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A BIM–LCA Approach for the Whole Design Process of Green Buildings in the Chinese Context

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Abstract: The integrated description of the building geometry and the element attributes of the building information model (BIM) can reduce the effort needed to acquire data for life cycle assessment (LCA) and life cycle costing (LCC) at each design stage while supporting their potential for analyzing life cycle performances and feeding back to the design process. To support this, several methods and tools have been proposed that aim to obtain the life cycle performances of buildings following the level of model fidelity with the life cycle inventory (LCI) database at different scales. However, inconsistencies in decision-making caused by regional differences in LCA/LCC data sources, benchmarks, and building standards cannot be ignored. In this study, a scalable LCA/LCC method integrated with the BIM platform is proposed for the whole green building design process in the Chinese context, and it is implemented with a developed tool based on Revit. A national-/regional-specified database of building elements and materials is established. Referring to China's carbon-neutral target and relevant standards for green buildings, the baseline values are deduced, and a reference building is defined accordingly to facilitate the evaluation and improvement of the design scheme. According to the Assessment Standard for Green Building (GB50378-2019) and the survey of architectural design practices in China, the key parameters at different design stages are defined. The method and tool are demonstrated using the case study of a school building, analyzing its life cycle carbon emissions and life cycle costs throughout the design process. The results show that the proposed method can facilitate the improvement of the scheme at different design stages and that it can cope with different data accuracies and different LODs in the building information model in the Chinese green building design process. Lastly, the uncertainties raised by the data quality and time-associated factors are discussed.

Keywords: BIM; China; design process; green building; life cycle

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Citation: Li, Q.; Yang, W.; Kohler, N.; Yang, L.; Li, J.; Sun, Z.; Yu, H.; Liu, L.; Ren, J. A BIM–LCA Approach for the Whole Design Process of Green Buildings in the Chinese Context. *Sustainability* **2023**, *15*, 3629. https://doi.org/10.3390/su15043629

Academic Editor: Antonio Garcia-Martinez

Received: 15 December 2022
Revised: 19 January 2023
Accepted: 3 February 2023
Published: 16 February 2023

1. Introduction

In China, buildings account for 46% of primary energy consumption and 51% of carbon emissions [1] throughout their life cycles, as revealed by relevant estimations. The number of 'green' buildings has been surging, since energy efficiency and emission reduction standards are becoming increasingly rigorous.

Life cycle assessment (LCA) and life cycle costing (LCC) are defined as the fundamental methodologies for building sustainability assessment in international standards [2]. They are capable of calculating buildings' resource consumption and environmental and health effects, while quantifying their long-term monetary costs. A life cycle-based method should enable the horizontal integration of different performances and the vertical integration of the project and the building's life cycle. The results of every planning decision should be directly transmitted to all parts of the building in all aspects. Thus, it is imperative to propose a scalable LCA/LCC method to perform the progressive description of buildings.

BIM serves as an effective information integration platform for the LCA of buildings by integrating and interacting graphic and nongraphic information. A BIM-enabled LCA method should be able to cope with differences in the availability of project data and the key parameters to be considered at each stage. Several methods and tools which integrate BIM and LCA/LCC (e.g., One Click LCA [3] and BIMEELCA [4]) have been proposed for the whole design process. However, methods and tools are accompanied by their own national- or regional-specific LCI databases and standards for the assessment and the resulting feedback, which may cause misleading results in decision-making if applied in a different context. Accordingly, the above methods and tools cannot fully meet the needs of China's green building design.

The contribution is organized as follows: a literature review of the existing BIM-based LCA/LCC methods and tools applied in different design processes is provided in Section 2, in which the research gaps and local applicability are highlighted and the national or regional approaches in the Chinese context are discussed. Section 3 lists the objectives of the study. Section 4 presents the method of the study, including the scalable database, the progressive BIM–LCA/LCC method, the key parameters to be considered during the design process, and the developed tool, IBLAT. In Section 5, the proposed method and tool are demonstrated using the case study of a primary school building in northern China. First, a reference case and the baseline value are established. Then, different solutions in the schematic design, design development, and construction design stages are analyzed with IBALT the decision making. Section 6 discusses the connections and gaps in the results from different design stages, as well as the uncertainties caused by data sources and time-related factors. Section 7 concludes the contribution.

2. State of the Art

The methods for building life cycle assessment have developed from guidelines on the measures to be considered in each aspect and life cycle stage to the quantification of the performances and benchmarks with LCA and LCC. An integrated LCA and LCC method incorporates the quantification of resource, environmental, social, and economic aspects into the same physical framework [5] while significantly increasing the consistency of data and the efficiency of building description. Moreover, more efficient methods of data exchange, analysis, and feedback should be developed to handle the increasing complexity of building projects [6]. Thus, the BIM-enabled ingrated LCA and LCC has become a major research topic over the past few years.

