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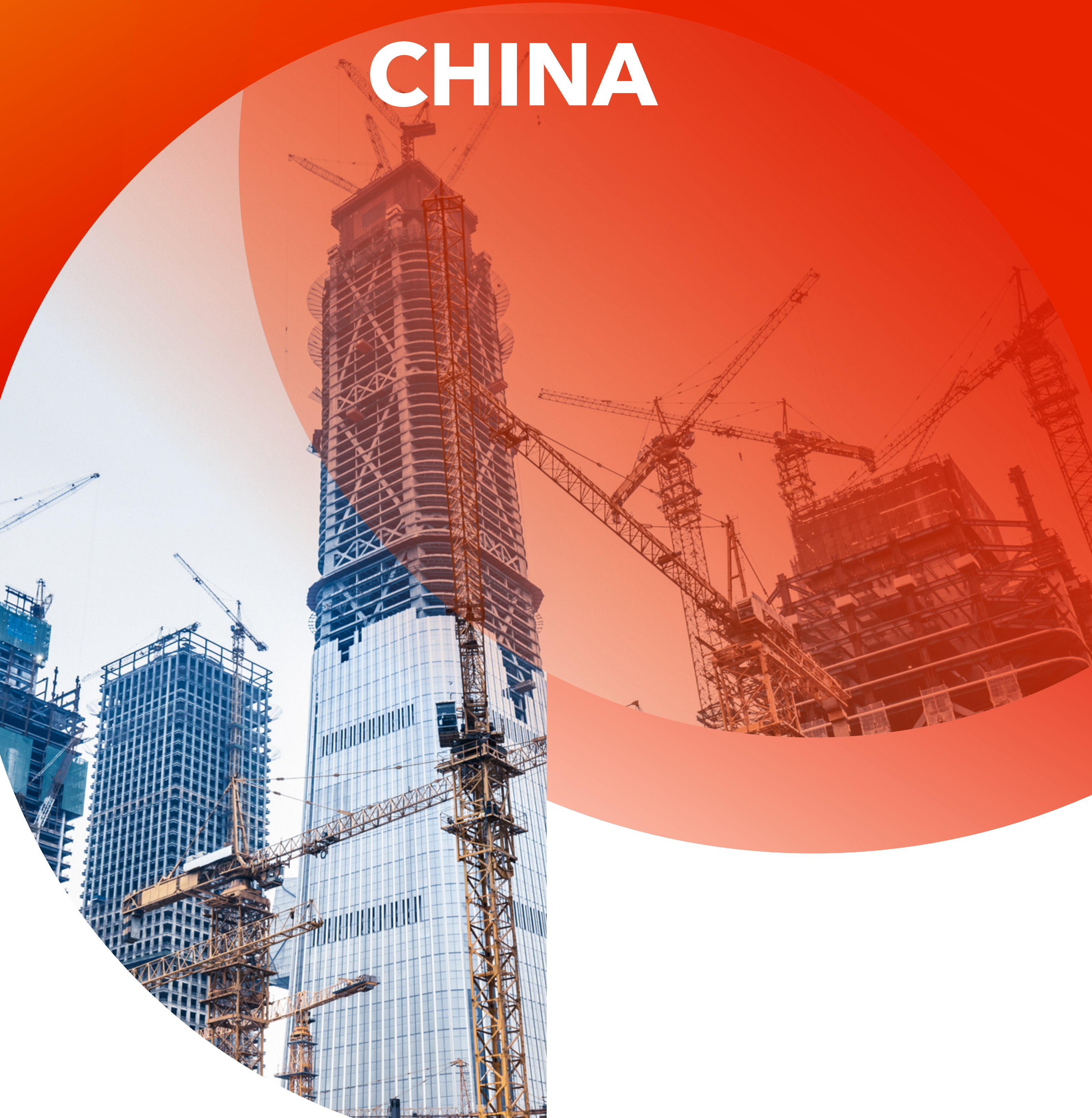
Circularity in the Building Sector

CHINA



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Introduction

Purpose of the Report

This report provides an overview of the current state of circularity and sustainability in China's building and construction sector. It aims to offer practical insights and recommendations to facilitate the transition towards a more circular and sustainable model. By reviewing relevant policies, the report highlights the status quo, key stakeholders, areas for improvement, and actions needed. It also presents examples of practices at different construction stages, showing the diverse solutions and challenges when applying circular economy principles and implementing sustainable consumption and production (SCP) strategies in China. The findings and recommendations are in line with China's national goals for carbon neutrality and its international commitments, such as the Paris Agreement on Climate Change, the 2030 Agenda for Sustainable Development, and the New Urban Agenda.

The report is part of a broader SWITCH-Asia Technical Advisory (TA) project aimed at strengthening SCP and circularity in the building and construction sector across multiple countries. It outlines key policies that shape the performance of the value chain and practices within the building and construction sector in China, breaking down action areas sector with responsible authorities. The cases presented in the report highlight diverse solutions and challenges across various construction stages, offering practical insights to enhance energy efficiency, environmental performance, and potential to promote sustainable consumption and production in particular. Moreover, by performing the report, several stakeholder groups, including government bodies, industry players, and researchers are engaged. By providing China-specific insights, identified strategic needs, challenges, and opportunities, the report can inform and support stakeholders to formulate targeted strategies and actions towards a circular economy, and contribute to the broader TA project's goals. Therefore, it contributes to the global effort to scale up SCP policies and practices, as well as the international commitments, including the Sustainable Development Goals (SDGs) and the Paris Agreement.

Scope

China's building and construction sector is an important pillar industry in China's national economy, which plays a crucial role in promoting economic growth, alleviating social employment pressures and advancing new urbanization. During the 13th Five-Year Plan period (2016 to 2020), China's construction industry expanded 5.1% annually in value-added output, maintaining a contribution of over 6.9% to the national GDP. In 2020, the total output value of the construction industry reached 26.39 trillion yuan, with a value-added output of 7.2 trillion-yuan, accounting for 7.1% of the national GDP. The total construction area amounted to 14.947 billion square meters, and the sector provided jobs for approximately 53.66 million people[1].

The is also one of the key areas for both energy consumption and carbon emissions in China. In 2020, the sector's total carbon emissions throughout the entire lifecycle reached 5.08 billion tons of CO_2, accounting for 50.9% of the national carbon emissions[i]. The main sources of these emissions were the production of building materials and the operation of buildings, contributing 28.2% and 21.7%, respectively[2].

Given the development experiences of developed countries, factors such as accelerated urbanization, improved living standards, and an increased emphasis on the tertiary industry are driving higher demands for environmental quality and living standards. It is expected that there is still room for growth in building area and energy consumption levels. Thus, China's building energy consumption will continue to grow for an extended period, presenting significant challenges for energy conservation and better environmental performance in the sector.

The report covers China's building and construction sector, involving cases from regions across different climate zones of the country. It also includes cases at various stages of the construction lifecycle, planning and design, material manufacturing, operation and management in particular. The report also highlights the

i In the calculation, the whole-process carbon emissions refer to the carbon emissions in three stages: building material production, construction, and operation.

importance of integrating renewable energy technologies and digital solutions in construction, manufacturing and maintenance to reduce energy consumption and environmental impact.

Methodology

Data collection and analysis approaches

The sources of data included statistical databases and sector reports, which provided detailed insights into energy consumption, carbon emissions, and other relevant metrics of the sector. Besides, extensive online research was conducted to gather comprehensive information from various sources, such as governmental and organizational websites, news articles and official social media accounts. Additionally, publicly available data from project consortiums were collected, which often included specific details on project progress, outcomes, challenges, and innovative solutions. Expert consultation and stakeholder engagement further supplemented the quantitative data, providing a deeper understanding of policy implementation, technology application, and practical challenges faced on the ground. By integrating different data sources, the report aims to provide a holistic view of the sector's current state and future potential for circularity and sustainability.

Identification and Engagement of Key Stakeholders

Key stakeholders were identified through the researcher's organizational network, previous project collaborations, and expert networks developed through conferences and events attended. These stakeholders included local administrations' staff, experts and networks associated with the Ministry of Housing and Urban-Rural Development (MOHURD), the Ministry of Science and Technology (MOST), other relevant agencies, enterprises as well as research institutions. The project outreach strategy focused on maintaining these key governmental partnerships to influence policy-making and actions. Through the strategic engagements, a broad range of sector stakeholders was involved, contributing to the formulation of reflective and practical recommendations.

The report provides an overview of the integration of circular economy principles in China's building and construction sector. It presents practical solutions at different stages of the lifecycle, highlights key stakeholders, opportunities and suggests areas for improvement. Key insights include the importance of considering circularity and sustainability from the planning stage through to construction and operation. Besides, collaboration among stakeholders, including government agencies, private sector partners, and academic institutions, is crucial for driving innovation, increasing efficiency, and reducing environmental impact. The use of digital tools, green materials, and smart infrastructure has proven effective in improving efficiency and sustainability. However, challenges remain in standardizing practices and ensuring consistent application across projects due to the complexity of the value chain in China. These findings emphasize the need for comprehensive technical guidelines and policy support to enhance circular economy practices in the building and construction sector in China.

This report contributes to the understanding and integration of circular economy principles in China's building and construction sector. By reviewing the policy landscape and value chain performance, highlighting practical solutions and identifying key challenges, the report offers insights for improving resource efficiency and reducing environmental impact. It emphasizes the importance of collaboration and innovation in driving the transition towards a more circular and sustainable construction industry, aligning with broader sustainable development goals. The findings and recommendations can inform future projects and policies, promoting the widespread adoption of circular economy practices globally.

1. Screening the Building Sector's Value Chain

1.1 Background

China has experienced the largest and fastest urbanization process in human history. At the end of 1949, when the People's Republic of China was founded, the urbanization rate was 10.64%. With the recovery and growth of the national economy, the number of people working and living in urban areas increased substantially. By the end of 1990, it had reached 26.41%. By 2011, it surpassed the 50% mark, reaching 51.83%, and climbed to 67.00% by the end of 2024, with an average annual increase of about 0.75 percentage[3].

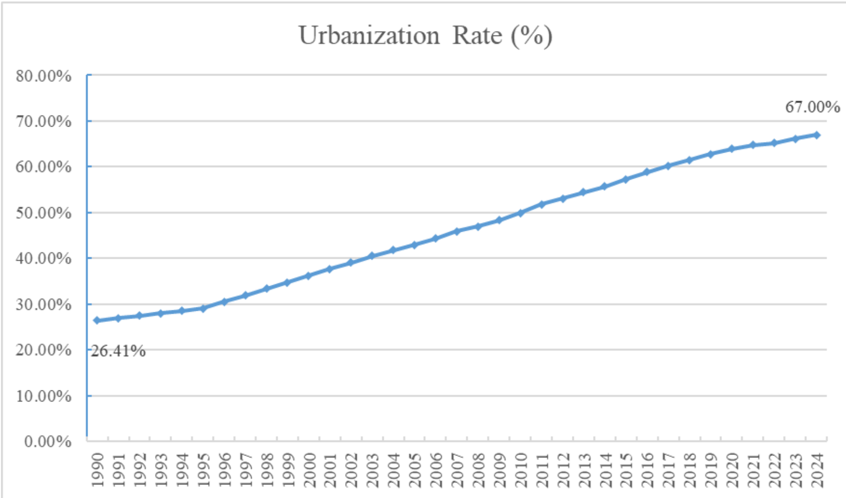

Figure 1 Urbanization rate of China from 1990 to 2024[ii]

As a fundamental industry crucial to the national economy and people's livelihood, the building and construction industry is a key component of the national economy and a significant part of urbanization. Its development trajectory is highly consistent with China's urbanization process. In 1952, the total output value completed by construction enterprises across the country was 5.7 billion yuan. By 2011, this figure was 11.6 trillion yuan, and by 2023, it had reached to 31.6 trillion yuan, with an average annual growth rate of 12.9% from 1953 to 2023[4]. In 2023, construction enterprises nationwide achieved an added value of 8.6 trillion yuan, accounting for 6.8% of the Gross Domestic Product (GDP). The contribution rate of the construction industry's added value to GDP was 8.8%, and its average growth rate has long outpaced the overall growth of the national economy (ibid). The construction industry was also among the first sectors in China to embrace reform and opening up since 1978. After the reform and opening up, the scale of the construction industry continued to expand and the number of enterprises increased. By the end of 2022, there were 143,000 construction enterprises nationwide, marking a remarkable leap in the industry's scale (Figure 2).

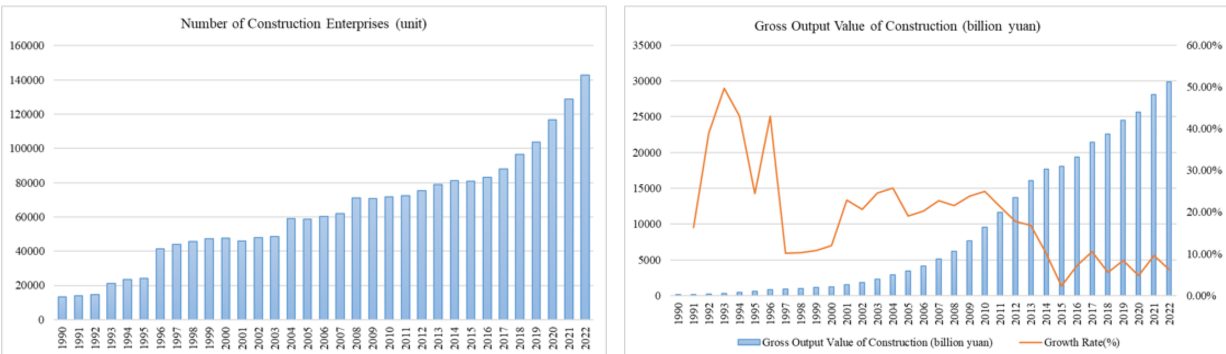

Figure 2 The number of construction enterprises (left) and the gross output value of the construction industry (right) from 1990 to 2022

ii The annual statistics on the total number of the population does not include Hong Kong, Macau special administrative region and Taiwan province and overseas numbers. Data were derived from the database of the National Bureau of Statistics of China. In addition, unless otherwise mentioned, all the figures (such as charts and graphs) presented in this report are created by the author.

