown in Figure 7, more attention on the impact of recycling steel and concrete—especially in China where there is rapid construction and abundant demolition—is needed.

LCA and MFA integrated with GIS can help to further understand the energy demand and environmental performance of building stocks across spatial scales. GIS-based inventory modeling of production processes allows several refinements to LCA. GIS technology offers spatial data and analytical functions to quantify flows by location using lifetime, building material types, and quantities data.[88] Sustainable planning and policy making becomes easier with the application of GIS. Potential policy decisions may include refraining from short lifespan buildings, supporting adaptive reuse of buildings, and urban mining of building materials.[89] Moreover, coupling LCA with MFA and GIS can significantly advance LCT.

OVERCOMING LIFE CYCLE THINKING CHALLENGES

The LCT principles we have introduced provide direction for mitigating the environmental impacts of building materials from the

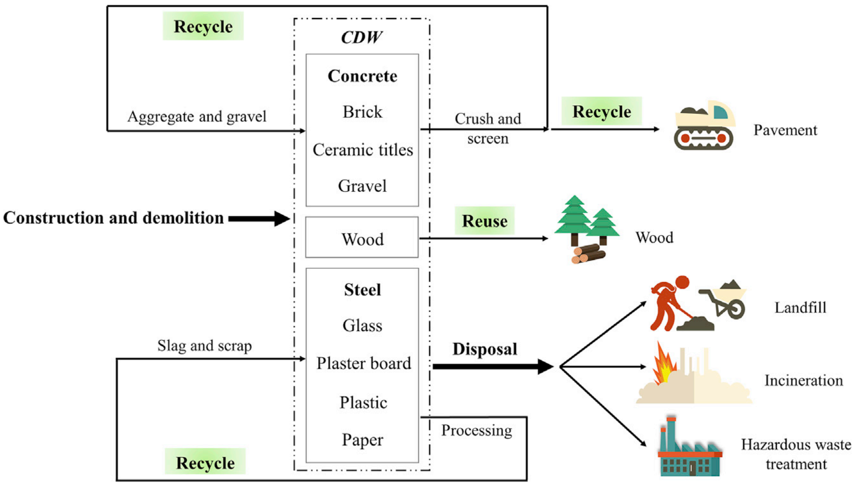
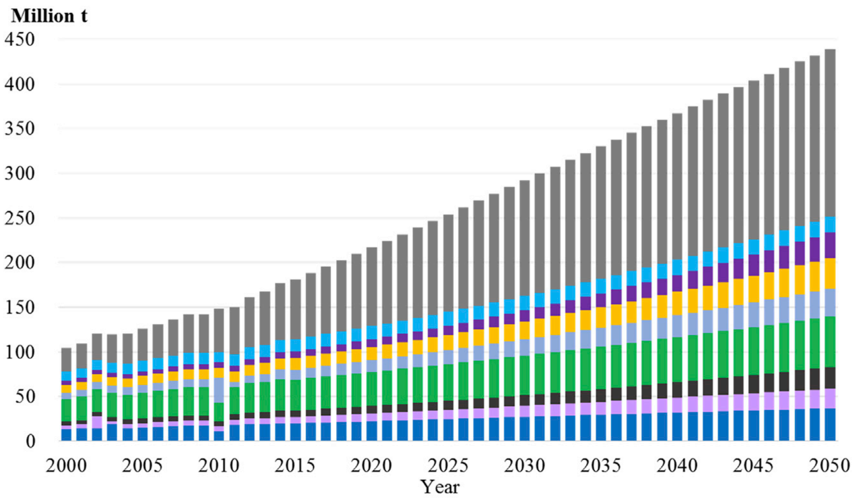


Figure 6. Construction and Demolition Waste Treatment and Recycling

A **Demolition waste-steel**



B **Demolition waste-concrete**

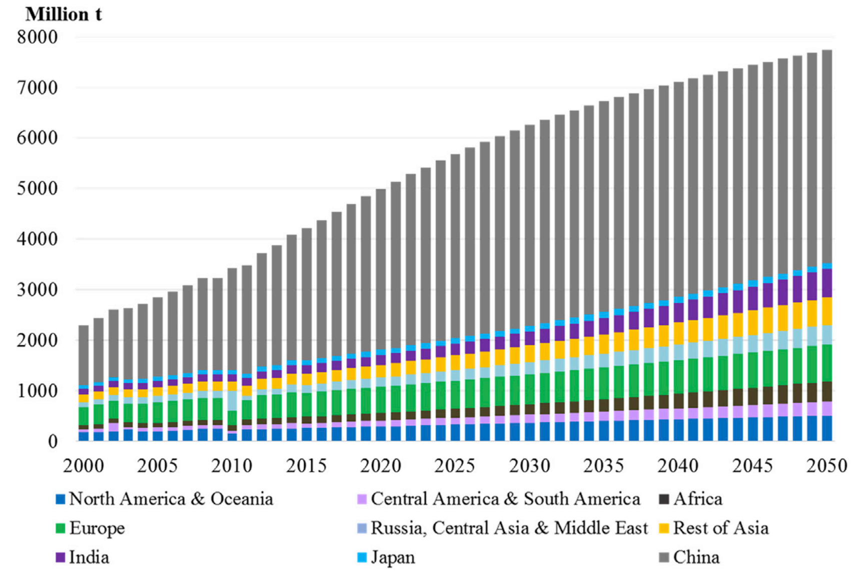


Figure 7. Global Steel and Concrete Demolition Waste Estimates, 2000–2050

(A) Demolition steel and (B) demolition concrete. Values arereclassified and calculated based on data from Deetman et al. (2019).[6] Only the median assumptions are obtained from their result presentations, the uncertainty estimates are unavailable. Details of the analysis are available in Tables S2 and S3.