Data interaction between different areas of building information lays the basis for the integration of BIM and LCA. Manual and quasi-automatic data [7–9] import has been progressively substituted with automatic data extraction over the past few years [10–13]. Originally, the quantity data of building materials were extracted from the building information model and input manually into an LCA or LCC tool, which was inefficient and difficult to implement early in the design process. By linking an external LCA tool through file exchange with the interface of a BIM platform, a quasi-automatic LCA/LCC can be performed. However, the effectiveness of the feedback on the design process for improvement is still limited. Automatic data interaction enables LCA/LCC analysis with developed plug-ins in the unified BIM environment. It has achieved a significant improvement in the efficiency of data exchange between the LCA tools and BIM, as the life cycle performances can be calculated and easily updated when a change is made to either the building geometry or an element attribute.

2.1. BIM Based LCA/LCC Method

Generally, there are three different categories in the BIM-enabled LCA/LCC methods and tools in terms of their integration with the building design process. The first category performs LCA in the detailed design stage with refined building information. The second category aims at early estimation and parametric optimization with simplified LCA approaches. The third category applies hierarchical databases for conducting progressive LCA through the entire design process. Table 1 summarizes the existing literature in the three categories.

Kaveh Safari et al. [14] found that more than half of the contributions to BIM–LCA have placed a focus on the early design stage since this stage most significantly affects buildings' life cycle performance [7,15]. However, LCA is usually conducted at the construction design stage when the project information is nearly defined. To increase the applicability of the LCA method at the early design stage, researchers have attempted to develop simplified LCA methods [16], which have been supported by external databases with pre-assembled solutions for the respective element category [17,18]. On that basis, concise LCA results and visual design guidance can be provided [11], or the LCA results can be predicted by statistical analysis [19]. However, due to the large granularity of the data, the simplified methods often lead to results of low accuracy and with a certain deviation from the final results, such that the above methods do not apply to detailed LCA calculation.

The sketchy methods applied in the early stage of design cannot match the level of detail of the project model with the increase in information. Accordingly, tools and methods with a detailed material database are required for the later stages, in which more detailed project information is available. Russell-Smith et al. [20] built a computational framework by adding a hierarchical database to the respective element in the building information model. Tally [21] read the quantity data and construction details for the respective element and linked them to the material database combined with their LCI data. Raja Shahmir Nizam et al. [22] developed a framework to estimate the embodied energy contained in the native BIM environment. Although the above existing research has better supported LCA with high-precision building information models and the preliminary design options of the building materials, it is still challenging to involve early low-precision models in the same platform.

The geometric and attribute parameters of the building and the elements can be automatically optimized on the basis of LCA and LCC results and the target values under a certain context with the support of the BIM–LCA method. Several studies have proposed multi-objective optimization methods for different design stages [23–25]. However, the method is often applied at the early design stage, and the architects usually do not make decisions for the building form and the element material and dimensions simultaneously. Moreover, the proposed geometric prototype usually limits the variety of building forms. Accordingly, some authors have argued that the comparison between different solutions proposed by architects can be more plausible.

Projects constantly evolve and change throughout the design process. Rúben Santos [4,26] proposed the BIMEELCA tool to conduct LCA at the early and later design stages with different levels of development (LOD) of the BIM model. This tool enables the users to edit the impact and cost information linked to the materials, thus enhancing the accuracy and representativeness of the results. The research of Alexander Hollberg et al. [27] was based on the architectural design process (34 stages in total), which highlighted the differences between LCA calculations at the respective design stages. More researchers have considered how to use the LCA method to monitor the entire process. Farzaneh Rezaei [28] established a functional database that comprises assemblies, layers, and materials for a wide variety of design stages. Carmine Cavalliere et al. [29] proposed a framework for continuous LCA calculation throughout the entire design. This framework extracts data from the 3D model in Rhinoceros to an Excel spreadsheet. Despite some limitations in platform integration and the comprehensiveness of the assessment indicators, the above research has manifested a valuable attempt in developing decision-making methods throughout the life cycle for the entire design. However, the above studies primarily investigated the embodied impact in Europe. Some of them did not include operational energy or LCC. One Click LCA [3] allows quick LCA calculations based on building shape and size, as well as the definition of the quantity and types of materials with more detailed information. It is able to conduct LCA in each design stage. However, it does not contain any local element and assembly data for China. Although relatively well-developed BIM-LCA assessment tools and methods have been proposed worldwide, there are still some limitations in the application scope of the basic databases, the focused design stages, the data structure, the integrated assessment system, etc. As a result, they cannot assist the decision making related to green building design in the context of China.

Table 1. Summary of the literature on BIM–LCA methods and tools.