With the progress of fast urbanization and the improvement of people's living standards, China's construction sector has been on the rise (Figure 3). In terms of construction capacity in 2024, the national construction industry had a total construction area of 13.68 billion square meters and a completion area of 3.44 billion square meters. This covered various building types, such as residential, factories, scientific research, and office buildings (Figure 4). The area of residential buildings is the majority in the last two decades.

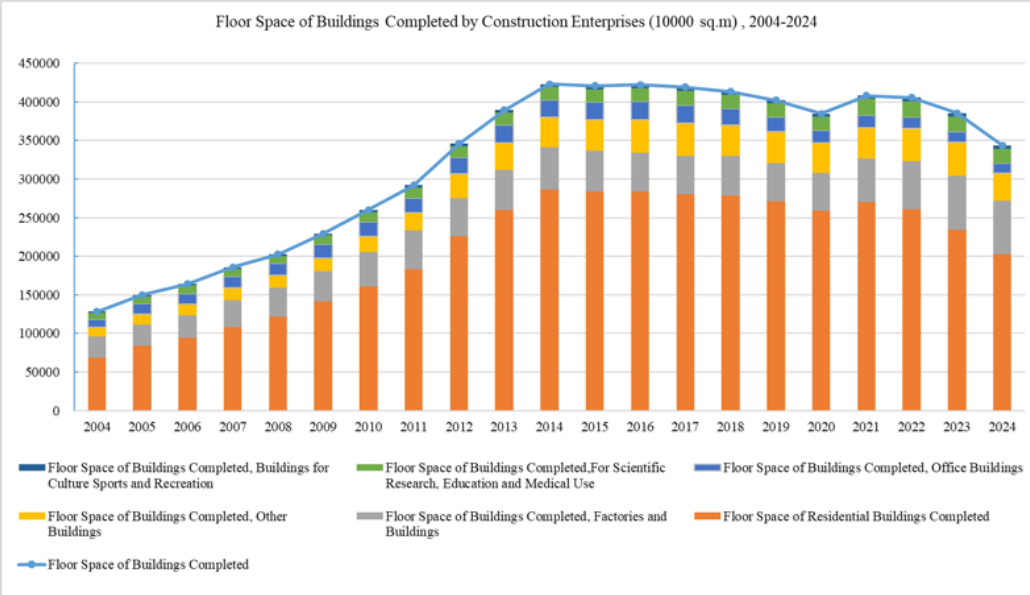

Figure 3 Area of buildings completed by type from 2004 to 2024[iii]

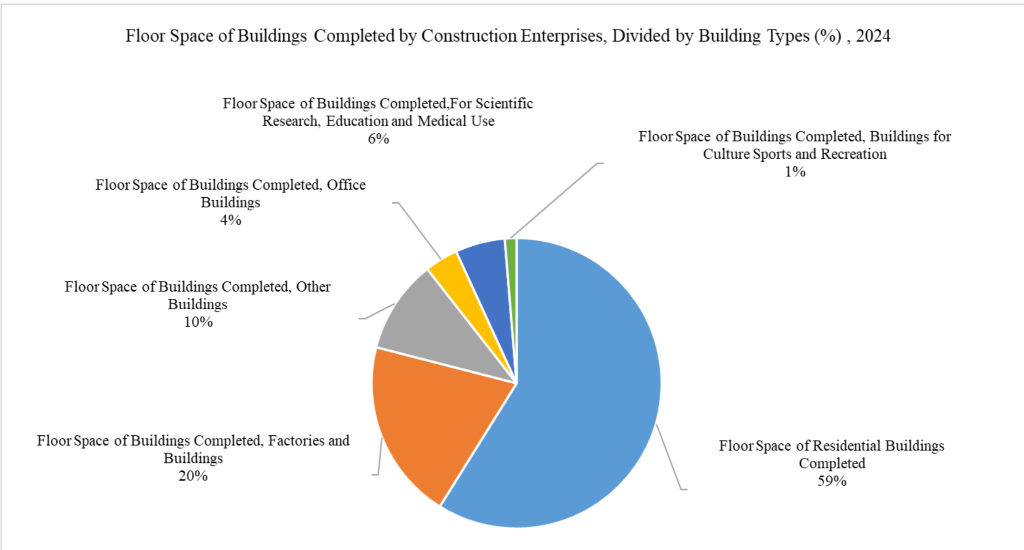

Figure 4 Area of buildings completed by type in 2024

China has a substantial existing building stock, likely the largest in the world. According to the EU Building Stock Observatory factsheet, the total floor area in EU27 was approximately 27.2 billion square meters[5]. By comparison, it is estimated that in 2020, the total building stock in China was 69.6 billion square meters, of which 80% were residential and 20% were public buildings. Urban residential buildings accounted for of 32.0 billion square meters, accounting for 58% in the residential building floor area[2]. Currently, the construction industry is experiencing a significant transformation, with accelerated progress in green building retrofitting. By the end of 2022, the cumulative green building area constructed nationwide had exceeded 11 billion square meters, and the cumulative energy - saving building area had exceeded 30.3 billion square meters[4]. Energy-saving buildings accounted for over 64% of the urban civil building area. Moreover, more than 1.8 billion square meters of existing urban residential buildings had been retrofitted for energy efficiency (ibid).

iii Floor space completed refers to the area of all buildings completed in the reference period, which have been appraised and accepted or come up to the designed standards and have been put into use.

Regarding the materials, China is a major global producer and exporter. Since 2014, the production volumes of major building materials products such as cement, concrete and cement products, architectural technical glass, and architectural sanitary ceramics, have each reached historical peaks successively and then started to decline. In the domestic market, fixed asset investment has been the main driving force for the development of the building materials industry, with nearly 70% of the building materials industry's dependence on real estate investment and infrastructure investment[6]. In recent years, as China's real estate investment and infrastructure investment have been on a continuous decline, especially with the profound adjustment in the real estate industry commencing in the second half of 2021, the economic operational speed of the building materials industry has also been on a downward trend since 2022. This has directly or indirectly affected related building materials sectors such as cement, architectural glass, commercial concrete, and architectural sanitary ceramics.

Meanwhile, with the consumption upgrade in China and the emergence of new markets, the emerging markets of industrial consumption and household final consumption have been increasingly driving the building materials industry. New industries or new consumer demand markets with terminal product attributes have become new development drivers for the building materials industry, thereby promoting the development of industries such as technical glass and composite materials. For example, resident terminal consumption represented by decoration and renovation has maintained rapid growth in recent years. Promoting the product upgrading and sustainable development of the building materials industry in the full life-cycle has becoming the core directions for future development.

In terms of international trade, China's building materials export covers multiple regions globally, with a focus on industrialised countries, mainlyEurope and US, as well as developing economies along the "Belt and Road Initiative." Data shows that since 2021, both the import and export values of building materials and non-metallic mineral products have both shown a downward trend. In 2023, China's export amount of construction materials and non-metallic mineral products was 43.96 billion US dollars, a decrease of 11.0% compared to the previous year[7]. Specifically, the export amount of building materials and non-metallic mineral products to the US decreased by 20.7% compared to the previous year, and the export amount to EU member states decreased by 10.2%. The import amount of building materials and non-metallic mineral products was 34.59 billion US dollars, a decrease of 1.2% compared to the previous year. In 2024, the export amount of building materials was 35.6 billion US dollars, a year-on-year decrease of 13.4%, and the import amount of building materials was 21.47 billion US dollars, a year-on-year decrease of 35.3%. These figures indicate that China's import volume of building materials is relatively small, mainly relying on domestic production capacity.

The export of Chinese building materials and construction products is subject to the laws of the exporting countries. Taking the EU region as an example, Chinese building materials exports need to comply with the Construction Products Regulation (CPR, (EU) No 305/2011)[8]. This regulation requires all construction products to pass CE certification and provide proof of environmental sustainability, covering products such as doors and windows, cement, steel, and insulation materials. These requirements have had a significant impact on the import of building materials. In October 2023, the EU's Carbon Border Adjustment Mechanism (CBAM) came into effect and entered a transition period, covering building materials and construction products such as steel and cement[9]. It requires companies to declare the full life cycle carbon emission data of their products. In June 2024, the European Parliament and Council adopted Regulation (EU) 2024/1781, the Eco-design for Sustainable Products Regulation (ESPR), which establishes a comprehensive framework for setting eco-design requirements and further strengthens the environmental sustainability requirements for building materials products[10]. These regulations cover not only the full life cycle management of building materials but also aspects of sustainability such as recycled material traceability, carbon footprint, and environmental footprint disclosure. For example, for building insulation materials, it is necessary to have good thermal insulation performance while ensuring that energy consumption and harmful substance emissions during the production process meet the regulations.

To comply with EU regulations, Chinese building materials enterprises need to improve their production processes, raw material sourcing and waste management, leading to increased operational costs. These challenges, however, drive technological innovation and industrial upgrading. The sector us compelled to increase R&D investments, optimize manufacturing efficiency, and accelerate the transition toward low-carbon production, circular resource utilization, and intelligent systems, which are also in line with the 2030

Sustainable Development Goals.

Given the impact of the EU regulations on the exports of Chinese building materials and construction products, it is important for enterprises to strengthen their technical capabilities. This includes the understanding of the scope, compliance frameworks, enforcement mechanisms of EU laws (e.g., ESPR, CBAM). There is also a need to have practical guidelines. These include effectively integrating eco - design principles into product development processes. By doing so, products can better meet the environmental sustainability requirements set by the EU. Additionally, adopting digital tools to enhance supply - chain transparency is crucial. This not only helps in demonstrating compliance but also in building trust with international partners.

Introduction to key concepts for bringing circularity to the built environment's lifecycle

The global construction industry constitutes a major sector of resource utilization and environmental repercussions, accounting for approximately 50% of all extracted raw materials, 40% of total energy usage, and over one-third of worldwide waste production, predominantly from construction and demolition (CDW) activities. This significant environmental impact results directly from its persistent commitment to a linear economic model defined by a 'take-make-dispose' value cycle.

This paradigm accelerates the exhaustion of limited virgin resources, exacerbates landfill pressure, and leads to considerable economic and material value loss at a building's end-of-life, while the high embodied carbon from manufacturing new materials significantly contributes to global greenhouse gas emissions. In addressing these systemic difficulties, the circular economy (CE) offers a transformational framework designed to unlock economic activity from resource consumption. It aims to reinvent value generation by closing material loops, prolonging the functional lifespan of buildings and structures, and eliminating waste from the initial design phase onwards.

At the same time, the built environment consumes a large amount of energy for heating, cooling, lighting and other services. Thereby, the construction and building sector play a significant role in driving global carbon emissions, accounting for nearly 40% of total energy-related CO_2 emissions when considering both direct operational emissions and embodied carbon from construction. Decarbonizing the building sector, which targets the planning, construction materials, construction, occupation/use, and demolition phases, is therefore a critical component of global efforts to combat the climate crisis and moving toward more sustainable, circular consumption patterns. By integrating material- and energy-efficient circularity-oriented building designs and renewable energy systems, buildings can drastically cut down on greenhouse gas emissions and other pollutants and decrease their material footprint. Optimising both the materials production and the use of materials not only minimises this material footprint but also extends the lifespan of buildings, reducing the frequency of resource-intensive construction cycles.

The 10 R model of activities implementing circular economy principles

A key operational framework for implementing CE principles within the built environment is the 10 R model, which provides a hierarchical ladder of circularity strategies, prioritizing higher-value retention actions to guide decision-making from project inception through to deconstruction and material recovery. The 10 R model provides a framework for a more resource-efficient system, starting with the most preferred options:

R0	Refuse	Make product redundant by abandoning its function or by offering the same function by a radically different (incl. digital) product or service.
R1	Rethink	Make product use more intensive through product-as-a-service, reuse and sharing models or by putting multi-functionality
R2	Reduce	Increase efficiency in product manufacture or use by consuming fewer natural resources and materials.
R3	Reuse	Re-use of a product which is still in good condition and fulfills its original function (and is not waste) for the same purpose for which it was conceived.

R4	Repair	Repair and maintenance of defective product so it can be used with its original function.
R5	Refurbish	Restore and old product and bring it up to date (to specified quality level).
R6	Remanufacture	Use parts of a discarded product in a new product with the same function (and as-new conditiion).
R7	Repurpose	Use a redundant product or its parts in a new product with different function.
R8	Recycle	Recover materials from waste to be reprocessed into new products, materials or substances whether for the original or other purposes. It includes the reprocessing of organic material but does not include energy recovery and the reprocessing into materials that are to be used as fuels or for backfilling operations.
R9	Recover	Recovering energy content of materials in the waste stream.

Figure 5 - 10 R model

The implementation of the 10 R model in construction also operationalizes Sustainable Consumption and Production (SCP) patterns within the built environment. The highest-order strategies—Refuse, Rethink, and Reduce—directly target the consumption nexus by enhancing resource efficiency during the design phase. This entails the application of advanced methodologies such as Design for Disassembly (DfD) and Design for Adaptability (DfA), which integrate future value recovery into the initial building design, alongside the implementation of lean construction principles to reduce material offcuts and waste.

The five activities ranging from Reuse, Repair, Refurbish, Remanufacture to Repurpose are fundamental to a sustainable production system. Their emphasis is on maintaining the embodied energy, carbon, and economic value of existing buildings and components, which extends their functional service life and reduces the need for primary resource extraction and virgin material production. This systemic transition is dependent on various enabling factors. Digitalization can become an essential tool, as Building Information Modelling (BIM) progresses into detailed “digital twins” and “material passports” that offer specific data on component specifications, maintenance history, and deconstruction protocols, thereby enabling future reuse and remanufacturing. This could also mean a shift in business models, for example from linear take-make-waste models to Product-as-a-Service (PaaS) systems, wherein manufacturers maintain ownership of assets such as facades or HVAC systems and lease their functionality, thereby promoting durability and facilitating end-of-life take-back.

