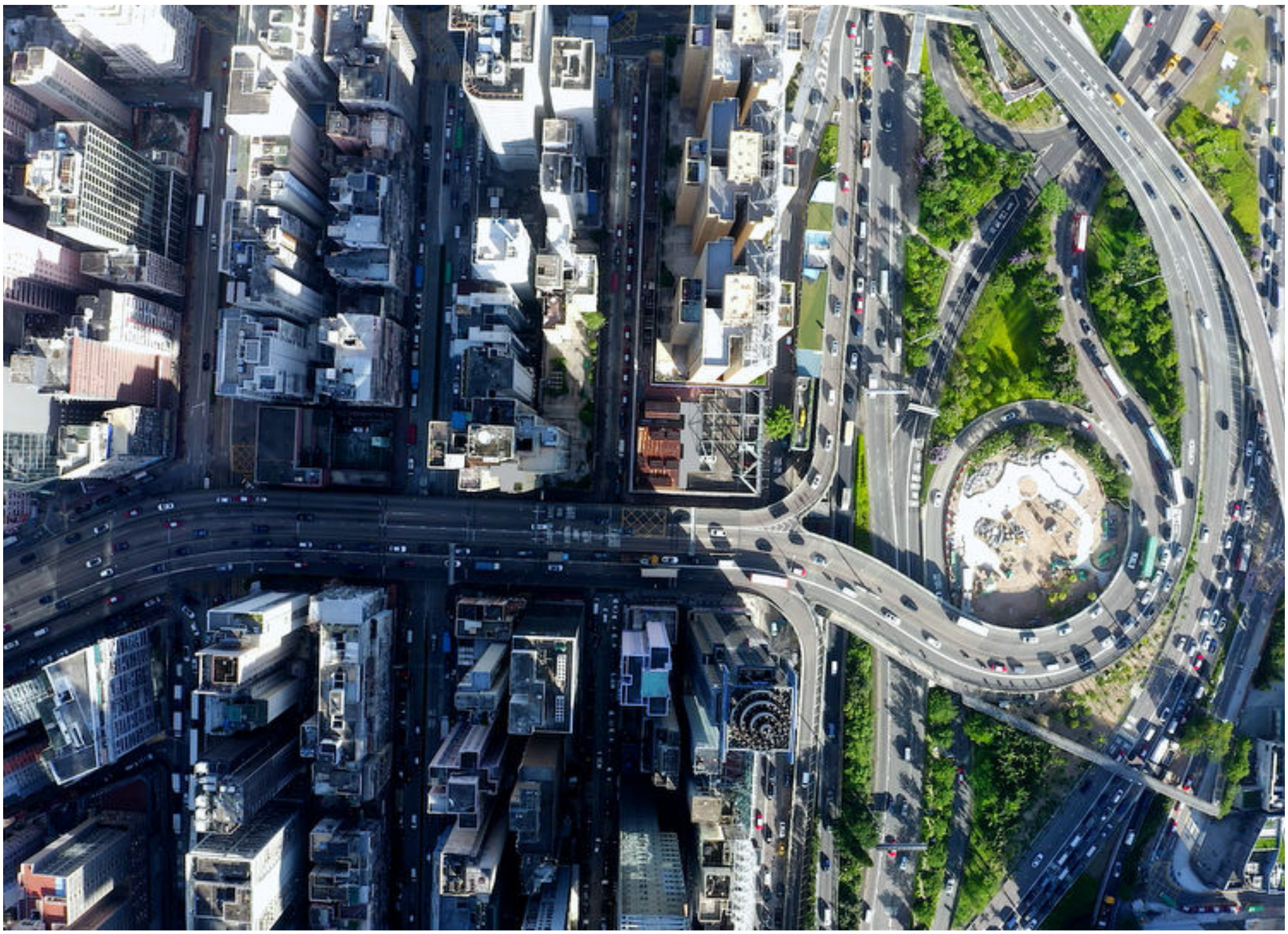
Carbon Analysis: Decarbonizing the Infrastructure Sector



How to harness data and digital solutions for carbon accounting and management

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Bentley

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Executive summary

This document provides a comprehensive approach to carbon accounting in the construction sector, showcasing Bentley's web-based solution, Carbon Analysis, as a key enabler of decarbonization. It highlights the sector's significant contribution to global carbon emissions and underscores the need for strategic action across all project phases, from decision-making to on-site activities.

Bentley supports sustainable infrastructure throughout its lifecycle by leveraging digital twin technology. This technology provides a comprehensive view of an asset, enabling professionals to optimize project delivery and performance. Built on Bentley’s iTwin® Platform for infrastructure digital twins, Carbon Analysis empowers designers and engineers to calculate, report, and visualize the embodied carbon footprint for lifecycle stages A1-A3. Integrating with LCA providers EC3 and OneClick LCA, it offers a practical, data-driven solution for sustainable construction, facilitating informed decision-making to monitor and mitigate emissions from design through construction.

Key drivers of decarbonization include political incentives, regulatory frameworks, green investments, low-carbon technologies, and social and environmental factors. Achieving low-carbon outcomes in construction demands a systematic approach, leveraging data-driven methods to quantify and manage emissions across sectors and project phases. Various strategies can reduce carbon footprints throughout the project lifecycle, with Carbon Analysis offering a versatile solution for evaluating the impact and scale of these practices at any stage. Many of these strategies are within reach but are not utilized to their full potential. By focusing on resource efficiency, circular solutions, and meticulously planned construction processes, the sector can enhance cost efficiency while significantly lowering carbon emissions. By providing comprehensive data insights, digital innovations enable effective carbon management and help project teams to allocate time and resources to sustainable design, construction, and asset management.