Literature	BIM Tool	LCA Tool	Integrated Tool/Method	Data Source	Analysis with Green Building Rating System	Indicator	Results Feedback
Early design stage							
[11]	Revit-Dynamo/MS Excel	-	A script in Dynamo	Ecoinvent/Swiss SIA MB 2032	-	GWP	The potential to improve the total building impact is indicated by SDEV and color
[24]	Rhinoceros (Grasshopper)	-	Bombyx	Ökobilanzdaten im Bauberiich (KBOB)	-	UBP, PE-nr, PE-r, GWP	Values in Grasshopper
[30]	SketchUp/Rhinoceros; interface in ArchiCAD and Revit	-	CAALA	Ökobau.dat 2016 I, manually added EPD from users	-	PENRT, EP, AP, POCP, ODP, GWP	Comparison of variants, values, and proportion charts in results
[31]	Rhinoceros (Grasshopper)	-	-	Oekobau.dat database, Bauteilkatalog, Milieuprofiel van gebouwelemente, Baubook	DGNB	LCP	Equal to 100% of the DGNB points related LCA criteria.
[32]	Revit/MicrosoftAccess	Athena	Revit DB link	Ecoinvent	-	Environmental impacts: GWP, AP, PM, EP, CFCS, ODP	Severity index classification
Detailed design stage							
[21]	Revit	Tally	-	GaBi	-	AP, EP, GWP, ODP, SFP, PED, NRE, RE	Provide different scenarios comparing, values and proportion charts in results
[22]	Revit	-	Revit plug-in	ICE Version 2.0 database	-	Energy	Values and proportion charts
[33]	Revit/Green Building Studio	Tally	-	GaBi	-	AP, EP, GWP, ODP, SFP, PED, NRE, RE	Comparison of different scenarios; only values and charts
[34]	Revit	Simapro	-	Ecoinvtent v3	-	Indicators within IMPACT 2002+	-
[35]	Revit	eBalance	-	China Life Cycle Database (CLCD) Ecoinvent	-	GWP	Values and charts

Table 1. *Cont.*

Literature	BIM Tool	LCA Tool	Integrated Tool/Method	Data Source	Analysis with Green Building Rating System	Indicator	Results Feedback
Entire design process							
[3]	Revit/Rhinoceros (Grasshopper)	-	One Click LCA	130,000 data points, mostly for Europe and America	More than 50 certifications	Indicators included in environmental impact assessment methodology; LCC	Embodied carbon benchmark; baseline building for early design stage
[26]	Revit	-	BIMEELCA tool	CML 2001 (specific data and region-free)	-	ADPE; ADPM; AP; EP; GWP; ODP; POCP; PE-NRe; PE-R, LCC	Sustainable target value (STV) design; single values and charts
[27]	Revit-Dynamo	-	Developed Dynamo script	Ökobilanzdaten im Bauberiich (KBOB) Ecoinvent v2	-	GWP, PE-nr	UBP
[28]	Revit	OpenLCA		Ecoinvent 3.3/Functional database	-	Relative indicators included in human health, ecosystem quality, climate change, and resources	Box–whisker plot through data extractor
[29]	Rhinoceros	-	-	KBOB	-	GWP	Range values and specific values within different stages
[36]	Revit-Dynamo	-	Dynamic tool for LCA developed in Dynamo	KBOB	-	Grey energy, GHG, UBP	Sustainability targets set by the 2000-Watt Society
[37]	BIM software	GENERIS®	BIM2LCA	Ökobau.dat	DGNB	Reference indicators of LCA/LCC	Building benchmarks, construction benchmarks, LCA/LCC results, and scenario comparison

2.2. National/Regionalized Approach

A nationalized or regionalized database is an essential basis and premise for building life cycle assessment [35,38–40]. Different countries and regions have established their own LCA databases and assessment tools for the construction industry [3,21,41]. They differ in terms of production conditions, electric mix, and relevant weight coefficients across countries and regions. Previous studies [38,39] have shown that a country-specific LCI database should be applied to obtain more referential results.

At present, China's Standard for Building Carbon Emission Calculation (GB/T 51366-2019) [42] provides carbon emission factors for common building materials, energy sources, construction machinery, etc., and some methods and tools have also been introduced [43–49]. Yet, the standard is only concerned with carbon emissions. Although China has been trying to develop EPDs of building materials, it is so far difficult to find open EPD data. Several Chinese institutions and universities are developing a comprehensive LCA database and too, e.g., the general online LCA tool eFootprint [50] with the CLCD [51] database, and the building LCA tool BELES [52] Tsinghua University's. However, the tools do not have interoperability with BIM, nor can they support decision-making for the whole design process. The above tools are more appropriate to be applied at the construction design stage, when detailed project data are available. For the early design stage, there is a lack of integrated LCA data of the predefined component information and estimated data for missing information (such as the structure). Furthermore, design uncertainties are not considered systematically.

The latest version of China's Assessment Standard for Green Building (GB50378-2019) [53] has dramatically increased the score for the application of BIM in the green building assessment criteria. However, there is a lack of comprehensive LCA/LCC databases and assessment indicators that integrate with the BIM tools and meet China's building assessment standards. This hinders designers from using the BIM platform to facilitate carbon emission simulations throughout the design.