The integration of circular principles, supported by policies like Green Public Procurement (GPP) and Extended Producer Responsibility (EPR), reduces the ecological footprint of the sector while also generating economic opportunities. This approach leads to new markets for secondary materials, creates skilled jobs in remanufacturing and deconstruction, and lowers the lifecycle costs of buildings and structures, while minimising their economic externalities, like pollution and waste, which are unaccounted for in the current linear paradigm.

The 10 Rs in a building’s lifecycle: the six “stages” of construction

Integrating circular economy considerations into the construction sector necessitates a systemic transition from the current linear model. Utilizing the 10 R framework, the principles of circularity can be mapped directly onto the specific phases, or “stages”, of a construction project’s lifecycle. The circularity requirement is simultaneously incorporated into every stage of the process, ranging from initial macro-level planning decisions to the detailed micro-level aspects of material recovery, and demolition as the final step for closing of the circularity loop. Each stage presents distinct opportunities and challenges, yet they are closely interconnected; decisions made in the initial phases significantly influence the circular potential achievable at the conclusion of a building’s life. Construction sector actors must cohesively apply these principles across all six stages of the lifecycle to fully embrace circularity.

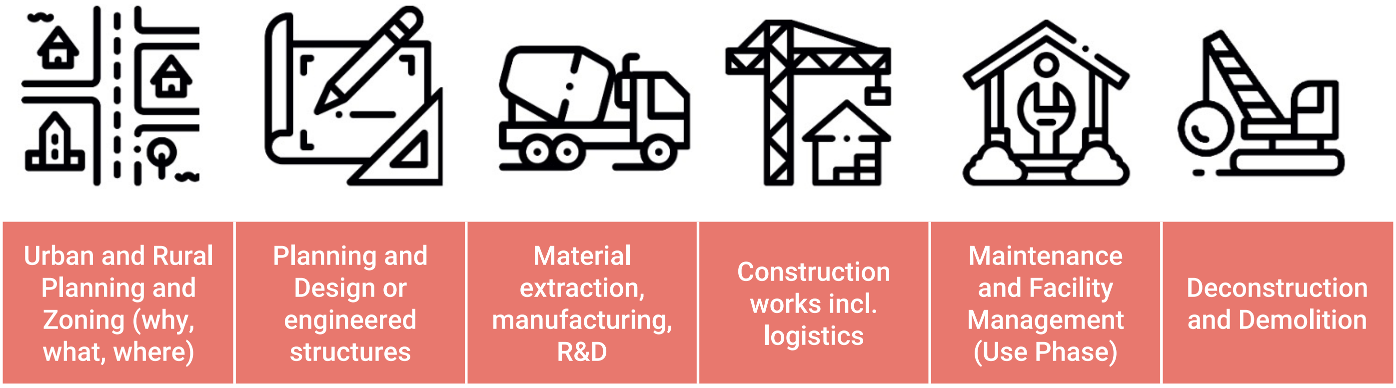

Figure 6 – Six stages of construction

In each stage, there are fundamental considerations for applying circular principles:

1. Urban and Rural Planning and Zoning (Why, What, and Where)

   This strategic stage offers the highest potential for circular impact by applying the principles of Refuse and Rethink. Instead of defaulting to new builds, planners can prioritize the adaptive reuse of existing structures.

2. Planning and Design of Engineered Structures

   This is where circularity is embedded into the physical asset through Rethink and Reduce practices. Architects and engineers have a critical role in designing for longevity, adaptability, and eventual disassembly allowing for Reuse, Repurpose, Remanufacture, and Recycle.

3. Material Use, Manufacturing, and R&D

   This stage focuses on closing material loops in the supply chain through Recycle, Remanufacture, and Reduce. It can also set the basis for Repurposing and Reuse.

4. Construction Works incl. Logistics

   Construction is based on decisions made during all prior phases. On-site execution is crucial for minimizing immediate waste; value preservation of materials is achieved through Reduce and Reuse strategies.

5. Maintenance and Facility Management

   The use-phase is where value is preserved and a product's life span is extended through Repair, Refurbish, and Reuse.

6. Deconstruction and Demolition

   This final stage in a circular model focuses on Reuse, Repurpose, Remanufacture, and Recycle.

The transition to a circular system is a complex and incremental process, requiring the cooperation of a multitude of actors over different time horizons. For example, the potential for value recovery during deconstruction is fundamentally determined by design decisions made in the planning phase. The initial and essential action is to commence the process by identifying committed decision-makers and implementers. Implementing a singular circular practice, such as enhanced on-site waste segregation or the design of a project for disassembly, fosters essential knowledge, illustrates economic feasibility, and generates the momentum required for wider systemic adoption. It also demonstrates the need to shift policy frameworks towards circularity, creating the right incentives at different governance levels. A comprehensive shift would also include sanctions for non-circular practices, and monitoring to inform where incentives and sanctioning mechanisms need adjustment, as well as making linear models less profitable and feasible at national level, for example through taxation and import requirements. This can spur innovation and a shift in market actors' priorities.

1.2 Key Challenges

1.2.1 Resource Consumption

The main primary materials used in China's building and construction sector are steel and cement, accounting for over 90% of the carbon emissions from the manufacturing stage of the value chain[iv], making them the largest contributors to carbon emissions in the industry. Other materials, such as lime, gypsum, sanitary ceramics, architectural glass, and wall materials, also play a role, with the entire production of building materials representing 28.2% of the country's total carbon emissions[2].

The sourcing of the materials is diverse, with a strong emphasis on domestic production. Steel and cement are predominantly sourced from large-scale domestic operations, although certain specialty or high-quality materials may be imported. China has been the top cement producer globally since 1985, currently producing around 55% of the world's total output. The real estate sector (40-45%) and infrastructure (35-40%) are the primary consumers of cement in China, which is extensively used for concrete, mortar, and other binding materials[11].

China also leads the world in steel production and consumption. In 2020, the country produced 1.06 billion tons of crude steel, representing 56.4% of the global output, and consumed 995 million tons, accounting for 56.2% of the world's steel usage[12]. Within China, the construction industry alone accounted for 58.3% of the country's steel consumption. Given the substantial production and consumption in construction, the materials manufacturing phase significantly contributes to the nation's carbon emissions and environmental impacts, therefore is a key area for future improvement efforts.

Despite the slowing urbanization and the peaking of carbon emissions in the civil construction, the building and construction sector, being a significant consumer of resources like steel and cement, continues to face demands due to ongoing urbanization and infrastructure maintenance and upgrading needs in cities.

One of the primary challenges is the management of construction and demolition (C&D) waste. The country generates approximately 2 billion tons of C&D waste annually, accounting for 30%-40% of total urban waste[13,14]. However, the recycling rate remains below 10%, which is significantly lower than the rates achieved in developed countries such as the European Union (approximately 90%), and the US (approximately 75%)[13,15,16]. This low recycling rate results in adverse environmental impacts, with common disposal methods being burial or landfill. The implementation of waste reduction at the source during design and construction phases remains inadequate. Many construction units do not adequately consider reduction measures, leading to significant material and construction waste.

Establishing a comprehensive management protocol is needed. China has made progress in developing regulatory frameworks for construction waste management, with regions like Beijing, Shanghai, Guangdong, and Sichuan implementing specific policies and facilities for waste reduction and resource utilization[17,18,19]. However, Inadequate sorting of construction waste, especially during renovation and demolition, complicates effective recycling efforts due to insufficient classification standards and enforcement. The commingling of household, construction, and hazardous waste further complicates subsequent treatment processes. The overall utilization rate of China remains low, and these facilities' processing capacities are limited.

Despite government policies that encourage the resource utilization of construction waste, including fiscal subsidies and mandatory use of recycled products, there are significant gaps in policy implementation. Market demand for recycled materials remains low due to high production costs and limited application scenarios, constraining their promotion and uptake[20].

Additionally, there are persistent issues such as inadequate monitoring of construction waste transportation and illegal dumping practices. In some areas, inadequate statistical data collection and the lack of comprehensive, information-based supervision prevent the formation of an effective management system. Establishing a robust monitoring and statistical system could positively contribute to the improvement of resource utilization[17].

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iv In the evaluation, the stages included in the value chain are: material manufacturing, construction and operation.

1.2.2 Environmental Impact

The building and construction sector in China is a significant contributor to CO_2 and greenhouse gas (GHG) emissions. It is reported that the sector's total carbon emissions throughout the entire lifecycle reached 5.08 billion tons of CO_2 in 2020, accounting for 50.9% of the national carbon emissions. The main sources of these emissions are the production of building materials and the operation of buildings, contributing 28.2% and 21.7%, respectively.

The resource-intensive nature of the sector described in section 1.2.1 also generates direct environmental impacts beyond carbon emissions: the extraction and processing of materials such as steel, cement, and sand can affect natural habitats and biodiversity, while improper disposal of construction waste occupies land resources and leads to soil and water contamination.

Furthermore, buildings in operation consume a significant amount of energy, particularly in heating, cooling, and lighting. According to the 2022 China Building Energy Consumption and Carbon Emission Research Report, the estimated energy consumption of buildings in operation accounted for 21.3% of the total national energy consumption in 2020[2]. Traditional energy usage patterns result in substantial energy consumption and greenhouse gas emissions. Although China has been promoting green buildings for a long time, the adoption and implementation are still limited, indicating a need for more aggressive promotion and application of energy-saving and emission-reduction strategies within the construction sector.

1.2.3 Regulatory Barriers

The construction sector in China faces several legislative and implementation challenges in promoting circular economy practices, largely due to the complex nature of its value chain. The sector involves multiple stages and a wide range of stakeholders, from the design and construction to demolition, each with distinct regulatory requirements. This complexity often results in inconsistent policy execution across different government departments and regions.

China's efforts to promote circular economy and sustainable development within the building and construction sector are supported by a cross-departmental and dynamic policy-making process and framework. Under the overarching guidance of the central government, national, provincial, and municipal authorities at different levels share the responsibility of formulating, and implementing a diverse range of policies and action plans. Multiple national ministries are engaged in this process, with no single ministry taking full responsibility.

Adding to these challenges is the absence of a comprehensive technical standard and certification system for circular practices, apart from those related to energy conservation, green building certification, and waste treatment. Such a system is crucial for guiding the repropose and reuse of construction materials, thereby minimizing the total environmental footprint of the value chain. Additionally, the market acceptance of recycled materials remains a work-in-progress. Shifting market behaviors and perceptions towards these materials remains challenging.

Despite these challenges, existing regulations have driven innovation in the construction sector. For example, policies have encouraged the development of green buildings through environmentally friendly designs and materials. The promotion of digital solutions, such as Building Information Modeling (BIM) and Artificial Intelligence (AI), is also leading the digital transformation of the industry. Economic incentives, including tax breaks, financial subsidies, and loan support, play a key role in mitigating costs and encouraging investment in innovation and technical applications.

Additionally, regional differences in policy implementation and market development are evident. The eastern regions generally exhibit higher levels of circular economy development compared to the western regions, with significant spatial autocorrelation and polarization trends. Addressing these regional disparities and strengthening policy coordination are essential for advancing circular economy practices nationwide.

1.3 Opportunities

1.3.1 Innovation Potential

Several new technologies and methods are instrumental in driving circularity within China's construction industry. This includes design and process optimization techniques that utilize digital building models and process management tools to enhance efficiency in design, construction, and operation, thereby reducing waste and improving material utilization. Modular construction facilitates the swift assembly of prefabricated modules, reducing construction durations and simplifying the deconstruction and recycling processes at the end of a building's lifecycle.

Incorporating green building materials that are either recyclable or biodegradable significantly lessens the construction's environmental footprint. The integration of energy-saving technologies and renewable energy sources, such as solar power, in building design leads to decreased energy usage and reduced carbon emissions. Water conservation is also addressed through the integration of water collection and recycling systems, which are used for irrigation and other non-potable applications, thus preserving water resources. In addition, green roofs and walls, featuring vegetation, improve insulation, can reduce urban heat island effects, and support local biodiversity.

Moreover, the application of advanced sorting and recycling technologies can enable the conversion of waste into valuable recycled materials, such as recycled concrete and aggregate, which can then be repurposed in new construction projects.

China's ongoing digital transformation of the construction industry is also creating significant opportunities to improve resource efficiency and circularity across the project lifecycle. Design optimization tools such as Building Information Modelling (BIM) enable designers to simulate and refine building structures with greater precision, reducing material waste from the outset. The Internet of Things (IoT) supports real-time monitoring of construction progress, environmental conditions, and worker safety on site, enabling more responsive planning and resource allocation.

Project management software streamlines construction coordination, avoiding delays and budget overruns with improved oversight. Intelligent building management systems enable the monitoring of energy use and operational efficiency, leading to optimized energy consumption and prompt maintenance.

Supply chain management tools can optimize the procurement and distribution of materials, reducing inventory costs and the energy used in transportation. Virtual reality (VR) and augmented reality (AR) technologies provide customers with an immersive experience in the design phase or refurbishment, which increases satisfaction and reduces the need for later modifications. As big data and AI technologies continue to evolve, they promise even more opportunities in the way digital tools serve the construction industry, driving further improvements towards circularity and sustainability.

These technologies can be applied at different stages of one construction project to increase the sustainability of the buildings. For example, the Beijing 2022 Yanqing Olympic Zone prioritized ecosystem-compatible circularity in its design. During construction, its BIM-GIS platform optimized stadium layouts digitally, which minimized terrain disruption. The "zero-waste materials strategy" used on-site excavation stone for gabion walls and untreated red cedar shingles that weather naturally, eliminating chemical treatments. The project also involved legacy-driven design, the temporary infrastructure could be repurposed into a low-carbon tourism hub, with snowmaking waste heat recycled for facility heating. Another example is the Building No. 7 (Yuanju Building) at the iHarbour campus of Xi'an Jiaotong University in Shaanxi province demonstrates the application of these technologies across different stages. During the construction phase, modular prefabrication of its BIPV façade (23% solar coverage) allowed rapid on-site assembly, which are also designed for disassembly and reuse, aligning with the "design for deconstruction" principle. Incorporated green roofs and intelligent building management systems optimized the energy use and enhanced insulation during the operational stage. These integrated technologies not only increased the construction projects' energy efficiency, reduced the environmental impacts, but also demonstrate the potential and opportunities for future building and construction projects.