Terminology

Term	Explanation
Carbon accounting	The process of quantifying the amount of greenhouse gases (GHGs) produced directly and indirectly from products, assets, or an organization’s activities within a set of boundaries.
Carbon management	Proactive reduction of the carbon footprint by using carbon accounting as a numerical method.
Carbon footprint	The sum of GHG emissions and removals in a product system expressed as CO2 equivalent and based on an LCA using the single impact category for climate change (ISO 14067).
Carbon handprint	An indicator of the climate change mitigation potential. Describes the GHG emission reduction in a user's activities that occurs when the user replaces a baseline solution with the offered solution.
Carbon dioxide equivalence (CO2e)	A metric measure used to compare the emissions from various GHGs based on their global-warming potential (GWP) by converting amounts of other gases to the equivalent amount of carbon dioxide with the same global warming potential.
Digital twin	A digital representation of a physical entity, with data connections that enable synchronization between the physical and digital states at an appropriate rate.
Embodied carbon	Consists of emissions coming from material sourcing and manufacturing, logistics, and construction activities, including those associated with demolition and waste processing.
Environmental Product Declaration EPD	A standardized and verified report that transparently presents credible information about a product’s impact on the environment. The foundation of an EPD is a lifecycle assessment (LCA). It can include a whole lifecycle or only a part of it, depending on the standardization.
Greenhouse gas (GHG) emissions	Gases in the earth’s atmosphere trap heat, thus contributing to the greenhouse effect. Carbon dioxide (CO2), methane (CH3), and water vapor are the most important GHGs.
Global Warming Potential (GWP)	A measure of how much heat a GHG traps in the atmosphere over a specific time (usually 100 years), compared to CO2. GWP-total is a parameter used in carbon accounting, and it accounts for all greenhouse gas emissions. Units are measured in CO2e.

Handprint contributor	Mechanisms by which the environmental footprint of a user can be reduced and generate a handprint.
Lifecycle assessment, LCA	A methodology to quantify and assess the inputs, outputs, and potential environmental impacts of a product system throughout its lifecycle.
Operational carbon	The emissions from a building or infrastructure's ongoing operations and energy consumption.

1. Sustainability in the built environment

1. Carbon footprint of the construction sector

The construction sector is among the largest contributors to global carbon emissions, significantly impacting climate change. In 2022, global greenhouse gas (GHG) emissions reached a record 57.4 $GtCO_2e$ (UNEP 2023), continuing an upward trend observed since the 1990s. The built environment alone accounts for approximately 39% of global annual carbon-equivalent emissions (WGBC 2019), comprising both operational carbon—emissions resulting from energy use during an asset's operational phase—and embodied carbon, which includes all CO_2e emissions associated with materials.

2. Embodied and operational carbon

Embodied and operational carbon are terms frequently mentioned in discussions about the climate impacts of construction. Emissions associated with the production, transportation, installation, maintenance, and disposal of construction materials throughout all lifecycle phases are referred as embodied carbon. Operational carbon includes emissions associated with energy and water used during an asset's lifetime. The significant role of embodied carbon in construction has been widely recognized, as most of it is emitted as upfront carbon during design and construction. It has been estimated that 65%-85% of total embodied carbon emissions occur during the product (A1-A3) and construction (A4-A5) phase in building projects. (Figure 1) Since embodied carbon emissions are largely determined in the design phase, architects and engineers have a key opportunity to influence the carbon footprint.

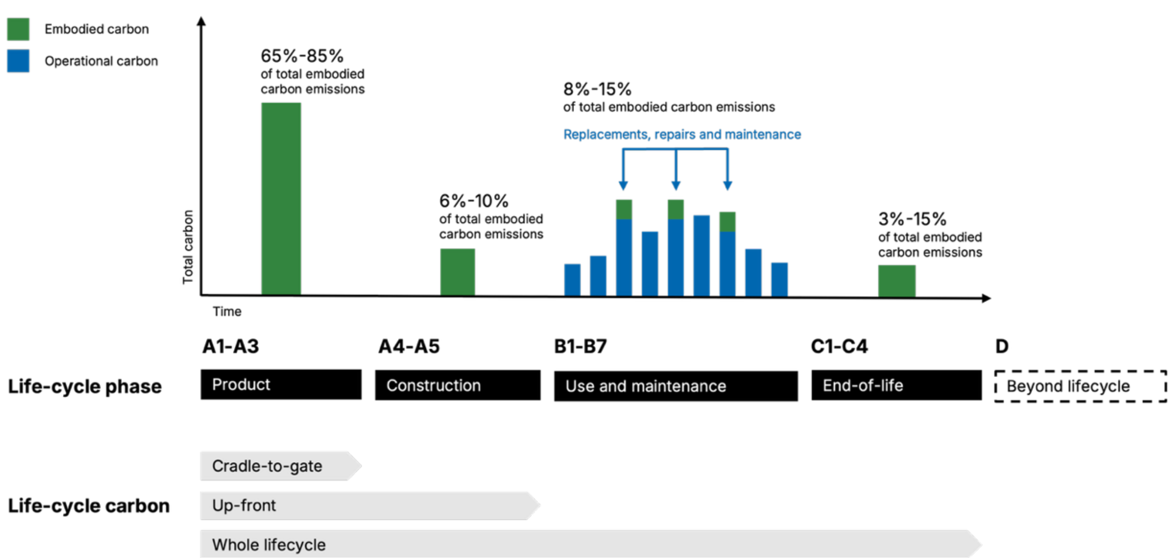

Figure 1 - Embodied carbon is defined in assets early lifecycle phases. An infrastructure asset's lifecycle has four phases (A, B, C, D), covering cradle-to-gate, upfront, and whole lifecycle stages. Image adapted from RMI 2023.

A common denominator for high embodied carbon in construction is emissions-intensive materials, mainly cement and steel, which together correspond to 14%-16% of all global GHG emissions (World Steel Association 2023, WorldGBC 2019). The embodied carbon emissions are expected to account for half of the total carbon footprint of new construction by 2050, posing a significant risk to our remaining carbon budget. It's been estimated that 75% of the infrastructure existing in 2050 is yet to be built (CDRI 2023), which underlines the importance of assessing embodied carbon emissions in the construction sector.