3. Main Objectives of the Study

The literature review revealed that, while methods and tools of BIM-LCA/LCC and their application in the design process are maturing, there are still research gaps in supporting decision-making in the Chinese context, such as the lack of databases of scalable building elements and materials, inefficient platform integration, and insufficient integration with the green building design process.

The main objective of the study was to develop an integrated BIM-based LCA/LCC method and tool for China's green building design process. The key goals were as follows:

(1) To establish a scalable LCA approach and database coping with the progressive description in the building design process based on Chinese LCI data and the national BIM coding system;

(2) To identify the key parameters to be considered in each design stage referring to the requirements in China's Assessment Standard for Green Building (GB50378-2019) [53], and then propose the BIM-LCA/LCC method throughout the green building design process with consideration of the LOD of the model accuracy in an integrated BIM environment.

(3) To develop a tool that can integrate with the Revit platform to implement the method into the whole design process of Chinese green buildings, and then apply it in a case study of a school building.

(4) To discuss how data sources and time-related factors can affect the life cycle performance assessment of the building.

4. Method

4.1. Overview of the Method

This study aimed to analyze the life cycle performance throughout the design process on the BIM platform. The method in this study comprised three parts:

1. Scalable database development,
2. BIM-LCA workflows in the design process,

3. Implementation of the methods.

The bases and prerequisites of the method comprise the hierarchical databases of the Chinese building materials and those of the building elements in accordance with the local detailing standards and codes. The BIM–LCA workflow, combined with the Chinese energy efficiency standards, is the core of the method to facilitate the decision-making in the designing process. Through the four-step cyclic operation, the life cycle performances of a project can be analyzed and processed into visual information for design decisions. To implement the method, a BIM–LCA tool integrated with China's Assessment Standard for Green Building (GB50378-2019) [53] is developed, which is capable of dealing with different accuracies of the project model throughout the design process (Figure 1).

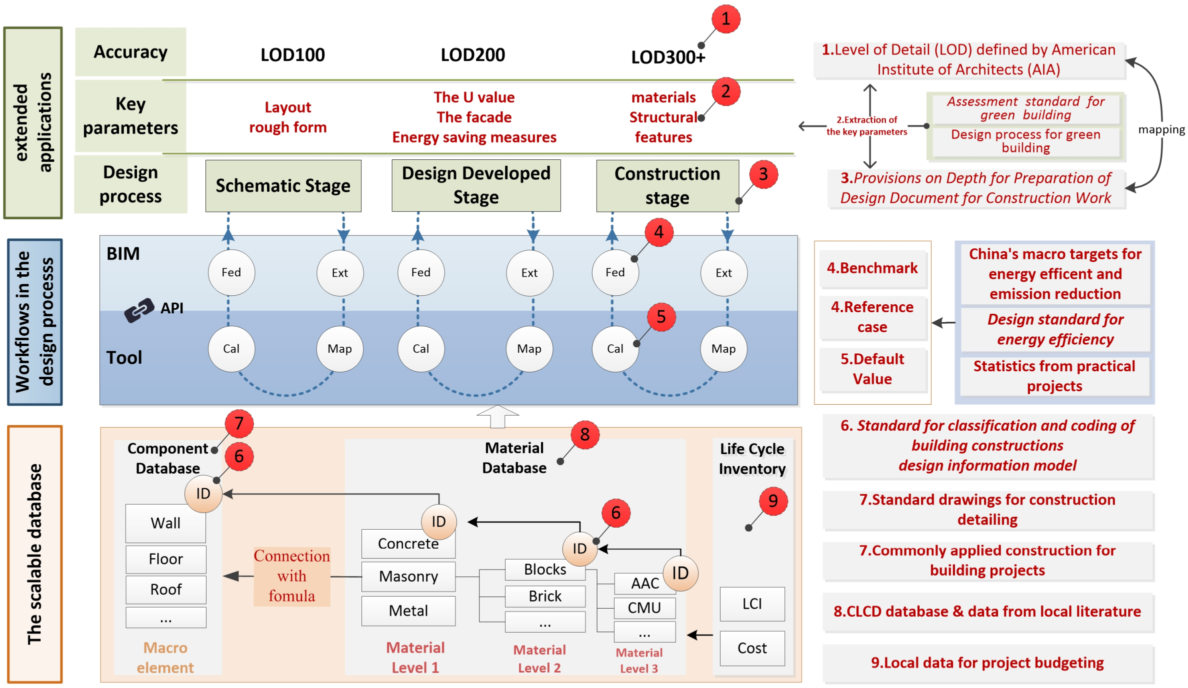


Figure 1. The BIM–LCA method for Chinese green building design proposed by the study. **Ext:** information extraction, **Map:** data matching, **Cal:** calculation and comparison, **Fed:** interpretation and feedback of the results.

4.2. The Scalable Database

4.2.1. Data Sources

In the context of China, the LCI data of materials are primarily derived from the CLCD database, with some missing data supplemented by the literature and by the global generic data quoted from the Ecoinvent database. Moreover, the LCA data of building components are obtained in accordance with the LCI of the relevant material. The cost information is based on industrial data in the Chinese market.