1.3.2 Market Trends

Based on the current state of urbanization and technological applications, the construction industry in China is experiencing transformations at various levels. Generally, the development logic of the construction industry in China has experienced dramatic changes. Digital reform aimed at improving quality and efficiency has become the current focus of the industry's development from policy-making to the market orientation. Data-driven decision-making is becoming more prevalent, allowing for better prediction of project costs, timelines, and resource requirements through the collection and analysis of large datasets. Digital tools are shifting the industry from traditional manual and paper-based methods to digital operations.

At design stage, the widespread use of the internet and 5G networks in China enables real-time collaboration and updates among design teams, improving communication efficiency and reducing errors. Digital technologies also monitor and manage construction processes. The monitoring systems are able to track energy consumption, environmental conditions, and equipment status, leading to efficient energy management and preventive maintenance. Full lifecycle management is also a trending topic, emphasizing green and environmental principles from design to maintenance. This involves considering user demands, policies, and the life span of buildings and facilities while aiming to minimize environmental impact by reducing carbon emissions and increasing carbon absorption at every stage.

For consumers, public education and social participation are gaining importance. Environmental news, commercials and public engagement raise awareness about sustainable buildings and materials, encouraging involvement in the selection of housing and community design. Such participation sometimes Incentives such as tax benefits and subsidies motivate investment in green buildings, while green financial markets support funding. Resident participation fosters the development of green communities and promotes energy-efficient, environmentally friendly lifestyles, including the creation of better housing and the implementation of aging-in-place modifications.

In China's construction sector, consumer preferences are increasingly influential in driving the sustainability of civil construction products. A growing number of Chinese consumers are leaning towards purchasing green buildings, showing a strong awareness of environmental responsibility. They value the long-term environmental benefits, energy savings and the quality-of-life improvements that green buildings offer. Government and media campaigns are also playing a significant role in educating the public about the benefits of green and healthy buildings, thereby enhancing their popularity. For many years, China's real estate industry has focused primarily on location rather than sustainability. However, as the industry shifts its focus from quantity to quality, there is a growing opportunity for sustainable buildings to gain popularity, indicating a significant potential for market growth in the sustainable and circular residential building industry.

In the public building and infrastructure sectors, government procurement requirements and standards have a substantial impact. In 2020, the government issued the "Notice on Pilot Work for Government Procurement to Support Green Building Materials and Promote the Improvement of Building Quality," marking the first instance of linking green building materials to government procurement and initiating pilots in cities to support green buildings and materials. This policy was further expanded in 2022 with the release of the "Green Building Materials Government Procurement Demand Standards," applicable to government procurement projects including hospitals, schools, and office buildings, providing technical specifications for pilot cities to carry out their work. The progress in this area is evident in the increase in green building areas and the government's commitment to executing related standards in new constructions.

1.3.3 Policy Support

In China, the promotion of circular economy and sustainable development in the construction sector is supported by a cross-departmental and dynamic policy formulation process and structure. Under the guidance of the central government, national and local authorities at various levels, such as provincial and municipal governments, share the responsibility of issuing and implementing various policies and action plans. In China, multiple national ministries are involved in the formulation and implementation of these policies, with no single ministry taking full responsibility.

Under the guidance of the State Council, the principal governing body of China, various national ministries are responsible for developing relevant policies. The main central government ministries and commissions involved in policy formulation for the building and construction value chain include the National Development and Reform Commission (NDRC) and the Ministry of Housing and Urban-Rural Development (MOHURD). Other ministries and commissions, such as the Ministry of Industry and Information Technology (MIIT), the Ministry of Ecology and Environment (MEE), and the Ministry of Natural Resources (MNR), the Ministry of Science and Technology (MOST), the National Energy Administration (NEA), the Ministry of Agriculture and Rural Affairs (MOAR), and the Ministry of Finance (MOF), are also involved. These policies address key areas such as energy conservation, environmental protection, rural revitalization, digital management, and land use, which are crucial for the transformation of building and construction related industries towards circular and sustainable development.

Amongst the NDRC, as a macroeconomic regulatory agency, focuses on the overarching strategic planning and policy formulation related to energy conservation and carbon emission reduction in the construction sector. It is instrumental in setting targets for energy efficiency and greenhouse gas emissions reduction in alignment with China's commitments to the Paris Agreement, 2030 Agenda for Sustainable Development and the nation's dual carbon goal. For example, the NDRC has been leading the development and implementation of the "Action Plan for Carbon Dioxide Peaking Before 2030," which outlines a comprehensive strategy to achieve energy conservation and carbon reduction across various sectors, including building and construction.

The MOHURD is responsible for the direct regulation and supervision of the construction industry. It develops and implements policies that govern building standards, green building practices, and energy efficiency in both new and existing buildings. MOHURD has been actively promoting green construction and retrofitting initiatives to reduce energy consumption and carbon emissions in the built environment. For example, MOHURD has issued the "14th Five-Year Plan for Building Energy Conservation and Green Building Development," which sets clear targets and measures to enhance energy efficiency and promote green buildings.

The Ministry of Industry and Information Technology (MIIT) plays a significant role in promoting green manufacturing and accelerating the adoption of digital technologies in the construction process. The Ministry of Ecology and Environment (MEE) is instrumental in setting standards for environmental impacts and emissions, ensuring that construction projects are developed within the framework of sustainable practices. The Ministry of Natural Resources (MNR) is responsible for managing the use of land and mineral resources in the context of construction, balancing development needs with the preservation of natural resources. The Ministry of Science and Technology (MOST) contributes by funding research and development in green building materials and technologies, driving innovation in the sector. The National Energy Administration (NEA) focuses on enhancing energy efficiency in buildings and promoting the use of renewable energy sources within construction projects. The Ministry of Agriculture and Rural Affairs (MOAR) ensures that rural construction aligns with green development principles, supporting the sustainable development of rural communities. The Ministry of Finance (MOF) provides financial oversight, ensuring that budgetary allocations and tax policies support and incentivize the adoption of green and sustainable construction practices across the country. Also, there is the National Bureau of Statistics (NBS), which provides essential data and statistical analysis that inform policy decisions and support research. The NBS also collaborates with other ministries such as the NDRC and MOHURD in policy making and implementation.

These institutions aim to form a comprehensive institutional mechanism that continuously drives the building and construction sector and steer it towards a green and low-carbon direction. Through coordinated efforts, the policies cover various issues at different stages of the life cycle, from planning and material selection to operation and end-of-life management.

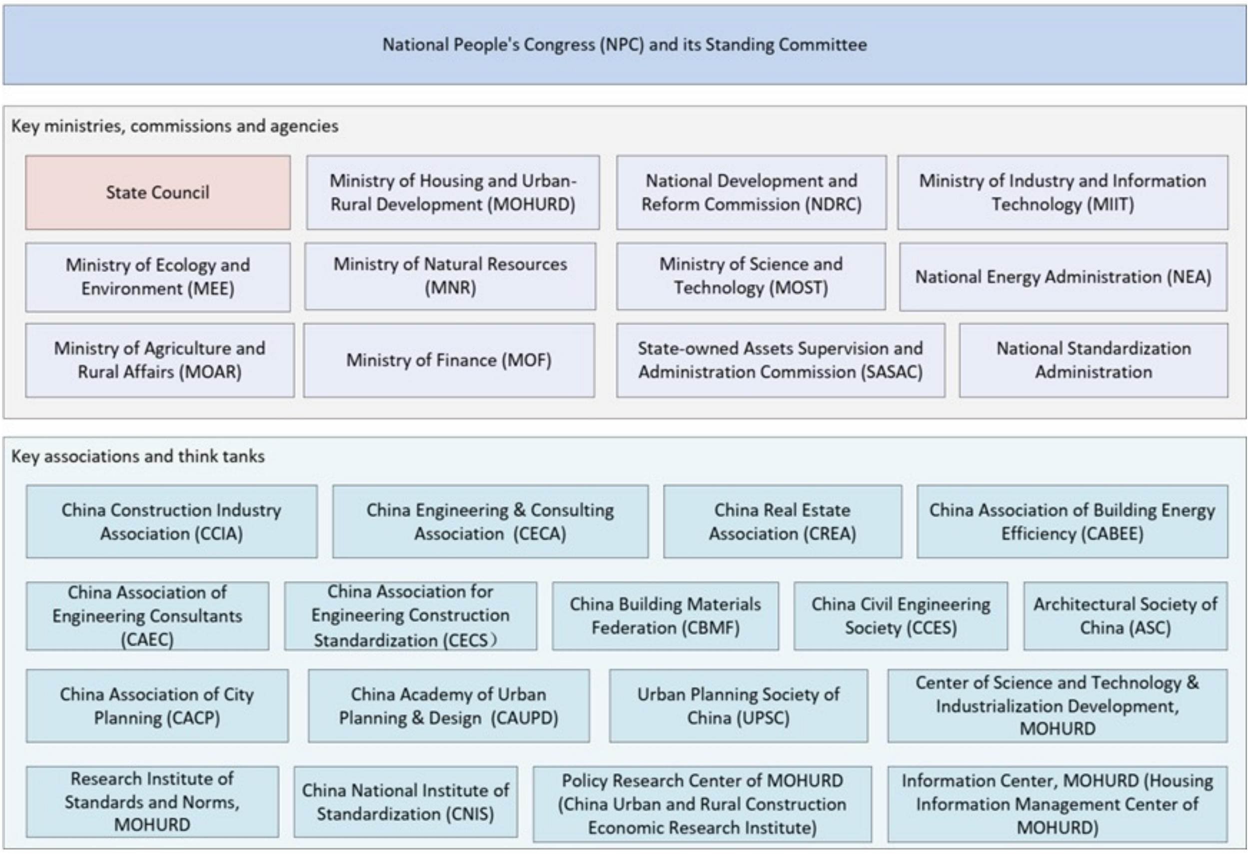

Figure 7 Key authorities and organizations involved in China's building and construction sector[v]

To promote the implementation of green and low-carbon development in the construction industry, a series of policies have been issued. Many specific policies are introduced as a response to the nation's dual carbon goal and the commitment to the Paris Agreement. For instance, in 2022, the Ministry of Housing and Urban-Rural Development and the National Development (MOHURD) and National Development and Reform Commission (NDRC) released the "Carbon Peaking Implementation Plan for the Urban-Rural Construction Sector," serving as the main guide for peaking carbon emissions in this field[21]. The plan sets a primary goal of achieving peak carbon emissions in the urban and rural construction sector by 2030 and aims for a comprehensive green and low-carbon transformation of the construction model by 2060. The plan specified several action areas and targets, for instance, the plan calls for continuous efforts to promote green building initiatives. By 2025, all new urban buildings will be required to meet green building standards, with over 30% of new buildings achieving star-rated green building status. Additionally, all new government-funded public buildings and large public buildings will be required to reach a minimum one-star rating. The plan also encourages the large-scale development of low-carbon buildings and promotes the construction of zero-carbon and near-zero energy buildings. To further enhance energy efficiency, the plan emphasizes strengthening energy-saving retrofit assessments and developing specialized retrofit plans. Buildings that are suitable for retrofitting should be fully renovated to meet current energy-saving standards. Moreover, the plan aims to advance key cities in public building energy efficiency improvements, with all prefecture-level and above key cities completing retrofit tasks by 2030, resulting in an overall energy efficiency improvement of over 20%.

China's green building sector has also grown rapidly due to the policy initiatives and targets. In October 2021, the MOHURD issued the mandatory national standard "General Code for Energy Efficiency and Renewable Energy Application in Buildings (GB55015 - 2021)" which clarified requirements in areas such as energy conservation in new buildings, energy-saving retrofitting of existing buildings, and the application of renewable energy in buildings. For example, it specifies that new, expanded, and renovated buildings, as well as energy-saving retrofits of existing buildings, must all undertake energy conservation design[22]. In March 2022, the MOHURD released the "14th Five-Year Plan for Building Energy Conservation and Green Building Development," which explicitly called for raising the energy conservation level of new buildings and strengthening the energy-saving and green retrofitting of existing buildings. Specially, it set targets that by 2025, over 350 million square meters of existing buildings should be retrofitted for energy conservation,

v Note: the figure does not provide an exhaustive presentation of institutions.

over 50 million square meters of ultra-low energy consumption and nearly zero-energy buildings should be constructed, and the proportion of prefabricated buildings in new urban buildings should reach 30%[23]. It also emphasized increasing research and development investment in green building materials and key technologies, accelerating the certification of green building materials, establishing and improving the trust mechanism for green building materials to promote the quality improvement of building materials, and leading the use of green building materials in government-invested projects to significantly increase the proportion of green materials in new urban buildings (ibid).

Besides, China is actively exploring management systems and policies for construction waste. The General Office of the State Council issued the "Pilot Work Plan for the Construction of 'Waste-Free Cities'" in 2019 and the "14th Five-Year Plan for the Construction of 'Waste-Free Cities'" in 2021, which clearly propose improving statistical methods for construction waste and promoting its comprehensive utilization. The NDRC further specified in the "14th Five-Year Plan for the Development of a Circular Economy" issued in 2021 that by 2025, the comprehensive utilization rate of construction waste should reach 60%. In 2020, the MOHURD released the "Guidance on Promoting the Reduction of Construction Waste," followed by Beijing, Shanghai, Guangzhou, and other regions and cities introducing and updating relevant policies on construction waste reduction and reuse. A brief summary of key policies released in 2017 to 2024 is provided in the Appendix Table 1.

Besides policy instruments, the standard system is an effective means of guiding construction work towards circularity. For instance, the national standard Assessment Standard for Green Buildings (GB/T 50378), which has been continuously upgraded since its promulgation, places a stronger emphasis on energy conservation and carbon reduction performance requirements. This encourages construction projects to focus more on carbon emission reduction. Beyond the green building evaluation standards, China has issued a range of technical standards and management methods related to green building identification, building energy efficiency, and renewable energy utilization. There are also multiple technical standards for the construction process, covering stages such as building design, construction and acceptance, operation and maintenance, as well as testing and evaluation (Appendix Table 2). Yet, there is no standardized approach clarifying how the circular economy and sustainable principles are identified and integrated into various stages along the value chain in the building and construction sector.