Embodied carbon emissions are often locked in during the construction project design phase, representing an opportunity for professional service providers, such as architects and engineers, to directly influence the carbon footprint. Therefore, opportunities for substantial reductions in embodied carbon depend on decisions made in the early lifecycle stages, as reducing it after construction is challenging. Operational carbon can be decreased during the use stage with new innovations, such as the introduction of fossil-free fuels. As operational carbon is reduced, embodied carbon will continue to grow in importance as a proportion of total emissions. Additionally, infrastructure typically has a long lifespan—often around 100 years for linear structures—and is usually renovated rather than demolished multiple times. As a result, the structure may never truly reach the end of its lifecycle, highlighting the importance of addressing embodied carbon during the design phase.

3. Main drivers for the decarbonization

Decarbonizing the construction sector presents a unique challenge, balancing the urgency of climate change mitigation with the ongoing need to develop and maintain infrastructure. Identifying the external factors, or drivers, that influence this balance is essential for informed decision-making in the pursuit of decarbonization. Digital solutions, such as Carbon Analysis, are important tools for bringing understanding to the impacts of different drivers, enabling stakeholders to assess and quantify the potential effects of various decarbonization strategies.

These drivers have been mapped using an analysis tool called PESTLE, which stands for the macro-economic factors Political, Economic, Social, Technological, Legal, and Environmental analysis. This tool is predominantly used to monitor and evaluate macro-economic factors that may influence the performance of a policy, regulation, or organization. In this context, the analysis has been applied to the drivers of decarbonization. The drivers are mapped in Table 1 and will be presented in greater detail later in this chapter.

Table 1: Key drivers of decarbonization in the construction sector are categorized by macroeconomic factors using the PESTLE analysis.

Factor	Key points
Political	- Paris Agreement and other regional policies - National and international net-zero targets
Economical	- Sustainability linked loans (SLLs), green investments, and green procurement - Carbon taxes, budgets, and market-based carbon pricing mechanisms
Social	- Public perception and demand for sustainable practices - Social impacts of climate change, particularly on vulnerable communities
Technical	- Sustainability certifications (e.g., BREEAM, LEED) and standards - Innovation in low-carbon technologies and development in construction practices
Legal	- Regional climate reporting regulations (e.g., CSRD, TCFD) - Compliance with carbon regulations and policies
Environmental	- Prevention of negative impacts from climate change - Biodiversity loss

Political and legal drivers

Climate change has been addressed through several international and national agreements aimed at creating common guidelines and targets to limit the rise in temperature. The most prominent international treaty is the Paris Agreement, a legally binding treaty on climate change adopted by nearly every nation in the world in December 2015 under the United Nations Framework Convention on Climate Change (UNFCCC). The main goal of the agreement is to limit global warming to well below 2°C above pre-industrial levels, with an additional target of pursuing efforts to limit the rise to 1.5°C. Its strategies are being implemented through various national and international regulations and policies. Most G20 countries have set net-zero targets, with some taking significant steps to strengthen and implement these commitments.

Nations and regions are pursuing net-zero targets by enforcing regulations and policies to reduce greenhouse gas (GHG) emissions. Several national and international regulations now require companies to disclose their emissions and present comprehensive emission reduction plans. These regulations reflect a global shift for greater GHG transparency. Leveraging data-driven solutions, Carbon Analysis plays a crucial role not only in successful carbon accounting, but also in supporting the acceleration of the sustainable transformation process.

> **European Union:** The European Green Deal and the CSRD (Corporate Sustainability Reporting Directive) require large corporations to report Scope 1, 2, and 3 emissions starting in 2025, with this mandate extending to smaller companies in the upcoming years. The CSRD places impact reporting on par with financial reporting through a double materiality assessment, which considers both sustainability factors that may pose financial risks to the company (outside-in) and the social and environmental impacts the company's activities (inside-out).
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> **United Kingdom:** Task Force on Climate-related Financial Disclosures (TCFD) serves as a framework for evaluating and reporting climate-related financial risks, strongly encouraging companies to disclose their GHG emissions. Large U.K. companies are required to report on their annual energy use and associated carbon emissions under SECR (Streamlined Energy and Carbon Reporting) regulations.
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> **Australia:** The NGER Scheme, Australia's primary framework for mandatory carbon reporting, requires large companies to report Scope 1 (direct) and Scope 2 (indirect from energy use) emissions. Scope 3 emissions are not currently required under NGER; however, companies are encouraged to voluntarily report Scope 3 emissions as part of their broader sustainability efforts. Similarly, Scope 3 reporting is encouraged under the ASFI (Australian Sustainable Finance Initiative) and as part of corporate sustainable reporting in certain sectors.
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> **California:** The newly adopted AB 2446 (Carbon Intensity of Construction and Building Materials Act) requires the reporting of embodied carbon in construction and building materials. The law requires new non-residential buildings, along with residential projects of a certain size, to provide lifecycle assessments and product-specific Environmental Product Declarations (EPDs) for the materials used in construction. Additionally, the law requires the California Air Resources Board (ARB) to develop a framework for monitoring and reducing GHG emissions from building materials.

Technical drivers

Certifications and frameworks

Several international and national certifications and frameworks have been developed to support decarbonization efforts and meet political and legal requirements. These certifications enable construction sector stakeholders to adopt standardized approaches and facilitate comparisons between projects. The construction sector faces diverse challenges and requires tailored solutions for different stakeholders—public bodies, private organizations, material manufacturers, construction companies, and design engineering firms. Decarbonizing the sector requires common guidelines and collective actions from all parties, supported by robust data analysis and management.

Prominent certifications for the built environment include BREEAM Infrastructure, Envision, LEED, and several frameworks established by the Green Building Councils, the World Green Building Council, and The World Business Council for Sustainable Development (WBCSD). Certifications such as LEED are well-established and widely used for buildings due to their relative uniformity, whereas the diverse and complex nature of linear infrastructure projects has made it challenging to develop and implement equally applicable and widely adopted certification frameworks. However, the use of infrastructure-specific certifications is increasing, reflecting the growing demand for a more sustainable built environment. These certificates set also requirements and guidelines for GHG assessment, emphasizing the need for streamlined and routinely performed carbon assessments in any construction project.