4.2.2. Life Cycle Scope

In the Standard for Building Carbon Emission Calculation (GB/T 51366-2019) [42] in China, a building's life cycle comprises three major stages, production and transportation, construction and demolition, and operation. Referring to this definition and the international and European standards, the life cycle stages that are defined in this study involve material production, transportation, construction, operation, replacement, demolition, and recycling, corresponding to stages A1–A3, A4, A5, B4, B6, C4, and D of European Standard EN15978, respectively (Table 2).

Table 2. Life cycle processes for LCA and LCC considered in the study.

Life Cycle Processes		System Limit of LCA	LCI data source	System Limit of LCC	Cost Data Source
Stages					
A1–A3	Material production	•	CLCD; Ecoinvent	•	Local quantity survey data
A4	Transportation to the site	•	CLCD	•	Local quantity survey data
A5	Construction on the site	•	CLCD; The literature [52,54]	•	Local quantity survey data
B4	Component replacement	•	CLCD; Ecoinvent component life span [55]	•	Local quantity survey data
B6	Operational energy use	•	CLCD; standard for carbon emission; national policy	•	Local energy prices
C4	Processing and disposal of waste material	•	CLCD; Ecoinvent; Oekobau.dat;	•	The literature [56]
D	Reuse/recycling potential of building wastes	•	CLCD; Ecoinvent	•	The literature [56]

4.2.3. Database Structure

The database was programmed in SQL2012, and it comprised an elements library and a materials library. The LCI data in the materials library laid the foundation for the database, which contains materials that are commonly employed in the Chinese market. The materials library was classified in accordance with the Standard for Building Constructions Design Information Model (GB/T 51269-2017) [57]. Subsequently, the life cycle environmental impacts and costs of the respective functional unit of the building materials were input into the database. Furthermore, physical properties (e.g., density, thermal conductivity, and transmittance (glass)) were recorded in the database for material identification and screening.

On the basis of the LCI data of the materials library, the elements library comprised building components defined by conforming to the national standards of China and the local handbook of detailed drawings. Moreover, the components were classified according to the BIM coding system to facilitate the designers in selecting and matching them to the Revit model. Per square meter was set as the functional unit of most components, and the reference flows were obtained on the basis of the material compositions of the components. Furthermore, the attributes related to LCA (e.g., material density, the component U-value, the cost, and the lifespan) were specified. Figure 2 illustrates the structure of the scalable database and its correlation with the building description.

4.3. BIM–LCA/LCC Workflows in the Design Process

To support the decision-making in the green building designing process, the proposed BIM-based LCA/LCC method is implemented in four steps: (1) project information extraction; (2) data matching; (3) computation and comparison; (4) result interpretation and feedback.

4.3.1. Information Extraction

The geometric information in the BIM models with different levels of detail can be extracted for LCA and LCC to match the project information of different design stages. At the schematic stage, the model volume and the component area are extracted. Furthermore, the above information tends to be replaced by the material type and thickness of the construction layer with the advance of the design process.