To advance sustainable development in the building and construction industry, having a comprehensive policy framework would be essential. This framework should consider sustainability as a core principle across the lifecycle, and involve relevant government departments and regulatory bodies. Besides, clear standards or guidelines would be helpful. Specific criteria for circular products and practices should be defined, with regulations encouraging environmentally friendly practices throughout a building's lifecycle—from design to deconstruction. This includes using eco-friendly materials, implementing energy-saving measures during construction, and ensuring proper waste management and resource recycling after demolition. These standards could provide a clear roadmap or action points for the industry, promoting consistency and accountability in sustainable practices.

Economic incentive policies are also important. Tax benefits and subsidies may drive investment towards sustainable construction by offsetting the initial costs associated with green building practices, making them more financially viable for developers and investors. For example, tax breaks for companies using sustainable recycled materials or adopting energy-efficient technologies can encourage wider adoption.

Regular lifecycle assessments (LCAs) can be implemented for evaluating the environmental impact of buildings from construction to demolition. By considering the full lifecycle, including operational energy usage, maintenance requirements, and end-of-life disposal, stakeholders can make informed decisions that minimize negative environmental impacts and increase circularity and sustainability of the projects.

2. Capacities and Capabilities Assessment

2.1 National Contractors

2.1.1 Strengths

China has accumulated extensive experience in construction industry and the construction technology has been continuously advancing. The contractors are skilled in construction projects with expertise in high-speed railways, bridges, and tall buildings. They can build in tough conditions like cold weather and high altitudes and are known for their large bridges, tunnels, and airport projects. They also use digital technologies like CIM, BIM, big data, AI, mobile networks, cloud computing, and IoT to improve their work.

China's green building sector has grown rapidly, supported by mandatory national standards such as the General Code for Energy Efficiency and Renewable Energy Application in Buildings (GB55015-2021) and the 14th Five-Year Plan for Building Energy Conservation and Green Building Development (2022). National contractors have demonstrated the capacity to meet and implement these increasingly stringent requirements, reflecting a growing technical strength in delivering energy-efficient and green buildings at scale. By the end of 2022, China had over 11 billion square meters of green building space and more than 30 billion square meters of energy-saving buildings, covering 64% of urban residential buildings and over 1.8 billion square meters of urban residential buildings were also renovated to save energy[4]. Chinese construction enterprises have accumulated considerable expertise in green architectural design, energy-saving technologies, and the use of eco-friendly materials.

Some iconic projects could highlight the industry's capabilities. For instance, Shanghai Tower is not only one of the tallest buildings in the world but also a leader in sustainable design. It features a double-skin facade, advanced energy recovery systems, and rainwater harvesting systems, showcasing China's ability to integrate green technologies into skyscraper construction. The venues for the 2022 Beijing Winter Olympics were also a testament to the principles and technologies of sustainable construction. The National Sliding Center implemented ecological restoration measures, conducting baseline surveys of animal and plant resources, and adopting a compensation-before-use and compensation-before-construction approach to ecological restoration. Additionally, the venue achieved the three-star green building standard, marking the first time in Olympic history that a venue was powered by 100% green electricity. The treated recycled water was used for road watering, landscaping irrigation, and toilet flushing, significantly improving water resource efficiency. The National Alpine Skiing Center utilized BIM technology for the design of the ski slopes, achieving precise design by constructing models of the existing mountain and the designed slopes. The indoor design employed a "grading and zoning" strategy, providing design services throughout the process, meeting the requirements for functionality during the event and post-event use, and allowing for future functional changes of the venue.

2.1.2 Weaknesses

In terms of technological innovation and application, there is still a gap in China's sustainable construction technologies and materials. The development and application of high-performance building materials, intelligent building systems, and zero or near-zero energy consumption building designs need to be further strengthened. Additionally, incentive mechanisms for the transformation of scientific and technological achievements into practice remain insufficient, limiting technology transfer across enterprises and innovation centers.

Regarding green standards and certification systems, although China has established its own green building assessment standards, such as the GB/T 50378, their popularity and influence are yet to match those of international authoritative certification systems like LEED and BREEAM. Moreover, there is an unevenness in the enforcement of these standards and their market acceptance.

With the active promotion of transformation and modernization in the construction industry, prefabricated construction and digital technologies are gradually being adopted. However, the early planning, feasibility studies, engineering design, and production construction of related projects in China are often completed by different enterprises. The various segments of the entire industry chain have not yet been effectively connected, leading to ineffective information sharing among participants, difficulties in collaboration and management.

From a resource perspective, sustainable construction emphasizes the full lifecycle management of buildings. Currently, China's management system for building demolition and resource recycling is undeveloped, resulting in low efficiency in the management of construction waste and a low rate of resource recycling.

2.2 Material Suppliers

2.2.1 Strengths

China's building materials market is one of the largest globally, and in recent years, it has shown a fluctuating growth trend driven by continuous government investments in infrastructure construction and real estate development, as well as promoted by strategies for new urbanization and rural revitalization. The market is not only large in scale but also complex in structure, covering a wide range of products including cement, steel, glass, ceramics, and various chemical building materials.

Chinese material suppliers demonstrate strong competitiveness, especially in terms of quality, availability, and cost-effectiveness. Due to technological innovation and standardized production, Chinese building materials such as high-strength steel and concrete are not only superior in performance but also highly durable. Strict quality control systems, including ISO certifications, ensure product consistency and reliability. As one of the world's largest producers of building materials, China possesses large-scale production capacity that can efficiently meet both domestic and international market demands. Its efficient supply chain management system ensures quick response to orders and timely delivery. Furthermore, Chinese suppliers offer a diverse range of building materials, from traditional materials like bricks, tiles, wood to modern materials such as aluminum alloys and glass, catering to different architectural styles and needs. The economies of scale and relatively lower labor costs also bring cost advantages to Chinese building materials. With increasing emphasis on environmental protection, the material sector is actively developing green and eco-friendly materials such as recycled materials and low-carbon materials, demonstrating its commitment to environmental sustainability. With government policy support, continuous technological innovation and enhanced environmental sustainability, the market share of Chinese building materials is expected to grow further.

The building materials industry in China is a key driver of sustainable construction. It contributes to the sustainable development of the construction sector through a range of measures such as the research and application of green materials, improving building energy efficiency, promoting circular economy models, and advocating for green certifications and standards. The industry is investing heavily in green building materials, making progress in low-carbon tech and new products like ferrous aluminate cement and carbon-absorbing building goods. Revenue from green building materials is growing over 10%, with 72 types of materials certified as green. Over 5,300 companies have green building material certifications, which boost energy efficiency and reduce environmental impacts[5]. Production processes are also getting cleaner, reducing pollution and environmental impact. The industry uses waste in innovative ways, creating partnerships like "coal-building materials" and "chemicals-building materials." It also backs new construction methods, including modular buildings and prefabricated parts, which save resources and make buildings more efficient.

2.2.2 Weaknesses

The Chinese building materials industry has been significantly impacted by the deep adjustments in the real estate sector, leading to a noticeable downturn in economic operations since 2022. This has directly or indirectly affected industries such as cement, construction glass, commercial concrete, and sanitary ceramics. Against this backdrop, the industry is pushing for transformation, with over 40% of the sector shifting from investment-driven to consumption and industry chain-driven models[6]. The rapid development of emerging industries like photovoltaic glass and new energy vehicles has promoted the diversified development and green, low-carbon transformation of the flat glass industry.

However, there are still many challenges in the green transformation development. The industry mainly faces the issue of severe overcapacity, which is evident to varying degrees across all sectors, particularly the cement industry. This has led to a significant reduction in cement product prices, a clear decline in economic benefits, and the impact has spread through the industry chain to related industries, thereby affecting the overall benefits of the building materials industry. In terms of building a circular economy industry system, the building materials industry is still in its infancy, with a low level of resource comprehensive utilization and a low proportion of cascade or value-added utilization products. The disposal of construction waste is still in its early stages. Additionally, the research and development and production of green building materials require high initial investment and technological innovation, which poses a significant barrier for many small and medium-sized enterprises. These companies often lack sufficient funds and R&D capabilities, making it difficult to quickly adapt to the needs of green transformation. The market promotion and consumer acceptance of green building materials are also a challenge. Although green building materials have environmental advantages, they often come with higher costs, requiring time to educate and guide consumers to recognize their long-term benefits. The building materials industry also needs to establish a more efficient and transparent supply chain system to ensure that every link from raw material procurement to product delivery meets environmental protection and circular development requirements.

To address these challenges, the building materials industry should focus on reducing overcapacity by consolidating and optimizing the industry structure. Also, the industry could invest more in R&D to develop cost-effective green building materials that can compete on price while maintaining environmental benefits. The industry also needs to enhance its circular economy practices by improving resource utilization rates and promoting the use of recycled materials in production, for example encouraging the development and application of new technologies for waste management. The industry could also work on engaging in extensive marketing campaigns to raise consumers' awareness about the long-term cost savings and environmental benefits of green building materials. Digital technologies can help to improve the supply chain management, ensuring that all stages of production and delivery align with sustainable practices.

3. Case Selection and Analysis

3.1 Criteria for Selection

3.1.1 Relevance

The cases were selected based on their innovative construction methodologies and their potential to positively influence industry practices. To ensure alignment with circular economy and sustainable development goals, criteria such as resource efficiency and the use of sustainable materials and technologies were considered. Projects that showed a commitment to minimizing environmental impact and promoting long-term sustainability were prioritized. By reviewing the performance and challenges the projects face, the selected cases are expected to provide references for other regions or future practices. This selection process ensures that the projects reflect the industry's shift towards greener practices and possible approaches in different settings.

3.1.2 Diversity

The process of buildings and construction can cover a wide range. In the collection of practices, efforts have been made to select representative types of buildings and construction projects, from intimate community-based initiatives to expansive infrastructure developments. This includes academic buildings, residential and public buildings, sports architecture, and includes projects as part of larger urban renewal programmes. Some of the projects are buildings that have been completed for many years. These projects can provide references regarding the effectiveness of the design considerations. They can show how construction techniques and standards were applied in the past and how the buildings have performed over time in terms of durability, energy consumption, and functionality.

There are also practices where modern information technology is being integrated into the sector. By combining modelling and big data analytics at different stages, it is demonstrating how construction efficiency, building energy performance, and building management can be improved. It also shows the role of technology in sustainable development planning, emphasizing not just the building or construction itself, but also the process's other stages and the inclusion of other stakeholders.

Geographical representation is also diverse, with projects chosen from both developed and developing regions, urban and rural settings. This broad geographical presentation provides a comprehensive view of how construction practices and circular economy principles can be adapted to fit specific local conditions and stages of construction. In this way, the cases reveals the importance to have standardized approach across segments of the value chain while promoting circular economy principles and sustainable solutions.

3.2 Case Studies

Case 1: Yanqing competition zone of the Beijing 2022 Winter Olympic and Paralympic Games

Project Overview

The construction was designed for the Beijing 2022 Winter Olympic and Paralympic Games, including venues like the National Sliding Centre and National Alpine Ski Centre.

Demonstration of Circular Economy Principles:

The project considered sustainability and the use of green technologies from planning and design to construction and facility management. It involved a Public-Private Partnership (PPP) model for post-game utilization, with a 30-year project span including a 5-year construction period and a 25-year operation period. It also contributed to the release of a national standard for event sustainability evaluation (GB/T 44160-2024), demonstrating a commitment to sustainability throughout its lifecycle.

Key Insights

The project emphasized the consideration of sustainability from the beginning, successfully integrated sustainable design and green technologies, leading to the release of a national standard. The PPP model for post-game utilization reduced environmental impacts, ensured the long-term sustainability of the venues and facilities.

Yet, coordinating multiple stakeholders was complex, the lack of a standardized technical approach made the measurement and monitoring of sustainable and circular factors challenging. To address the issues, a collaborative approach and clear communication mechanisms were established. The case also developed a local standard, Guidance for event sustainability evaluation (DB/T 1892-2021), which later on evolved into a national standard event sustainability evaluation (GB/T 44160-2024) that could provide a framework for assessing the sustainability of major events.

Impact Assessment

The project adopted green technologies and sustainable design principles, which leading to the reduction of energy consumption and waste generation. Besides, the post-game utilization plan ensures that the infrastructure continues to serve a useful purpose, reducing the need for new construction.

In addition, the project contributed to the development of a national standard for event sustainability evaluation (GB/T 44160-2024), which includes 35 indicators covering infrastructure and venues, procurement and resource management, environmental protection, transportation, low-carbon and climate change initiatives, staff and public engagement, and smart and innovative practices, providing a benchmark for future event projects[24]. The PPP model for the venue utilization also offers a sustainable approach to the development, construction, management and operation of large-scale sports facilities.

Case 2: Building No. 7 (Yuanju Building) of the iHarbour Campus, Xi’an Jiaotong University

Project Overview

No.7 building (Yuanju Building) was constructed as part of the iHarbour (Western China Science and Technology Innovation Harbour) Campus construction project at Xi’an Jiaotong University in Shaan’xi province. The project aimed to promote energy conservation and technology integration in academic campus and buildings. It was jointly designed by the faculty and students of the School of Human Settlements and Civil Engineering of the university.

The project fostered the integration of technological innovation into practical use, advancing green energy technology innovation and transformation. The building was designed to be a model of green building which integrated multiple renewable energy technologies, including modular prefabrication of its BIPV façade and solar photovoltaic/thermal (PV/T) systems. It received the “2023 World Engineering Organization Federation Engineering Construction Excellence Award,” highlighting its commitment to sustainability.