Envision: Envision is a holistic sustainability framework and rating system that enables a thorough examination of the sustainability and resiliency of all types of civil infrastructure. Envision was developed by the Institute for Sustainable Infrastructure (ISI), and the first version was introduced in 2012. The framework consists of a guidance manual with 64 sustainability and resilience criteria, project assessment tools, professional training, and third-party verification. Envision is widely used in the U.S. and Canada by public agencies and private organizations and associations, and it has also been adopted in selected countries worldwide.

BREEAM Infrastructure: BREEAM Infrastructure (formerly CEEQUAL) is the evidence-based sustainability assessment, rating and awards scheme for civil engineering, infrastructure, landscaping and public realm projects. The framework influences decision-making across the design, strategy, and management of projects in civil engineering, infrastructure, landscaping, and the public realm. BREEAM Infrastructure consists of eight categories, each relating to a specific area of sustainability. These are further split into 30 specific assessment issues, against which projects and contracts are awarded credits across 248 criteria. Projects seeking BREEAM infrastructure accreditation are third-party verified. This framework is widely used in Europe and selected Middle East and Asian countries.

LEED: LEED is a rating system developed by the U.S. Green Building Council (USGBC) to evaluate the environmental performance of buildings and measure their sustainability. The framework consists of various rating systems tailored to different types of buildings, spaces, and communities. LEED ratings are based on a point system, with buildings earning points for meeting certain criteria in categories such as energy efficiency, water conservation, and indoor environmental quality. LEED is widely used in the U.S. and internationally.

Low-carbon technologies

Innovation in low-carbon technologies plays a pivotal role in driving the decarbonization of the construction sector. As a major part of the asset's whole lifecycle emissions are tied to embodied carbon and especially to design and construction lifecycle phases, it is crucial to innovate solutions to reduce these emissions. Low-carbon technologies include new sustainable and low-carbon materials to replace existing emissions-intensive materials, especially concrete and steel. Using circular economy as an approach can help to minimize the carbon footprint of construction activities through recycling, reusing, and waste reduction. Moreover, advanced building systems, smart technologies, and renewable energy integration enable us to reduce operational carbon emissions.

Innovation can work also as a driver for economic viability as innovative technologies often result in long-term cost savings through energy efficiency, reduced maintenance, and increased asset longevity. Low-carbon and resilient solutions help the sector meet stringent environmental regulations and carbon reduction targets and thus meet regulatory compliance and market demand. Innovating low-carbon solutions can also be a competitive advantage for companies.

Economic drivers

Legal and political regulations create economic drivers by requiring companies, asset owners, and policymakers to prioritize sustainability in their operations and investments. These drivers include economic tools such as sustainability-linked loans (SLLs), green investments, green procurement policies, and carbon pricing mechanisms, all of which provide incentives to adopt and enhance sustainable construction practices.

- Sustainability-linked loans are loans provided to organizations where the terms, such as interest rates, are tied to the borrower's achievement of predefined sustainability targets. Unlike traditional loans, SLLs encourage borrowers to meet specific sustainability performance objectives, such as reducing their carbon footprint, increasing energy efficiency, or promoting diversity.

- Green investments refer to capital allocated to projects or companies that deliver environmental benefits, such as reducing emissions, conserving resources, or supporting renewable energy. These investments typically take the form of green bonds, equity investments, or dedicated green funds.

- Green procurement involves prioritizing environmentally friendly and socially responsible products, services, and practices throughout the procurement process. Green procurement is increasingly supported by public sector policies and regulations, which mandate sustainability criteria in tendering and contracting processes. This ensures that government-funded projects, such as transportation infrastructure or public buildings, led by example in reducing environmental impacts.

- Carbon-focused mechanisms, including carbon budgets and carbon taxes, are not yet widely implemented in the construction sector, but their use is expected to rise in future. These carbon pricing mechanisms place a financial value on emissions, urging stakeholders to innovate and adopt low-carbon solutions.

In the construction sector, different sustainability linked financial mechanisms are becoming essential for funding projects aligned with decarbonization goals. They are particularly beneficial in the construction sector as they motivate asset owners and contractors to adopt low-carbon materials, whole lifecycle sustainable designs, and other sustainable practices to achieve financial benefits. Carbon accounting is a critical tool for enabling and supporting sustainability-based economic drivers. It provides the foundation for understanding, managing, and reporting greenhouse gas (GHG) emissions, ensuring transparency and credibility in sustainability efforts.

Environmental and social drivers

The fundamental drivers behind decarbonization are adverse climate conditions resulting from climate change, which will have inevitable impacts on ecosystems and societal well-being. Environmental and social drivers are complex and interconnected. Biodiversity conservation supports ecosystem resilience, which directly benefits communities by reducing vulnerability to climate-related risks. Similarly, mitigating the social impacts of climate change fosters widespread acceptance of sustainable practices, reinforcing the construction sector's responsibility to balance ecological and societal needs. Addressing these challenges would require a comprehensive analysis, and this chapter highlights some of the most prominent drivers influencing the construction sector.

Environmental drivers

- Mitigation of negative impacts from climate change
    - Adverse climate events, such as floods, heatwaves, and other disasters significantly threaten infrastructure, emphasizing the importance of proactive mitigation strategies. Implementing proactive strategies reduces both the physical and economic risks associated with these events, safeguarding assets and communities. This includes minimizing long-term costs and enhancing the safety and well-being of communities. Proactive mitigation strategies also protect investments, ensuring the longevity and functionality of assets in a changing climate.

- Biodiversity loss
    - Climate change profoundly impacts biodiversity by altering ecosystems, disrupting species interactions, and threatening survival. These effects, compounded by human pressures including habitat destruction and pollution, intensify risks to biodiversity. Rising temperatures and shifting precipitation patterns degrade habitats and drive species extinctions as many fail to adapt. Climate change also disrupts ecosystem dynamics, such as migration and breeding, while essential services like clean water, air, and soil fertility face degradation.