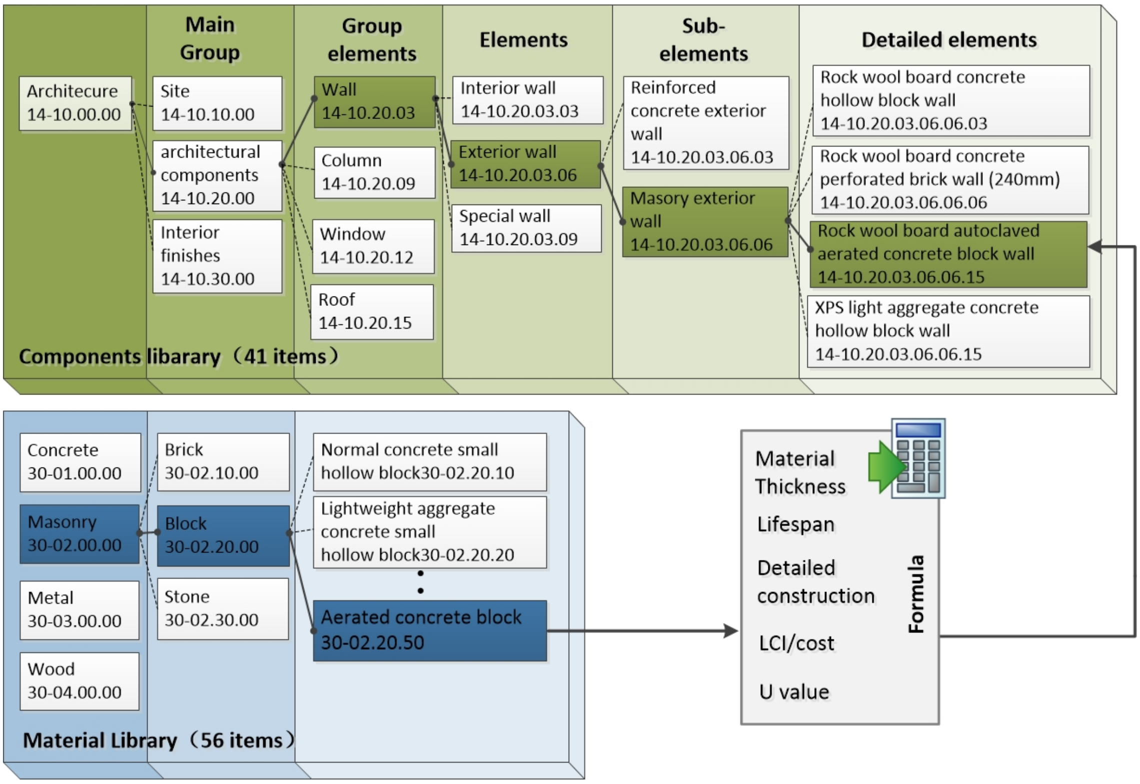


Figure 2. Structure of the scalable database for Chinese building materials and components.

4.3.2. Data Matching

The method and the associated tool, termed IBLAT (integrated building life cycle assessment tool), connects the names and codes of the material and the component LCA data to the names of the elements and materials in the Revit model to reduce the efforts of manually mapping the components with their life cycle data. LCA or LCC information for the components or materials can be automatically assigned when the names of the materials and components applied in the model match those in the database. If no equivalent name is identified, the LCA data can be manually assigned by designers to the corresponding components and materials by names or categories. The method largely reduces the manual effort in data selection and assignment, thus increasing the efficiency of the analysis and assessment. The users choosing appropriate model LODs in the LCA tool can always satisfy the different needs for decision-making of different design stages.

4.3.3. Calculation and Comparison

The indicators of life cycle environmental impacts considered in this study include global warming potential (GWP), primary energy demand (PE), ozone depletion potential (ODP), acidification potential (AP), eutrophication potential (EP), resource depletion water (WU), abiotic depletion potential (ADP), particulate matter (RI), and photochemical ozone formation (POFP). Moreover, the life cycle costing (LCC) and initial cost (IC) are also calculated. The operating energy data are calculated using external simulation tools or energy analysis in Revit.

Since many of the design parameters are indeterminate at the early stage, it is conducive to use the statistical average of the same type of building as the default value for supplementary calculation. The default values, defined in the functional unit of a square meter of building area, cover the life cycle economic and environmental values of the structural system (beams, columns, foundation, and stairs) and the service system. The default values tend to be replaced with the advance of the design process and with the increase in the model accuracy. The relatively completed life cycle model with a progressive description of the building project can help users achieve accurate LCA results progressively (Figure 3).

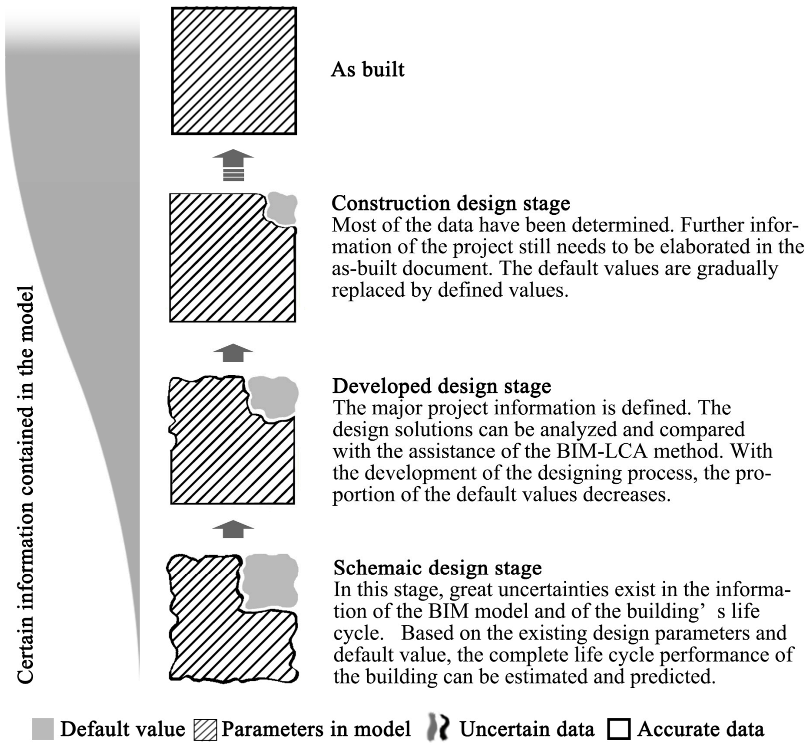


Figure 3. The progressive BIM–LCA method coping with the development of the building design process.

4.3.4. Results Interpretation and Feedback

The LCA or LCC results are presented as bar charts, proportion charts, and spider charts, which can be adapted to compare different schemes and to inspect the results of a single scheme. However, the results are not sufficient to assess the performance of a program since it is too abstract for non-LCA professionals to comprehend. Thus, designers refer to benchmarks to assess and improve their design schemes.