Key Insights

The collaborative design process between faculty members and students led to innovative solutions in green building construction. However, securing substantial funding and completing the construction work during the pandemic posed challenges. The project received financial support from multiple sources, including the National Development and Reform Commission and the private sector. Besides, integrating innovative design ideas and technologies into the construction process required specialized knowledge and resources. The project showed that effective communication is crucial to ensure that design requirements can be accurately transformed into the construction process, especially when multiple partners were involved. Also, this project demonstrated that public-private partnerships can provide the necessary funding and expertise for such project. Additionally, collaborative design processes can support the application of innovative solutions and better integration of sustainable technologies.

Impact Assessment

The project reduced energy consumption through the use of green energy construction technologies. It indicated that effective collaborative design process between academia and industry can lead to innovative and sustainable solutions.

Case 3: Delta Sunshine Primary School at Yangjia Town

Project Overview

The Delta Sunshine Primary School at Yangjia Town (Yangjiazhen primary school) was reconstructed after the Wenchuan earthquake in 2008. The project aimed to rebuild quickly and sustainably, integrating energy-efficient and earthquake-resistant designs, to provide a high-quality educational environment for local students.

The design was based on the first-prize-winning design from the “2009 International Solar Building Design Competition” and was modified according to the actual needs of post-disaster reconstruction. It was sponsored by private company and designed by state enterprise and research institutions.

The design applied several energy-saving techniques to ensure the building environment remains comfortable throughout the year, including optimizing ventilation, controlling humidity, and regulating temperature. The project also integrated solar water heaters in the design. Also, it used recycled building materials for landscape features, such as reclaimed stone, to reduce the demand for new resources and minimize waste, demonstrating a commitment to resource recovery and sustainable design.

Key Insights

The project was completed quickly and has been in use for over 10 years. The use of energy-efficient designs and recycled materials reduced the environmental impact of the reconstruction.

Rebuilding quickly after a disaster while ensuring sustainability was a significant challenge.

The project lacked a systematic consideration of sustainability and circularity, i.e., all 10 R principles, focusing primarily on reuse and reduce.

The project demonstrated that post-disaster reconstruction can be sustainable with the right design and material choices. And a more comprehensive approach to the 10 R principles could enhance the long-term sustainability of such projects.

Impact Assessment

The use of recycled construction waste and energy-efficient designs reduced the environmental footprint of the project. Such application and integration can be replicated in other post-disaster reconstruction.

Case 4: Research and demonstration on key technology integration for energy self-sufficiency rural houses

Project Overview

The project aimed to develop and demonstrate technology integration for energy self-sufficiency in rural houses across different climate zones in China. It involved research starting in November 2013, with construction beginning in 2015 and completion in December 2016.

By developing, integrating and applying energy - self - sufficient functional modules and single - building products, the project intended to provide advanced reference paradigms for rural housing construction. Results were applied in severely cold regions (Haotao Sea Ranch, Inner Mongolia Autonomous Region), cold regions (Chongli District, Hebei Province), and hot-summer-cold-winter regions (Tonglu District, Zhejiang Province), with a total area of 724 m2, 444 m2 and a prototype residential building being about 83 m2 demonstration, respectively. The project optimized the energy structure of rural houses in selected cases, reducing the dependence on conventional energy sources, and enhancing the overall performance of rural houses.

Key Insights

The project successfully developed and applied energy self-sufficiency housing technologies for different regions across various climate zones, which provided useful insights for future rural housing projects. The project indicated that tailored approaches are necessary for technology transfer in diverse climate zones.

It also formed a rural energy - self - sufficient housing paradigm in the hot-summer-cold-winter region for private-enterprise-invested construction and operation, featuring a system of “steel - structure system, good natural ventilation system, effective shading equipment, and efficient multi - energy complementary utilization”.

Impact Assessment

The project reduced energy consumption in rural houses, contributing to lower carbon emissions.

It demonstrated the feasibility of energy self-sufficiency in rural settings, reducing reliance on external energy sources. The project applied tailored designs for different climate zones, which offers a flexible approach to sustainable rural development.

Case 5: Public buildings’ renovation in Shenzhen

Project Overview

The project aimed to promote energy-saving renovations of public buildings in Shenzhen through a series of policies and measures. It used energy management contracts to improve efficiency, involving local government agencies, various companies, and energy suppliers. The project focused on reducing energy consumption and improving energy utilization efficiency in public buildings, aligning with the principles of reduce and reuse.

Key Insights

The project promoted energy-saving renovations in public buildings through the use of energy management contracts and public-private partnerships. Coordinating multiple stakeholders and ensuring consistent implementation of sustainability measures was challenging. Developing a standardized approach for measuring and ensuring the implementation of related principles across the lifespan of the value chain was a hurdle would be useful to tackle the issue.

The project revealed that public-private partnerships can be effective in promoting sustainable urban renewal. Standardized approaches and clear measurement systems are necessary for consistent implementation of sustainability principles.

Impact Assessment

The project reduced energy consumption in public buildings, contributing to lower carbon emissions. The use of energy management contracts and public-private partnerships offers a model for sustainable urban renewal. It also highlights the importance of policy-driven initiatives in promoting energy conservation in public renovations and the necessarily to develop standardized approach for the implementation of 10 R principles in building and construction projects.

Case 6: Integration of real-scene 3D technology for site selection of construction projects

Project Overview

The project focuses on the integration of real-scene 3D technology to support the site selection of construction projects in Hunan Province. Led by the Hunan Provincial Department of Natural Resources and the Third Surveying and Mapping Institute of Hunan, the initiative aims to develop a digital platform that leverages 3D visualization and spatial data analysis to optimize land use and planning decisions. These include the use of topographical data, which provides insights into the lay of the land, land - use information detailing how different areas are currently utilized, and environmental data that encompasses various ecological aspects. The system is designed to provide real-time data on terrain, infrastructure, and environmental conditions, enabling more informed and sustainable site selection processes. This approach aligns with the principles of circular economy by promoting efficient resource use and reducing the environmental impact of large-scale construction projects.

Key Insights

The project successfully developed a 3D visualization platform that integrates spatial data from various sources, including topography, land use, and environmental information. One unique strategy employed was the use of advanced mapping technologies to create detailed 3D models of potential construction sites. This allowed stakeholders to assess the conditions of different locations based on real-time data and simulations.

Challenges included the integration of diverse data sets and ensuring the accuracy of 3D models. To address these, the project team collaborated with local authorities and data providers to standardize data formats and improve data quality. The project highlights the importance of data integration and collaboration among stakeholders.

The application of real-scene 3D technology not only enhances the efficiency of site selection but also supports sustainable planning by providing detailed insights into environmental and resource conditions. Specifically, it can promote energy efficiency through natural lighting and ventilation, support the installation of renewable energy systems, and highlight areas of high biodiversity value. This information can inform the design and implementation of green infrastructure and habitat preservation efforts, contributing to the overall sustainability of construction projects.

Impact Assessment

The integration of real-scene 3D technology significantly improved the efficiency and sustainability of site selection processes. By providing detailed spatial data and visualization tools, the platform enabled planners and decision-makers to identify optimal locations that minimized environmental impact and maximized resource efficiency. This approach contributed to more sustainable land use and reduced the need for extensive site surveys, saving time and resources. The development of a comprehensive 3D visualization platform and its application in site selection and planning are innovative, demonstrating how digital technologies can support circular economy principles in the construction sector.

Case 7: Introducing green industrial materials production to promote the reuse of construction waste

Project Overview

The case was about the introduction of a new green industrial material enterprise to support the use of construction waste for building materials production in Lincang, Yunnan province. The practice was also aiming to promote local economic growth. Having only gained access to its first highway in 2017, Lincang has recently entered a phase of rapid urban development. This has led to an increased demand for construction materials for urban infrastructure and a rise in the generation of large volumes of solid construction waste. Through targeted investment promotion policies, Lincang High-Tech Zone Administrative Committee, and Lincang Municipal People's Government collaborated with private investment, as a result, Lincang Huawen Industrial Materials Co., Ltd. was established in Lincang in 2021.

As a National Innovation Demonstration Zone for Implementing the 2030 Agenda for Sustainable Development approved by the State Council of China, Lincang has a deeper understanding of sustainable development principles. The practice aligns well with the principles of green and sustainable development, addressing the resource consumption issues arising from rapid urbanization. The main objectives of the practice are to enhance the recycling capacity of construction waste, foster a circular economy, and promote sustainable urban and rural development in alignment with national policy. The enterprise ensures sustainable sourcing by converting construction demolition waste into environmental-friendly products that mainly serve as municipal building materials. Examples include inorganic terrazzo, imitation stone PC bricks, gas brick, dry powder mortar and other environmental protection building materials with more than 500 specifications and models.

Key Insights

The project successfully introduced a new enterprise for green industrial materials production in the city. The products are produced from recycled materials, offering environmental-friendly solutions while reducing the demand for new raw materials in urban construction. Although the case is not large in scale compared to the vast construction sector in Yunnan province, it serves as a model for local implementation, demonstrating how local practices can align with and contribute to national strategies and sustainable development goals.

The total investment of about 250 million yuan in four fully automated production lines is expected to yield an annual output value of 700 million yuan, demonstrating economic resilience and adaptability. Besides, once these lines are up and running at full capacity, they can collectively process all construction waste within the Lincang area, achieving an important milestone in construction waste management of the city. With the operation of the facility, the production of 370 standard bricks (240mm×115mm×53mm) per ton of construction waste and a reduction of carbon dioxide emissions by approximately 3.7 kg per ton. Yet, it was a challenge to secure the necessary capital and resources to establish the venue. After the establishment, ensuring the supply of raw material and market acceptance of the recycled materials was also an issue.

Impact Assessment

The project reduced the environmental impact of construction waste by reusing it into useful building materials. It contributed to the circular economy by promoting the reuse of waste materials. The introduction of a new enterprise for green industrial materials production highlights the importance of circular economy principles in waste management and resource recovery, especially for a less-developed region experiencing rapid growth.

Case 8: Development of 3D communicative planning tool

Project Overview

This case study focuses on the development of a three - dimensional (3D) communicative planning tool for community planning. The project aims to support sustainable community planning through the use of digital and visualization tools for evidence-based evaluation. Supported by several government-funded research projects, the tool has been tested and demonstrated in over 30 locations across China.

Through the digital platform developed in the project, planners can log into the system, collect basic data, and create preliminary planning scenarios. Subsequently, they can communicate with different users either online or offline at the site, design planning schemes, and conduct scientific analysis. In addition, this tool also supports rural participatory design, allowing researchers and local residents to quickly create landscape elements such as roads, environmental elements, boundary lines, and buildings, thus generating planning scenarios. By reducing the demand for physical resources during the planning and construction process, this project complies with the principles of “reduce” in the circular economy.

Key Insights

The project developed and demonstrated a 3D communicative planning tool in multiple locations across China. The development and testing processes require substantial resources and coordination efforts. To ensure the effectiveness and user - friendliness of the tool, the project team tested different modules at locations with various conditions and updated the functions according to the feedback. The interactive landscape planning and design module supports functions such as road creation, 3D building modeling, environmental element creation, etc., and provides operations such as selection, editing, copying, pasting, and deletion, further improving the flexibility and efficiency of planning. This tool provides a new approach for inclusive community planning and sustainable development.

By reducing the frequency of on-site meetings, the use of paper documents, and physical models, and leveraging digital tools, the project has optimized the efficiency of multistakeholder coordination. Meanwhile, through the participatory planning process, it has enhanced the transparency of planning and public participation.

Impact Assessment

The tool could significantly reduce the need for physical resources during the planning process, particularly for remote areas, contributing to lower environmental impact and cost effectiveness. Through digital approaches, the project has decreased the reliance on traditional physical resources such as paper documents and physical models. At the same time, through the on-site participatory planning process, it has optimized the efficiency of multistakeholder coordination.

Besides, the tool provides planners with a basis for the site selection of public service facilities and business service facilities through functions such as service radius analysis and space syntax analysis. Planners can reproduce the spatial distribution of landscape elements in a 3D environment and obtain 360 - degree landscape skyline curves and landscape hierarchy curves, enabling them to better compare the spatial form differences between the current community situation and different design schemes, and optimize the spatial layout of the community.

Case 9: Development of process management tool

Project Overview

This case focuses on the development of digital tools designed to track performance in the value chain, particularly within the building materials industry. The primary goal is to reduce inefficiencies in manufacturing processes. From raw material extraction, production, distribution, to end-use, the digitalization project aims to enhance not only its operational efficiency but also its overall sustainability. This application aligns with the principles of the circular economy, which is able to reduce waste generation, reuse available resources, and recycle materials wherever possible.

Key Insights

The project introduces digital tools for performance tracking in the building materials industry. One significant challenge was establishing and integrating different datasets into one platform. These datasets originated from multiple sources, including production equipment sensors, supply - chain management systems, and environmental monitoring devices, each with its own format, structure, and data collection frequency. This was addressed through collaboration and demonstration projects. By testing different integration methodologies and data standardization techniques, the data-driven platform is able to support closed-loop control, such as dynamic scheduling based on real-time energy consumption (e.g., cement kilns adjusted thermal parameters automatically, cutting energy waste by 5%). The initiative demonstrates that digitalization can significantly improve efficiency in the building materials industry, offering valuable insights for future projects.

Impact Assessment

The project demonstrates that digitalization has the potential to improve the operational efficiency and overall sustainability. By providing real-time visibility into different stages of the materials' value chain, these digital tools enable manufacturers to make more precise production plans, optimize resource allocation, and proactively address issues when needed. It can track the movement of raw materials from suppliers to the production facility, as well as the distribution of finished products to customers. This enables better inventory management, reducing the need for excessive stockpiling.

By accurately tracking production processes, digital tools can also identify areas where material waste is occurring. The integration of environmental monitoring data into the digital framework allows for the analysis of energy consumption patterns. As such, manufacturers can identify energy - intensive processes and implement measures to optimize energy use. By tracking the flow of materials throughout the value chain, it becomes easier to identify opportunities for recycling and reusing materials. It provides a model for more sustainable practices within the sector, highlighting the importance of innovation in promoting circular economy principles in traditional industries.