Social drivers

- Common perception and acceptance
  - The growing awareness of climate change and its impacts has shifted public perception, driving increased societal demand for sustainable practices. Communities, governments, and investors now prioritize low-carbon, environmentally conscious solutions. Agreed net-zero targets also present a reputational challenge for policymakers, urging them to take responsibility and implement actions to achieve these commitments. As the built environment directly affects everyone, there is a rising demand for social acceptance and a healthy, sustainable living space. This sets increasing pressure on the construction sector to deliver safe, sustainable, and inclusive environments for all.

- Social impacts of climate change
  - Climate change worsens existing social inequalities, disproportionately affecting vulnerable populations. Rising temperatures, extreme weather events, and resource scarcity pose risks to livelihoods, public health, and housing stability. Addressing these social impacts through sustainable construction is essential for protecting communities from worsening climate events, especially in the developing countries.

2. Carbon accounting and management

1. Tools for decarbonization

Decarbonizing the construction sector requires strategic and practical actions at all levels, from strategical decision-making to activities on construction sites. Carbon accounting and management are essential approaches to evaluate the climate impact of the various actions, whether potential or implemented, and to optimize and validate low-carbon design solutions. Carbon management refers to the systematic process aiming to measure, understand, and, ultimately, reduce carbon emissions, while carbon accounting provides a quantitative framework to support this process. Several internationally recognized standards are available for performing carbon accounting or lifecycle assessments (LCA).

Lifecycle Analysis (LCA) is a standardized method for assessing a product's environmental impacts throughout its lifecycle. Recognized standards guiding LCA or carbon accounting practices include PAS 2080, EN 17471, and ISO 14067. A full LCA covers negative environmental impacts from raw material extraction to end-of-life. LCA is key for Environmental Product Declarations (EPDs), which are verified certifications providing information about a product's environmental impacts. LCA calculations can target specific lifecycle phases to understand emission mechanisms and explore emission reduction opportunities, commonly applied in EPD assessments.

Carbon accounting is a tool used to understand the mechanisms and reasons behind emission-intensive infrastructure projects. Performing carbon assessments can assist the infrastructure sector in developing low-carbon practices at all levels. However, carbon accounting can be laborious, starting from the collection of the bill of quantities to performing the actual accounting for many design elements. Often, this process is iterative throughout the design project lifecycle. Software solutions and tools can facilitate this process and reduce the burden on engineers, allowing them to allocate more time for carbon management to reduce the carbon footprint of assets and build sustainable infrastructure.

2. iTwin and sustainability

Bentley's iTwin Platform for digital twins, inclusive of supporting software and applications, delivers core outcomes necessary for sustainable and resilient infrastructure. The iTwin Platform is an open, vendor-neutral system that uses diverse data standards and open-source technology to aggregate data and promote collaboration across the supply chain. This interoperability helps monitor, report, and manage environmental impacts, such as GHG emissions, throughout different stages of infrastructure lifecycles.

Carbon Analysis is a digital twin solution being part of the iTwin Experience and it offers users the ability to analyse carbon emissions during the design process. As an evergreen asset model, a digital twin gives engineers, owner-operators, and infrastructure professionals the opportunity to understand infrastructure in complete context, including subsurface conditions and changes. This, in turn, allows them to manage compliance and regulatory concerns, monitor and reduce their environmental footprints, and prepare for and swiftly respond to the effects of climate change.

3. Bentley's Carbon Analysis

Bentley's Carbon Analysis is a series of capabilities that enable designers and engineers to efficiently calculate, report, and visualize the embodied carbon footprint from lifecycle stages A1-A3 (product stage) of their proposed design, using iTwin Experience. Carbon Analysis offers a hands-on solution for the construction sector to pursue a sustainable outcome. Carbon Analysis is included in all iTwin Experience licenses. Detailed technical information for using Carbon Analysis solutions can be found from Capabilities Data Sheet, or by reaching out to a Bentley expert.

Carbon Analysis allows users to consolidate project and asset data, whether from Bentley or other sources, into a unified iModel® (Figure 2). This approach soft facilitates the management of complex projects involving multiple stakeholders and diverse datasets. Once aggregated, the data can be processed for carbon accounting through automated quantity and volume calculations and organized into groups. Using a third-party LCA platform, including EC3 or OneClick LCA, the prepared data can be linked to corresponding emission factors and Environmental Product Declarations (EPDs). The user can complement the LCA with remaining lifecycles and other environmental impacts on the LCA providers platform. The resulting carbon data for lifecycle phases A1-A3 from EC3 can be imported back into iTwin, enabling the visualization and analysis of carbon emissions within the design through heatmaps.

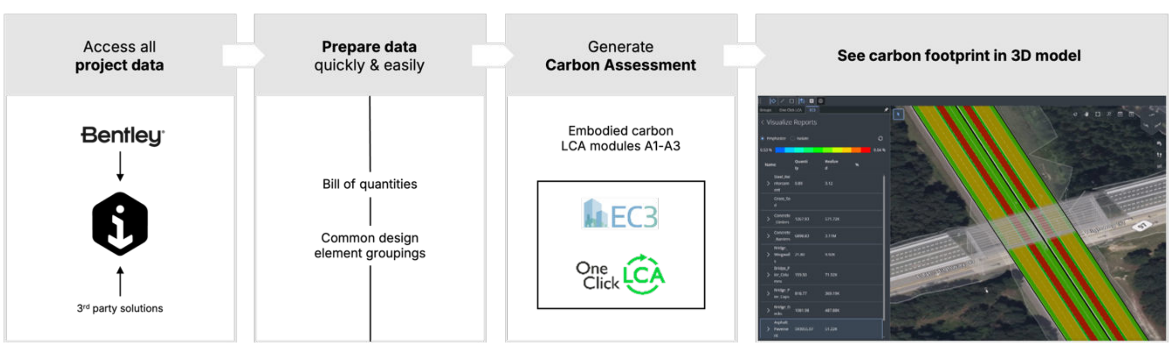

Figure 2 – Carbon Analysis process.