life cycle or value chain perspective. These measures can help support sustainable decisions and policies using life cycle theory. We would be remiss, however, if we did not clarify the challenges of LCT in this context.

Collecting inventory data for products is one such challenge. LCI refers to the LCA accounts data. LCI may provide data on raw materials, energy, and water usage; it also may include air, water, and land emissions.[90] Figure 3 shows that the life cycle of building materials involves several processes across a value chain. Collecting inventory data for products becomes even more difficult for building materials with a long lifespan. In addition, public building LCI and databases are mostly national averages, lacking local level data, which increases the difficulty of LCA.

Big data-based tools such as building information modeling (BIM) can aid data and information collection for LCA and LCT. With data efficiently collected and monitored during the life cycle of a building and its materials from design to deconstruction, material efficiency can be enhanced by minimizing the amount of oversupply and waste produced on site. Integrated inventory data collection—as in Figures 3 and 4—can facilitate the management of environmental impacts and enable designers, contractors, and owners to make more environmentally responsible decisions.[91]

Another major challenge for applying building materials LCT is managing multiple stakeholders within the construction and building materials industry.[92,93] Policy and market mechanism designs can motivate different stakeholders to complete activities for reducing the environmental burden of building materials. Extended producer responsibility is an option to encourage recycling of building materials, including concrete, steel, and wood.[94] Attaching producer responsibility to building materials and wastes encourages manufacturers to design more sustainable and recyclable building materials.[95]

To promote CDW recycling, process monitoring of CDW among emitters, collectors, transporters, and treatment companies should be reinforced. Regions where CDW treatment and recycling is not performing well could utilize a top-down regulatory system to standardize CDW management practices.[96] Regulatory measures could include penalties for illegal CDW treatment behaviors.[96,97] Market-based measures such as reliable recycled CDW product standards[58] could to help promote a mature CDW recycling market.

Additional LCT challenges include improving tools such as LCA, MFA, and GIS through better data and indicators, hosting and facilitating expert groups to manage and generate information, and disseminating their work through integrative and broad information outlets.

OUTLOOK

There is a need to be cautious about strategies that can mitigate environmental impacts in one stage but may have more adverse impacts in other life stages. Building material value chains, including prefabricated construction or CDW recycling, require comprehensive and thoughtful evaluation. There are technological, social, temporal, and geographic concerns that can result in complex trade-offs between environmental costs and benefits. LCT for building materials can inform decision makers in choosing the most sustainable approaches, rather than relying primarily on economic decision criteria. For example, reduction is more efficient than reuse and recycling of waste for sustainable buildings within circular economic and sustainability principles; yet reduction is usually ignored. More attention should be paid to approaches for enhancing building material efficiency and reducing environmental burdens.

Building designers need awareness of how to match building materials to specific designs, while minimizing their associated environmental impacts. Designs that include end-of-life disassembly of construction materials can help achieve higher levels of recycling of building materials. In addition, sustainable urban planning should be promoted to avoid shortening the lifespan of building and civil infrastructure, especially given rapid global urbanization.

We have proposed several LCT principles and practices to mitigate the environmental impacts of building materials across the value chain. A further question would be how to operationalize these principles effectively. Understanding the needs and values of different stakeholders is critical, but balancing the needs and requirements of various stakeholders is also challenging. Key stakeholders include building designers, building material producers, the construction industry, building users, CDW treatment companies, and policy-makers. Understanding each stakeholder's concerns and designing polices to motivate them to cooperate and promote sustainable building development will be a large, but necessary, challenge that needs to be met.

This perspective highlights that building materials have a range of environmental impacts, including but not limited to fossil fuel consumption and global warming. GHG emissions should therefore not be the sole focus of strategies for minimizing the environmental impacts of building materials. By taking the whole life cycle of buildings and their materials into consideration, LCT is key to comprehensively understanding the costs and benefits of each phase and offering options to holistically improve the sustainability of the building materials value chain.

SUPPLEMENTAL INFORMATION

Supplemental Information can be found online at https://doi.org/10.1016/j.oneear.2020.10.010.

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AUTHOR CONTRIBUTIONS

Conceptualization and Methodology, B.J.H.; Investigation, X.F.G. and B.J.H; Resources and Data Curation, X.Z.X. and J.L.S.; Writing – Original Draft, B.J.H.; Writing – Review and Editing, B.J.H., Y.G., J.S., T.F., H.W.K., and J.N.; Funding Acquisition, B.J.H. and Y.G.

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