Case 10: CIM platform in Langfang Airport Economic Zone

Project Overview

This practice focuses on the application of City Information Modeling (CIM) technology to develop smart and sustainable urban spaces in the Langfang Airport Economic Zone. The project involved integrating CIM technology and smart infrastructure to create efficient and sustainable urban spaces, allowing for real-time monitoring, analysis, and optimization of the environmental performance, such as energy efficiency and water resource management. The project started in June 2020 and was completed in December 2021, aligning with the circular economy principles by reducing resource waste and promoting sustainable urban development.

Key Insights

The project integrated CIM technology and smart infrastructure to create an efficient and sustainable urban space. It aggregates diverse information models like those of buildings, roads, and railways. It comprehensively integrates six categories and five levels of data resources, including spatial-temporal fundamentals, resource surveys and registrations, planning and control, engineering construction projects, public topics, and IoT - sensed information. This creates an urban digital base for the Langfang Airport area, serving as the fundamental operating system for local planning, construction, management, and smart city applications. It is an important supporting platform for realizing the digital twin of the smart city in the Langfang Airport Economic Zone and a crucial component of the new - type information infrastructure.

Based on the CIM platform, innovative applications of technologies such as BIM, the Internet of Things, and AI are carried out. For example, through the Smart Construction Site Supervision Platform, Engineering Project Digital Management Platform, and Dust Online Supervision Mini - Program, real-time digital supervision of the engineering projects across the region is achieved. At the same time, three major indicators, energy consumption per unit area, carbon emissions, and the utilization rate of renewable energy, can be integrated to support the energy efficiency management.

Integrating advanced technologies like CIM required significant investment and technical expertise. Ensuring the long-term sustainability and maintenance of the platform was a challenge, but the project overcame this through careful planning and ongoing maintenance efforts.

Impact Assessment

The practice promoted sustainable urban development through real-time monitoring and optimization. It provided a model for more efficient and sustainable urban spaces. The application of CIM technology in urban development offers a new approach to sustainable city planning and management.

4. Contextual Insights

4.1 10 R Framework Application

The following analysis applies the 10R Framework (see Figure 5) to the case studies, mapping each initiative against the ten circularity strategies — from the most preferred (Refuse, R0) to resource recovery (Recover, R9).

4.1.1 Implementation Examples

Refuse (R0)

The Yanqing competition zone of the Beijing 2022 Winter Olympic and Paralympic Games considered sustainability from the start, refusing wasteful practices. The 3D communicative planning tool development rethinks community planning by incorporating digital and visualization tools, helping to refuse wasteful planning practices and promote sustainable and evidence-based evaluation.

Rethink (R1)

The Yanqing competition zone reconsidered the purpose and function of the infrastructure after the event. The 3D communicative planning tool rethinks community planning by incorporating more stakeholders, therefore may extend the period of utilization of public facilities or buildings.

Reduce (R2)

The Yanqing competition zone used green technologies and sustainable design principles to reduce energy consumption and waste. Building No. 7 of Xi'an Jiaotong University reduced energy consumption through green energy construction technology innovation and transformation. Yangjiazhen primary school reconstruction integrated energy-efficient and earthquake-resistant designs to reduce energy use and the need for extensive repairs. The energy self-sufficiency rural houses research focused on energy self-sufficiency through technology integration to reduce energy consumption in rural houses. Public buildings' renovation in Shenzhen promoted efficient energy-saving equipment and optimized architectural design to reduce energy in public buildings. The 3D communicative planning tool development reduces the need for physical resources in planning and construction by using digital tools. Process management tool development reduces inefficiencies in the value chain through the development of new building materials and digital tools for tracking performance.

Reuse (R3)

The Yanqing competition zone will see the centers renovated and operated in a PPP model for reuse after the games. Yangjiazhen primary school reconstruction used recycled construction waste in the rebuilding process. The detachable assembled façade design applied in the Building No.7 at Xi'an Jiaotong University can be used for assembled façade replacement technology oriented to the maintenance and transformation of the building. Introducing green industrial materials production to promote the reuse of building waste involves reusing construction waste as new materials in the production of green industrial materials in a less-developed area.

Repair (R4)

The Yanqing competition zone's maintenance and facility management stage implies efforts to repair and maintain the infrastructure. The urban renewal and retrofitting projects also involve repair of infrastructure and facilities, for instance, in the public buildings' renovation in Shenzhen.

Refurbish (R5)

The Yanqing competition zone's maintenance and facility management stage implies efforts to restore the facilities and infrastructure.

Remanufacture (R6)

The Yanqing competition zone's renovation and operation in the PPP model could involve some level of remanufacturing or upgrading of the facilities to meet the needs after the events.

Repurpose (R7)

The post-game utilization of the venues in the Yanqing competition zone is a clear example of repurposing. The 3D communicative planning tool development could be repurposed for different community planning scenarios and locations. Process management tool development could also repurpose digital tools for different stages of the building materials industry.

Recycle (R8)

Introducing green industrial materials production to promote the reuse of building waste could contribute to the recovery of resources from construction waste.

Recover (R9)

The Yanqing competition zone involved the recovery of energy and resources through sustainable technologies and practices. The sustainable design and use of green technologies also contribute to the regeneration of the environment and resources. Public buildings' renovation in Shenzhen contributes to the regeneration of the urban environment through a "near-zero carbon" construction path, reducing carbon emissions and promoting a more sustainable urban landscape.

According to the cases, the principles of **Reduce (R2) and Reuse (R3)** had the most significant impact on sustainability across the cases. The principle of reducing energy consumption and waste was a common thread in many initiatives. For instance, the Yanqing competition zone incorporated sustainable design principles and technologies to minimize energy consumption and waste generation. Similarly, the practices in Xi'an Jiaotong University and Yangjiazhen primary school both focused on energy efficiency and the integration of sustainable design elements to reduce their environmental footprint. The research on rural housing also aimed to reduce energy consumption in rural settings, highlighting the importance of this principle in achieving sustainability.

The principle of reuse was also impactful, as seen in the post-game utilization plans for the Yanqing competition zone, where the infrastructure is set to be repurposed. This not only extends the life of the facilities but also ensures that the resources invested in their construction continue to serve a useful purpose after the events. The Yangjiazhen primary school reconstruction project also exemplified the reuse principle by utilizing recycled construction waste, thereby reducing the demand for new materials and minimizing waste, that is efficient especially after the natural disaster. Introducing green industrial materials production to promote the reuse of building waste in Lincang, Yunnan province, further highlights the significance of this principle in fostering a circular economy in less-developed urban setting.

While other principles such as repurpose (R7), recycle (R8) and recover (R9) also played important roles in the cases, reduce and reuse were highlighted consistently across multiple cases. These principles are foundational in the transition towards more circular and sustainable practices, as they directly address the reduction of resource consumption and the efficient use of existing materials.

4.1.2 Challenges and Solutions

One significant challenge was the lack of a standardized technical approach or guidance throughout the value chain in China. This made it difficult to prioritize and consistently apply the 10 R principles across diverse projects. The challenge showed in varying degrees when integrating these principles into existing systems and processes.

For instance, in the Yanqing competition zone of the Beijing 2022 Winter Olympic and Paralympic Games, adopting green technologies and sustainable design principles required extensive coordination among multiple stakeholders, including government agencies, private sector partners, and specialized design teams. Yet, without standardized technical system and the lack of similar previous projects in China made the measurement and monitoring of sustainability indicators challenging. To address this, the project developed a standard for the project, which eventually evolved into a city-level standard (DB11/T 1892—2021) and, in 2024, became a national standard (GB/T 44160-2024). Also, to ensure alignment with the sustainable development goals (SDGs), a collaborative approach and clear communication mechanisms were established among all stakeholders involved in the planning, design, and construction phases.

In the case of the Yangjiazhen primary school reconstruction after the Wenchuan earthquake, the challenge was to rebuild quickly and sustainably after the disaster. The project had to integrate energy-efficient and earthquake-resistant designs, which required innovative solutions and materials. The challenge was addressed by selecting an improved design from the International Solar Building Design Competition and using local materials. This approach not only ensured the quality of the reconstruction but also provided a model for post-disaster rebuilding project. However, it did not ensure that the 10 R principles were considered. The priority was to reduce the energy consumption of buildings. Similarly, in other projects, the lack of standard clarification and a standardized approach for building and construction projects meant that there was no consistent framework for measuring and ensuring the implementation of related principles across the lifespan of the value chain. While each project achieved some successes in specific areas of sustainability, the overall impact was limited. This situation highlights the need for the development of such standards and systems to promote circularity and sustainability in this sector.

4.2 Integration Across 6 Stages

The analysis below traces how circular economy principles were applied across the six stages of the building and construction lifecycle (see Figure 6). Circular economy principles were applied at various stages of the lifecycle of building and construction projects using different strategies. In the urban and rural planning and zoning stage, projects used data and digital tools to estimate the overall cost and environmental performance, and to make better use of resources, choose appropriate locations, and promote low-carbon practices. For example, communicative planning tools showed how real-time zoning and planning could help public facilities last longer. This stage highlighted the need to use land data and user preferences to make smart planning and location decisions, and to increase the inclusiveness. However, there is room for improvement in making these tools more user-friendly and accessible to a wider audience, as well as extending their application to other stages.

During the planning and design of engineered structures, collaboration and tailored designs were important for incorporating sustainability. Projects like the Yanqing competition zone for the Beijing 2022 Winter Olympics and the energy self-sufficiency rural houses project showed how green technologies and energy-efficient designs could be included from the beginning. These efforts emphasized the importance of communication and collaboration between different stakeholders and expert teams to ensure long-term sustainability, and environmental benefits in particular. The practices also demonstrated that a standardized approach is beneficial for implementing circular economy principles effectively in venues serving multiple functions.

In the materials stage, projects focused on using recycled materials and digital tracking tools to reduce waste and improve resource recovery. For example, the introduction of green industrial materials production in Lincang and the use of recycled construction waste in the Yangjiazhen primary school reconstruction demonstrated the potential for circularity in material sourcing. Developing digital tools for tracking material performance can help improve efficiency and ensure that materials can be reused or recycled at the end of their lifecycle.

Construction also benefited from green technologies and smart infrastructure. Projects like the Yanqing Olympic Zone and Shenzhen's public buildings' renovation used Public-Private Partnership (PPP) models and energy-saving renovations to make construction more efficient. These initiatives showed how combining financing models with sustainable practices could reduce waste and improve overall project outcomes. However, there is a need for more widespread adoption of these practices to have a greater impact on sustainability.

In the maintenance and facility management stage, real-time monitoring and energy management contracts were used to support long-term sustainability. Projects like the Langfang CIM Platform showed how digital tools could support efficient maintenance and facility management. This strategy helped maintain sustainability goals throughout the operational phase of the project. Continuous monitoring and updating of these tools are necessary to adapt to changing conditions and improve their effectiveness.

In the deconstruction and demolition stage, projects planned for the repurposing and recycling of materials to ensure circularity at the end of the lifecycle. For example, the Yanqing Olympic Zone and the green industrial materials enterprise in Lincang demonstrated how planning for material recovery and repurposing could reduce waste and enhance resource efficiency. Given the significant building stock that may require renovation in China, there is a need for more robust systems to ensure that materials are effectively recovered and reused in future projects.

The building and construction lifecycle is highly interconnected, and the early application of circular economy and sustainable principles can significantly enhance overall circularity. Throughout the stages, integrating these principles from the planning and zoning phase ensures that sustainable practices are considered throughout a certain engineering project. For example, incorporating circularity in the design stage facilitates the use of eco-friendly materials and technologies during construction of Yanqing competition zone of the Beijing 2022 Winter Olympic and Paralympic Games, which in turn simplifies maintenance and deconstruction, also enhances the sustainability. Such integration across stages is essential for maximizing sustainability and reducing resource waste.

Yet, each stage involves multiple stakeholders and complex administrative processes, which can sometimes lead to negative impacts on circularity. For instance, if cost-saving measures during construction lead to the selection of cheaper, non-sustainable materials, it can reduce the market share of eco-friendly materials and undermine the project's circularity. This highlights the need for consistent strategies and policies that support circular economy principles across all stages.

Effective communication and coordination between upstream and downstream stakeholders are critical. For example, close collaboration between planners, designers, material suppliers, and construction teams ensures that sustainable materials are selected without compromising cost or quality. This requires a cohesive approach where circular economy principles are consistently applied, monitored and supported by clear policies and management process.

Digital technologies play a pivotal role in enhancing these synergies. In urban planning, digital platforms can optimize land use and resource allocation. During construction, smart monitoring systems can track material usage and energy consumption, ensuring compliance with sustainability goals. In maintenance, real-time monitoring can identify issues early and enable sustainable solutions. These tools not only improve efficiency but also support the circular economy by enabling better decision-making.

Despite these benefits, there are areas for improvement. Digital tools must be user-friendly and accessible to all stakeholders to ensure widespread adoption. Additionally, policies should incentivize the use of sustainable materials, even if they are more expensive, to support the circular economy. Standardized methods for measuring material performance and tracking sustainability metrics are also needed to ensure consistency across projects.

5. Conclusion

The current state of circular economy practices in China's construction sector reflects significant progress and potential for further development. Despite a slowdown in growth rates, the sector continues to evolve, driven by regional land-use optimization, economic adjustments, and policy changes. The industry is also influenced by the increasing demand for public service facilities in rural communities, such as social service, medical, educational, cultural, commercial and financial facilities, as well as the need for retrofitting existing urban buildings to enhance energy efficiency.

The selected practices cover different stages of construction and reflect circular and sustainable principles in various areas, such as material efficiency, energy conservation, and sustainable design. Projects such as the Yanqing competition zone for the Beijing 2022 Winter Olympics and the energy self-sufficiency rural houses project demonstrate the integration of circular economy principles from planning to construction and operation. These practices highlight the importance of collaboration, innovation, and policy support in advancing sustainable construction practices.