4. Partnering with global LCA providers

Carbon Analysis is integrated with leading LCA providers, EC3 and OneClick LCA. Both providers support compliance with the world's essential regulations, standards, and requirements, including ENVISION, BREEAM for Infrastructure, PAS2080, and others. Carbon data generated in the LCA platform can be brought back from EC3 (OneClick LCA integration does not yet allow two-way integration).

EC3

The Embodied Carbon in Construction Calculator (EC3) is a free, open-access carbon accounting tool supported by an EPD database specifically designed for the construction sector. It is owned and managed by the nonprofit organization Building Transparency. The EC3 database provides access to thousands of digitized, third-party verified EPDs. The EC3 tool enables users to locate, compare, and use EPD data to assess the magnitude of a project's embodied carbon and to perform carbon accounting. It offers carbon assessment for the product and construction phases (A1-A4) and includes several carbon management features, such as the possibility to compare and plan building projects against each other or an estimated achievable baseline.

While the EC3 database and tool are primarily developed for building projects, they also apply to infrastructure projects. More information is available on Building Transparency's website, EC3 - Building Transparency, through EC3 tool website.

OneClick LCA

OneClick LCA is comprehensive lifecycle assessment (LCA) software designed to calculate and optimize the environmental impacts of buildings, infrastructure projects, and manufacturing products. The platform also allows assessment of circularity, lifecycle cost, and biodiversity. The LCA software database includes more than 250,000 qualified LCA datasets. OneClick LCA provides full lifecycle assessment, including all the phases from A to D, and compliances with all relevant international standards. OneClick LCA is license-based based, requiring a paid subscription, which is not part of the iTwin subscription. More information is available on OneClick LCA's website, where several resources and courses are also available.

3. Data-driven carbon management

1. Carbon data as decision-making parameter

Achieving low-carbon outcomes in construction requires a structured approach to manage and reduce emissions across all sectors. Incorporating carbon accounting into routine project management helps stakeholders monitor and mitigate emissions effectively. Agile carbon solutions that integrate assessment into daily design work are crucial for changing common practices. Carbon assessments should evolve with the project to provide accurate data and support informed decision-making, helping to reduce carbon before it becomes embedded in material choices and methods.

Understanding the levels of accuracy throughout a project's lifecycle is crucial. Using data-driven solutions like Carbon Analysis helps designers achieve low-carbon outcomes at each design stage. Carbon accounting becomes more accurate as the project progresses, with estimates in the conceptual phase and better precision closer to handover (Figure 3). However, decision-making capabilities decrease over time as decisions are made and designs are set.

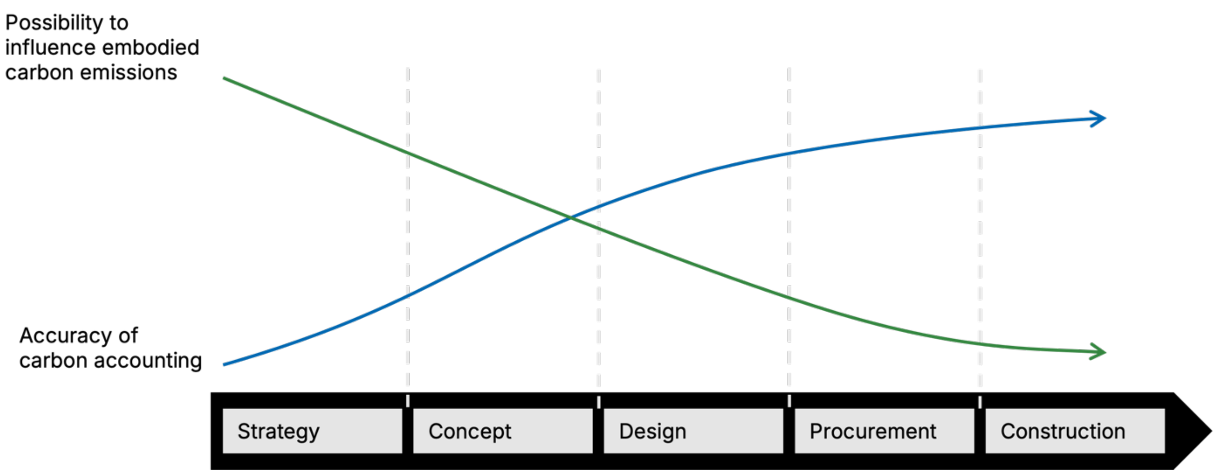

Figure 3 – Carbon accounting accuracy vs. ability to influence whole lifecycle carbon.

Infrastructure projects are complex, which also affects carbon accounting. Approaching carbon accounting from different perspectives helps to understand the sources of emissions. This understanding aids in developing low-carbon solutions and benefits both the project team and other stakeholders. Carbon analysis can be integrated into the design process, and its grouping functionality allows users to create customized groups for clearer carbon data interpretation. A comprehensive carbon assessment helps identify conflicts between disciplines, improves alignment, and provides a basis for project discussions.

Examples of different carbon accounting perspectives include:

- **Material** – Which material is responsible for the largest share of emissions?
- **Lifecycle stage** – Where are the lifecycle hotspots within each structure? How do design decisions reflect the operational phase?
- **Discipline** – How do different disciplines compare in terms of emissions? How do low-carbon solutions affect other disciplines?
- **Asset** – What is the most emission-intensive structure or area? How does it reflect public decision-making?