The benchmarks for life cycle assessment may comprise the baseline values for the minimum performance and target values to be pursued as objectives for the design optimization [58]. There have been no official benchmarks for the life cycle performances of Chinese buildings thus far, and the survey data are limited. Given this insufficiency, we tried to make plausible assumptions for the benchmarks of the vital indicators in accordance with the standards for building energy efficiency, the survey data, and the national macro-target. Furthermore, a reference case is defined to deduce the benchmarks as the supplement and verification of the top–bottom benchmarks.

Benchmarks for life cycle GWP

A previous study [59] indicated that the average carbon emissions of China's public buildings in their life cycles should be no more than 64 kg $CO_2/m^2/a$ to meet the targets of reaching the peak of carbon emissions before 2030, and reaching carbon neutrality by 2060 in China. According to the recently issued Energy Efficiency and Renewable Energy Use (GB 55015-2021) [60], a previous study [59] deduced the benchmarks using the bottom-up method and estimated the life cycle carbon emissions for primary school buildings in the cold climate zone of China as 55.8 $kgCO_2 \cdot m^2 \cdot a$ for the bottom line and 47.8 $kgCO_2 \cdot m^2 \cdot a$ for the target value.

Reference values for the initial and life cycle costing

The construction material, products, and labor costs of new school buildings in Tianjin were approximately 6000–8000 CNY/m^2 on average when the buildings were designed. The new construction cost of the optimal ranking ('3 star') green buildings is nearly 5% higher than that of the typical buildings as indicated by the survey labeled 'green buildings' in China [61]. For the case study building of this contribution, a reference scenario was defined in accordance with the baseline values in the national standard for building energy efficiency. The initial costs of the solutions selected for better environmental performances were no more than 5%, and the LCC was lower than the reference case. Thus, it was assumed that the price of energy remained constant over the building's life cycle.

Reference building

A reference building was defined to deduce the benchmarks from the bottom-up approach (Section 5.1), and its detailed life cycle performance information provides a reference value for the design options to be compared with.

4.4. Implementation of the Method

4.4.1. Scalable Approach for Design Process

Each stage of the building design process adds more information and makes further decisions related to the design solutions. In China, the building design process comprises three major stages (schematic design stage, design developed stage, and construction design stage) in accordance with Code for Construction Project Management (GB/T 50326-2017) [62]. The method developed in this study aims to optimize the design by comparing and assessing life cycle performance throughout the design process. The design solutions at the respective stage are compared with each other and with the reference case to determine the optimal option.

A scalable approach to the progressive building description is proposed to generate a whole picture of the LCA and LCC results of the design solutions throughout the whole design. The proposed approach is supported by hierarchical databases with the life cycle performance indicators of the components, the materials, and the processes (Figure 4). Different LCA databases can be selected in accordance with model precision in the scalable BIM-enabled LCA/LCC method and tools. Furthermore, the default values can be replaced with specific project data when they are available.

4.4.2. A Tool for BIM–LCA/LCC for the Chinese Context: IBLAT

A BIM–LCA tool IBLAT was developed to implement the above method into the design process. As an add-in to the Revit platform, IBLAT is programmed with the C# language of Microsoft Visual Studio, connected with the building information model through Revit API. The integrated BIM–LCA tool is capable of accessing the geometric and attribute data of the model, linking the extracted information to the LCA and cost databases, and displaying the results. The databases, integrated into the tool through C# programming, are established using the SQL server software. The data can be conveniently updated through the SQL server.

The tool can be triggered through the add-in window of Revit; on its initial interface (Figure 5), two operations can be carried out: (1) to create a new project to extract the existing model information and to conduct LCA (project creation); (2) view the information regarding materials or elements in the database (database management).

4.4.3. Match up with the design process

According to the level of detail (LOD, which is defined by the American Institute of Architects (AIA)) in the building information model, most of the materials of the building can be determined up to LOD 350. Alongside the design stages defined in the Chinese design standard, the material and element data are matched to the models of different LODs, the key design parameters are progressively analyzed and optimized with the support of the IBLAT tool (Table 3), and different levels are selected. On the other hand, the main design parameters are determined and considered at each stage according to the accuracy of the model, supporting the entire design process.