The integration of circular economy principles across different stages of the construction lifecycle has been demonstrated through collected projects. Yet, significant potential for consistent application and consideration along the value chain can be identified. Projects such as the Yanqing competition zone for the Beijing 2022 Winter Olympics and the energy self-sufficiency rural houses initiative highlight the importance of embedding circularity from the planning stage through to construction and operation. These efforts emphasize the need for collaboration among stakeholders, including government agencies, private sector partners, and academic institutions. The use of digital tools, green materials, and real-scene 3D technology, smart infrastructure has proven effective in reducing environmental impact while improving efficiency. However, challenges remain in standardizing practices and ensuring consistent awareness and application of circular principles across projects. The development of national standards and guidelines could provide a framework for sustainable development, but there is a need for more comprehensive technical guidelines that cover the entire lifecycle of construction projects.

To further promote circular economy principles in the construction sector, stakeholders should adopt a comprehensive and collaborative strategy. One key step supporting close collaboration is to develop standardized methodologies for clarifying, monitoring and evaluating sustainability, ensuring consistent application throughout the project lifecycle. Governments should continue to play a pivotal role by developing and enforcing policies that promote circularity and sustainability. For instance, incentivizing the use of green materials and sustainable practices in both the retrofitting of existing buildings and the construction of new ones can drive market adoption.

Given the rapid technological process, the industry should also actively adopt innovation by adopting digital tools and smart infrastructure solutions. Such utilization can optimize resource utilization and minimize waste generation, enhancing overall efficiency. Additionally, housing designs and community planning should become more adaptable to the changing needs of an aging society and evolving family structures in China, prioritizing safety, convenience, and environmental performance. Besides, integrating circular and sustainable practices into spatial planning processes can be beneficial, particularly for large-scale projects. For instance, aligning construction projects with strategies for predicting and mitigating disaster risks.

At the contractor level specifically, enhancing capabilities will be critical to delivering on these broader ambitions. To this end, contractors should focus on several key areas. Firstly, it is crucial to increase investment in research and development, particularly in high-performance building materials, intelligent building systems, and zero-energy building designs. Secondly, the sector should continue to promote standardization of circular practices, enhancing their popularity and influence. Additionally, optimizing the management of the entire industry chain is essential, involving improved integration and information sharing across project planning, feasibility studies, engineering design, and construction. Furthermore, strengthening the management of building demolition and resource recycling is necessary. Policy guidance and technical support can motivate enterprises to adopt advanced sorting, recycling, and processing technologies, thereby realizing the resource utilization of construction waste.

Through these efforts, diverse stakeholders can strengthen ongoing initiatives, ensuring that circular economy principles are ingrained at every stage, contributing to broader sustainable development goals.

Appendix

Table 1 Policies formulated at the national level to promote the low-carbon and sustainable development of the building and construction sector (2017-2024)

Time	Issuing organization	Policy	Highlight
February 2017	State Council	Opinions on Promoting the Sustainable and Healthy Development of the Construction Industry	Adhere to standardized design, factory production, prefabricated construction, integrated decoration, information management and intelligent application, and promote innovation in construction methods
April 2017	MOHURD	The 13th Five-Year Plan for the Construction Industry	Urban green buildings should account for 50% of new buildings and the application rate of green building materials should reach 40% by 2020.
December 2018	State Council	Pilot Work Plan for Waste-Free City Construction	Encourages a green development model and lifestyle to reduce the amount of solid waste generated at the source and recycle it to minimize the amount of landfill and environmental impact
September 2019	MOHURD	Notice on the Establishment of Ministry of Science and Technology Committee and Green Construction Specialized Committee	In order to implement the new development concept, promote green construction and the transformation and upgrading of the construction industry, and give full play to the expert think-tank, it has been decided to establish the Green Construction Professional Committee
October 2019	SAMR, MOHURD and MIIT	Implementation Plan for Green Building Materials Certification	Clarifies the technical ability and certification standards of green materials certification bodies and establish the evaluation system of green building materials
May 2020	MOHURD	Guiding Opinions on Promoting the Reduction of Construction Waste	Focuses on enhancing waste management standards, optimizing government procurement procedures, strengthening quality supervision, providing training and promotion, and offering incentives for enterprises
May 2020	MOHURD	Guiding Manual on the Reduction of Construction Waste at Construction Sites (Trial)	Sets construction waste management standards, emphasizes the importance of optimizing government procurement procedures, aims at reducing environmental impact and driving green development in the construction industry
July 2020	MOHURD, NDRC, MOST, and 10 others	Guiding Opinions on Promoting the Coordinated Development of Intelligent Construction and Construction Industrialization	Focuses on promoting the coordinated development of intelligent construction and construction industrialization, likely covering areas like technology integration and industry promotion

Time	Issuing organization	Policy	Highlight
July 2020	MOHURD, NDRC, the Ministry of Education, and four others	Action Plan for the Innovative Construction of Green Buildings	By 2022, the proportion of green building area in new buildings in cities and towns will reach 70%; the number of star-rated green buildings will continue to increase; the energy efficiency of existing buildings will continue to improve; the proportion of fabricated construction methods will steadily increase, and the application of green building materials will further expand
July 2020	MOHURD, NDRC, Ministry of Civil Affairs, and three others	Notice on Issuing an Action Plan for Creating Green Communities	Details measures for green community creation such as improving environmental quality, enhancing community facilities with an eye towards environmental protection and sustainable development goals
August 2020	MOHURD, MOE, MOST, and six others	Several Opinions on Accelerating the Development of New Construction Industrialization	Focuses on promoting new construction industrialization, including aspects like technological innovation, policy support, and industry - wide transformation to accelerate the development of this new form of construction industrialization
September 2020	MOHURD	Guiding Booklet for the Reduction of Building Waste at Construction Site	Outlines strategies and best practices for reducing construction waste at construction sites, which could include waste management plans, recycling initiatives, and guidelines for minimizing waste generation during construction activities.
October 2020	MOF, MOHURD	Notice on the Pilot Work of Supporting the Government Procurement of Green Building Materials to Improve Building Quality	Sets initiatives to support government procurement of green building materials, aiming to enhance building quality. It may include guidelines, incentives, or programs to encourage the use of environmentally friendly and sustainable building materials in construction projects.
January 2021	MOHURD	Management Approach for Green Building Labeling	Clarify the star level of green building labeling, stipulate the work of green building labeling at all levels of construction, and require that the three-star green building labeling be in line with the national standard, so as to promote the high-quality development of green buildings
February 2021	State Council	Guiding Opinions on Accelerating the Establishment of a Sound, Green, Low-Carbon and Circular Development Economic System	It is proposed to accelerate the green upgrading of basic design, implement the concept of green development in relevant spatial planning, and vigorously develop green buildings
March 2021	Communist Party of China Central Committee, State Council	Outline of the 14th Five-Year Plan (2021-2025) for National Economic and Social Development and the Long-Range Objectives Through the Year 2035	Promote the clean, low-carbon, safe and efficient use of energy, advance the low-carbon transformation in industry, buildings, transportation and other fields, and implement key projects such as the optimization of energy system and the transformation of energy-saving technology

Time	Issuing organization	Policy	Highlight
September 2021	Communist Party of China Central Committee, State Council	Working Guidance for Carbon Dioxide Peaking and Carbon Neutrality in Full and Faithful Implementation of the New Development Philosophy	Vigorously develop energy-saving and low-carbon buildings, continuously improve energy-saving standards for new buildings, and accelerate the development of ultra-low-energy, near-zero-energy and low-carbon buildings on a large scale
January 2022	MOHURD	14th Five-Year Plan for Construction Industry Development	To guide and promote the high-quality development of the construction industry during the “14th Five-Year Plan” period. Specifically, prefabricated buildings will account for more than 30 percent of the country’s new construction. Building waste at new construction sites will be lower than 300 tons per 10,000 square meters.
March 2022	MOHURD	14th Five-Year Plan for Building Energy Conservation and Green Building Development	By 2025, construct more than 50 million square meters of ultra-low-energy and near-zero-energy buildings
June 2022	NDRC, MOHURD	Implementation Plan for Carbon Peaking in the Urban and Rural Construction Sector	Continuously carry out actions to create green buildings, and by 2025, green building standards will be implemented for new building areas in cities and towns, and the proportion of star-rated green buildings will reach more than 30%
February 2023	NDRC, MIIT, MOF and five others	Guiding Opinions on Coordinated Energy Saving, Carbon Reduction, and Recycling to Accelerate the Update and Transformation of Product Equipment in Key Areas	Promote the update and transformation of product equipment in key sectors by coordinating energy-saving, carbon reduction, and recycling efforts
March 2023	MOF, MOHURD, and MIIT	Implementation Guidelines for the Government Procurement Supporting for the Green Structural Materials to Promote the Structural Quality	Cover aspects like defining green materials, procurement policies, monitoring, financial incentives, stakeholder engagement, and a phased implementation plan, with the overall goal of promoting sustainable and high - quality construction in line with environmental and quality objectives.
March 2023	MIIT, MOHURD, MARA and three others	Notice about Printing the Carrying Out the Activities of the Green Materials to the Countryside in 2023	Promote green building material product certification, their application, public awareness through various means like demonstrations in the countryside
March 2023	NDRC	Notice on Further Strengthening the Updating, Upgrading and Application of Energy-saving Standards	Covers measures in various sectors like industry and construction for energy - efficiency improvement, emphasizes the role of technological innovation and smart management, and details policy support and supervision mechanisms to ensure the achievement of more efficient energy use and a greener, more sustainable future

Time	Issuing organization	Policy	Highlight
April 2023	Standardization Administration of China, NDRC, MIIT and eight others	Construction Guidelines for Carbon Neutrality and Carbon Peaking Standard System	Provides a comprehensive framework for constructing a standard system to support carbon neutrality and carbon peaking goals
August 2023	MIIT, NDRC, MOF and five others	Work Programme for Stable Growth of the Building Materials Industry	A strategic approach to foster the stable growth and transformation of the building materials sector, the value-added industrial output of China's building materials sector to achieve year-on-year growth of approximately 3.5 percent in 2023 and 4 percent in 2024
August 2023	MEE, MOF, MNR and five others	Notice on Deepening the Pilot Construction of Climate-adaptive Cities	Ams to promote the climate - adaptability of Chinese cities, including aspects like criteria for pilot city selection, implementation of adaptation measures in areas such as planning and infrastructure, financial support and policy incentives, and monitoring and evaluation mechanisms
August 2023	NDRC, MOST, MIIT and seven others	Implementation Plan for Green Low-Carbon Advanced Technology Demonstration Projects	Clearly proposed the key directions, safeguard measures, and organization and implementation methods for green low-carbon advanced technology demonstration projects. The "Plan" mentions: In the construction field, the integration of photovoltaic buildings and other ultra-low energy consumption buildings, nearly zero-energy building technologies should be promoted
October 2023	MOHURD	Technical Specification for Assessment of Greenhouse Gas Reduction Volume Based on Projects - Wood Components for Building (Draft for Comments)	Specifies the assessment content, project boundaries and emission source identification, determination of greenhouse gas types, determination of project baseline scenarios, calculation of reduction volumes, monitoring and data quality management, and preparation of reduction volume assessment reports for the assessment of greenhouse gas reduction volumes of wood components used in buildings
December 2023	MIIT, NDRC, MEE and seven others	Implementation Plan for High-quality Development of Green Building Materials Sector	Outlines a series of strategic goals and measures to enhance the green development of the building materials sector. By 2026, the annual operating income of green building materials will exceed 300 billion yuan, with an average annual growth rate of over 10% from 2024 to 2026. A total of more than 30 characteristic industry clusters will be established, and more than 50 green building material application demonstration projects will be constructed. The number of cities implementing government procurement policies will be no less than 100.
March, 2024	NDRC, MOHURD	Action Plan to Speed Up Energy Conservation and Carbon Reduction in The Construction Sector	By 2025, a better institutional system of energy conservation and carbon reduction in the construction sector will be established, and green building standards will be thoroughly implemented on newly constructed urban buildings. By 2027, buildings with ultra-low energy consumption will see large-scale development

Time	Issuing organization	Policy	Highlight
May 2024	State Council	Action Plan for Energy Conservation and Carbon Reduction During 2024-2025	In 2024, energy consumption and carbon dioxide emissions per unit of GDP will decrease by about 2.5 percent and 3.9 percent, respectively. In 2025, non-fossil energy consumption will account for about 20 percent of total energy consumption, about 50 million tons of standard coal for energy-saving and carbon-reduction transformation in key areas and industries will be saved, and about 130 million tons of carbon dioxide emissions will be reduced

Table 2 National Standards related to green building identification, building energy efficiency, and renewable energy utilization

Time	Standard	Highlight
2006	Assessment Standard for Green Buildings (GB/T 50378)	Focuses on building green technology indicators and makes a series of requirements for building energy conservation, resource utilization, water resource utilization, and green operation management
2014	Assessment Standard for Green Buildings (GB/T 50378 - 2014)	Update in the in the "Improvement and Innovation" chapter: conduct building carbon emission calculation and analysis, take measures to reduce the carbon emission intensity per unit building area, and give "innovation points"
2019	Assessment Standard for Green Buildings (GB/T 50378 - 2019)	Constructs five major indicator systems such as safety and durability, health and comfort, living convenience, resource conservation, and livable environment on the basis of "energy conservation", "land conservation", "water conservation", "material conservation" and "environmental protection"
2019	Standard for Building Carbon Emission Calculation (GB/T 51366 - 2019)	Provides a carbon emission statistics method covering the entire life cycle of buildings
2019	Technical Standard for Nearly Zero - energy Buildings (GB/T 51350 - 2019)	Based on China's climate characteristics, building types, energy - use characteristics and development trends, and provides technical support for the design, construction, testing, evaluation, commissioning and operation - maintenance of nearly zero - energy buildings
2021	General Code for Energy Efficiency and Renewable Energy Application in Buildings (GB55015 - 2021)	Clarifies mandatory indicators and basic requirements for design, construction, commissioning, acceptance and operation management from three aspects: energy - saving design of new buildings, energy - saving of existing buildings, and renewable energy utilization
2021	General Code for Building Environment (GB55016 - 2021)	Clarifies mandatory indicators and requirements for design, testing and acceptance from four dimensions: building acoustic environment, building light environment, building thermal performance and indoor air quality.
2021	Management Measures for Green Building Labels	Clarifies information signs indicating the star level of green buildings and containing performance indicators

Note: Not all relevant details are included.

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