2. Handprint quantification

Handprint, the counterpart to carbon footprint, represents the positive impact of actions taken to reduce emissions (Pajula et al. 2021). The key difference between the definitions of carbon footprint and handprint lies in their perspective: a handprint is created by enhancing the performance of others, effectively reducing their footprint, whereas a footprint represents absolute emissions. Solutions and services, such as Carbon Analysis, are important tools to help infrastructure professionals pursue sustainable outcomes. Thus, the positive impact from these solution on infrastructure projects is described as the sustainability handprint. If we are simply talking about emissions, we can also refer to the handprint as "avoided emissions." The handprint of a product or service is calculated by comparing the footprint of a baseline scenario with that of the proposed solution when used (Figure 4).

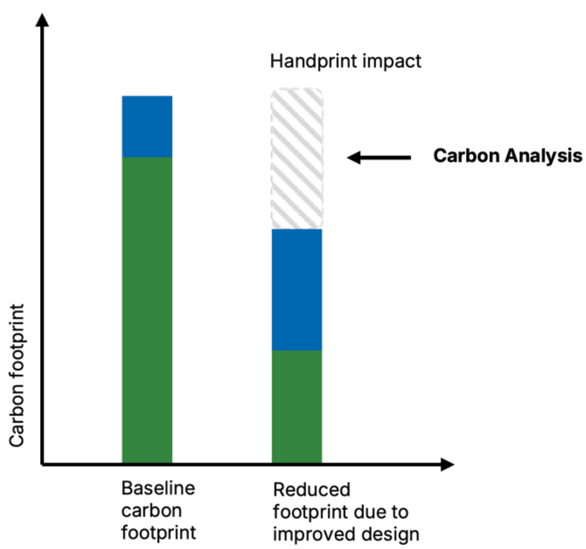

Figure 4 – Key for decarbonizing the built environment is to actively minimize carbon footprint and to develop solutions to maximize carbon handprint (according to Pajula et al. 2021).

Many decarbonization solutions for construction are already available but remain unimplemented due to limited resources (time, money), a lack of agile tools, and insufficient expertise. Software solutions can help bridge this gap by enabling and empowering engineers and all construction stakeholders to analyze and apply effective low-carbon practices and to innovate new solutions using the resources saved. This strategy advances the decarbonization of the construction sector and adds value across multiple levels.

Handprint generation lies on sustainable principles—software solutions can facilitate users to identify opportunities to apply these principles and further allow them to use the best sustainable practices into their designs. These solutions will result in minimizing asset owners' carbon footprint through the increased carbon handprint of the solution provider (Figure 5). Taking advantage of available software solutions for better design will improve awareness and ownership of sustainability.

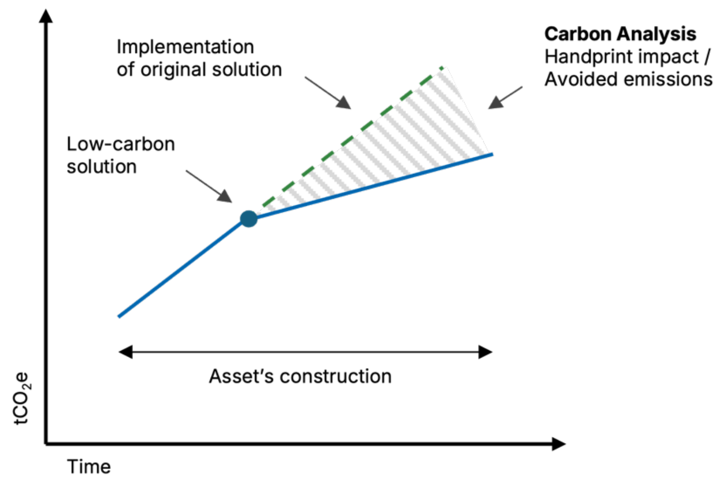

Figure 5 – Handprint can be generated by offering software solutions which allow users to develop construction design with lower emissions in comparison to the original solution (modified from WBCSD 2024).

3. Best decarbonization practices

Embodied carbon is focused on the upfront phase of an asset's lifecycle, which corresponds to the design and construction stages in construction projects. Minimizing carbon emissions during the design phase is critical to reducing lifecycle emissions. There are several solutions and approaches to mitigate the carbon footprint throughout the project lifecycle, and Carbon Analysis can be applied to any of these phases to understand the impact and magnitude of different practices.

Many proposed solutions are already standard practices. Prioritizing efficient, resource-optimized, and well-planned designs not only promotes cost-efficiency but also minimizes the project's carbon footprint. Carbon Analysis, along with other Bentley design software solutions, assists users in sustainable design efforts. Table 2 outlines some of the best low-carbon practices in each stage of project design, which can be facilitated through specialized digital solutions.

For example, Carbon Analysis enables users to utilize material estimates during early design phases to assess carbon-intensive options, allowing engineers to make well-informed decisions before finalizing the structure's location or choices. Similarly, Carbon Analysis can be used in the last step before construction to analyze the carbon emissions of individual solutions in procurement phase to support the final material selection.

Table 2: Examples of low carbon practices to apply in project lifecycle stages. Carbon Analysis can be used to collect and visualize A1-A3 embodied carbon at any stage.

Project phase	Best practices
All design stages	- Compare alternative solutions and locations in terms of embodied carbon - Use clash detection and synchronize disciplines needs and solutions for carbon optimized outcome - Establish and update carbon data management system
Design – Strategy and land-use planning	- Perform early carbon assessment and raise awareness of carbon hotspots - Pay attention to location of the project in terms of foundations solutions and need of new structures - Choose brownfield projects over greenfield projects
Design – Preliminary and detailed	- Establish a baseline for carbon emissions to follow and reflect reductive measures against the baseline - Plan to reuse and recycle existing resources and communicate the plans to construction phase - Optimize structures for material and carbon efficiency - Design structures for resilience, easy maintenance and adaptation
Procurement	- Utilize green procurement approach to implement low-carbon solutions - Use carbon accounting to compare different materials in the procurement stage
Construction	- Optimize transportation distances and trips - Aim to utilize excavation, temporary and demolition materials, and structures on-site or at other nearby projects
Operation	- Repair and recycle instead of demolition and rebuilding

4. Other environment benefits

Low-carbon design has various direct and indirect environmental benefits (Table 3). Carbon Analysis can support the whole lifecycle sustainability of an asset by helping to mitigate emissions and indirectly other adverse impacts. Typically, reduced costs, resources, and waste correspond to lower carbon emissions and the connection is two directional. Optimized transportation saves fuel and emissions while indirectly reducing traffic impacts. Lower A1-A3 emissions contribute to reduced lifecycle emissions; including maintenance during project design can further decrease operational phase emissions, reflected in lower maintenance costs and increased resiliency. Furthermore, resilient and adaptive assets have higher value and potentially higher ROI.

Circular economy is a key pilar of decarbonization, and digital solutions can facilitate the adoption of this approach. Recycling structures and materials reduces waste and space used for construction. Avoiding building green fields helps eliminate land-use changes often linked to the carbon sequestration potential of natural habitats. The circular economy has been connected to increased biodiversity, with recycled materials, reused structures, and nature-based solutions creating heterogenous environments that attract more species compared to homogeneous ones.

While many benefits of carbon management and sustainability in construction are measurable, others are beyond quantification.

- Practicing carbon management and sustainability supports the development of a sustainable construction sector.
- Carbon-optimized projects are well-regarded by the public, enhancing client and consumer perception.
- Manufacturers need customers to invest in innovative low-carbon materials.
- Recycling materials addresses resource scarcity and promotes circularity as a business concept.

Table 3: Potential direct and indirect impacts of applying carbon accounting tools, such as Carbon Analysis, in construction design projects.

Direct	Indirect
Reduced embodied carbon emissions	Reduced lifecycle emissions
Reduced use of raw material	Preventing loss of biodiversity
Less waste	Lowered maintenance costs
Lowered working hours	Fewer traffic-related impacts
Reduced costs	Reduced carbon taxes
Lowered land use	Lowered social cost of carbon
Reduced transportation needs	Improved ROI
Increased use of recycled material	Improved asset value and resilience
Awareness and ownership of sustainability	Increased biodiversity
Innovative low carbon solutions	Improved circularity as concept and business
Improved client/consumer perception	Improved environmental conditions

4. Bentley’s commitment to sustainability

Bentley software enables infrastructure professionals to sustainably design, build, and operate across the entire infrastructure lifecycle. Our digital twin technology provides a complete, integrated view of an asset so that professionals can optimize project delivery and ongoing performance. With a complete understanding of infrastructure in the wider “system of systems” in which they operate, engineers, owner-operators, and infrastructure professionals can create the right infrastructure and ensure it is built correctly.

Sustainable infrastructure includes three interconnected dimensions: environmental, social, and economic. The environmental dimension is the most well-known. Bentley is committed to global decarbonization and climate adaptation efforts. The social dimension captures the human element of sustainability. Bentley supports enabling infrastructure to equitably improve quality of life for all. Finally, the economic dimension, comprised of cost, time, and quality, is often the most prominent.

Sustainable infrastructure occurs when all three dimensions achieve balance and the trade-offs between dimensions are transparent and well understood. Sustainable, resilient infrastructure is profitable in the long term, reducing risk and boosting asset longevity. Bentley also believes it can be profitable in the short term when managed with the right tools. In summary, Bentley wants to help infrastructure professionals build better infrastructure and build infrastructure better.

Building better infrastructure means effectively designing, building, or operating the right resilient infrastructure, including projects for addressing core sustainability challenges such as energy transition, climate change, water supply, sanitation, or sustainable transportation.

Building infrastructure better means effectively and efficiently managing infrastructure in all lifecycle stages with a low environmental footprint, sustainably sourced materials, and equitable improvement of quality of life—all while keeping to the project cost and delivery schedule and ensuring the highest standards of safety. It's about doing more with less and doing better. Read more about how Bentley is helping to address sustainability challenges from Bentley’s sustainability stories and Bentley’s ESG Framework.

5. Bridging the decarbonization gap

The management of infrastructure projects is becoming increasingly complex due to the growing volume of data, long-living assets, a wider array of stakeholders, disciplines, tools, and variables. Effective and efficient data management is crucial to navigate this complexity and to achieve successful carbon management.

Software and other digital solutions play a crucial role in advancing decarbonization within the complex environment of the construction sector. While sustainable and low-carbon solutions rapidly evolve, from product manufacturing to public decision-making, deeply rooted construction practices often hinder this shift towards better outcomes.

Infrastructure digital twins incorporating Carbon Analysis offer a systematic approach for carbon analysis throughout the project lifecycle. They enable teams to evaluate and optimize design choices such as materials and systems integration. Engineers can identify carbon-intensive components, communicate implications to stakeholders, and understand trade-offs to minimize carbon impacts.

However, fully utilizing these digital twins and associated data and insights requires open platforms. Open data ecosystems facilitate integration and interoperability, ensuring data generated by stakeholders remains accessible throughout the project lifecycle. This improves collaboration, boundary control, minimizes silos, and avoids vendor lock-in. For instance, Carbon Analysis supports design teams by aggregating data from all sources, allowing users to seamlessly collect all data. Open data ecosystems foster innovation, encouraging the development of new applications and workflows, empowering stakeholders to derive greater value and adapt to evolving needs.

Continuous carbon optimization and improvement are enabled through these solutions, which also promote effective collaboration and communication with stakeholders. By aligning this approach with strategic sustainability goals, the infrastructure sector can take a leading role in advancing decarbonization efforts and setting a benchmark for sustainability across industries.

About Bentley

Around the world, infrastructure professionals rely on software from Bentley Systems to help them design, build, and operate better and more resilient infrastructure for transportation, water, energy, cities, and more. Founded in 1984 by engineers for engineers, Bentley is the partner of choice for engineering firms and owner-operators worldwide, with software that spans engineering disciplines, industry sectors, and all phases of the infrastructure lifecycle. Through our digital twin solutions, we help infrastructure professionals unlock the value of their data to transform project delivery and asset performance.
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