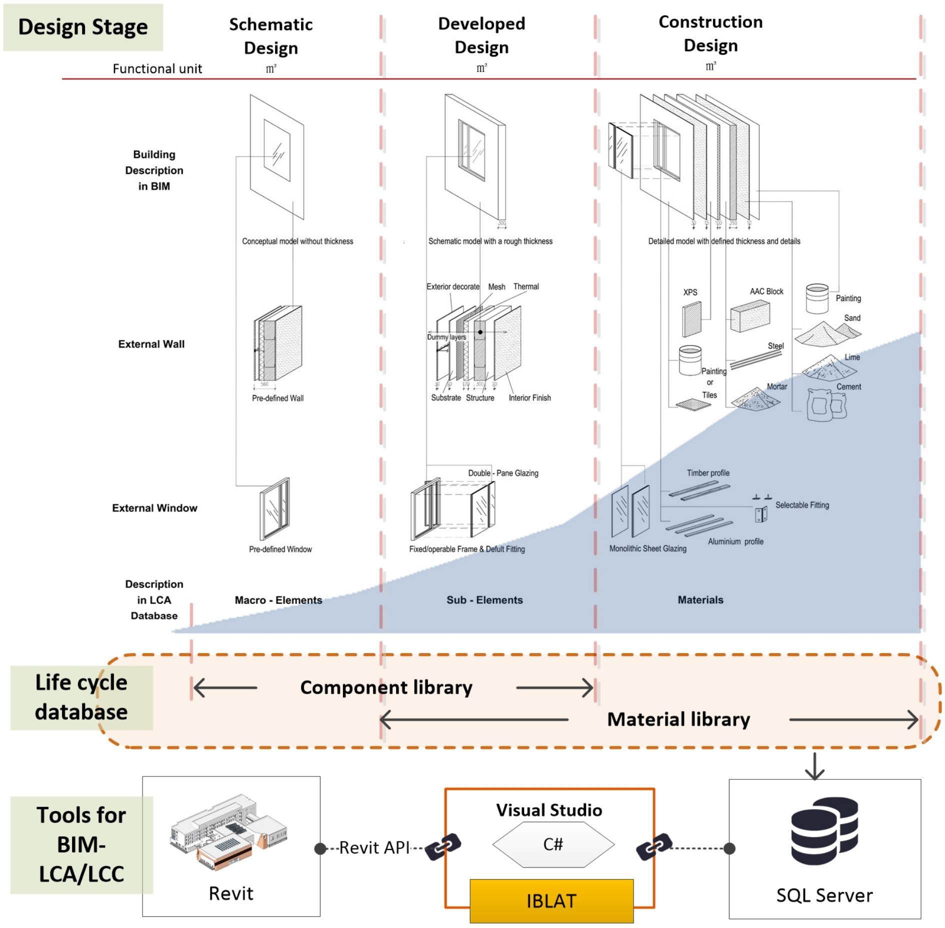


Figure 4. The progressive building description with BIM and scalable approach of life cycle performance assessment with the supporting tool.

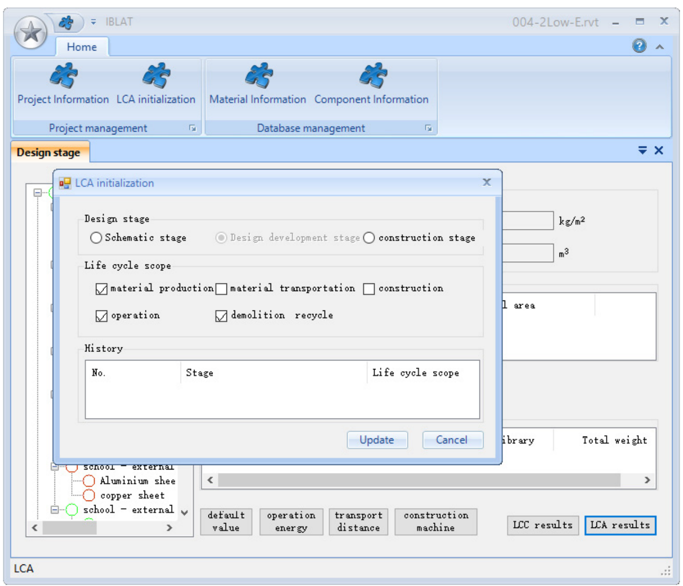


Figure 5. The initial interface of IBLAT.

Table 3. The interrelationship of the key design parameters, the model LOD, and the database matching each design stage.

Design Stages	Design Parameters	Level of Details	Database Linking	Model Description
Schematic design stage	Layout (orientation), rough size, volume ratio, façades	LOD100	Elements library	LOD100 has a basic shape, rough size, and volume. The model shows the location, shape, and orientation of the building, as well as the area information of the main components of the building.
Design development stage	Façade design, construction and space design, service system, heat transfer coefficient of the envelope	LOD200	Elements library and materials library	The model contains, size, shape, location, and orientation of the main parts of the building. The LOD200 model can reflect the rough geometric characteristics of the object itself. The main appearance size cannot be changed, and the detail dimensions can be adjusted.
Construction stage	Material selection, construction details	LOD300–LOD350	Materials library	The LOD300 model should contain accurate material component attribute information. The model is successfully used for cost estimation and construction coordination.

Schematic design stage: When selecting the building components, the detailed descriptions and overall heat transfer coefficients are used as references to make the first decision (Figure 6), to meet the energy-saving targets and relevant energy efficiency standards. The materials that make up the components can also be viewed by users to determine whether they meet their preferences. Then, the LCA and LCC results are analyzed and compared to assist the final decision from different design options.

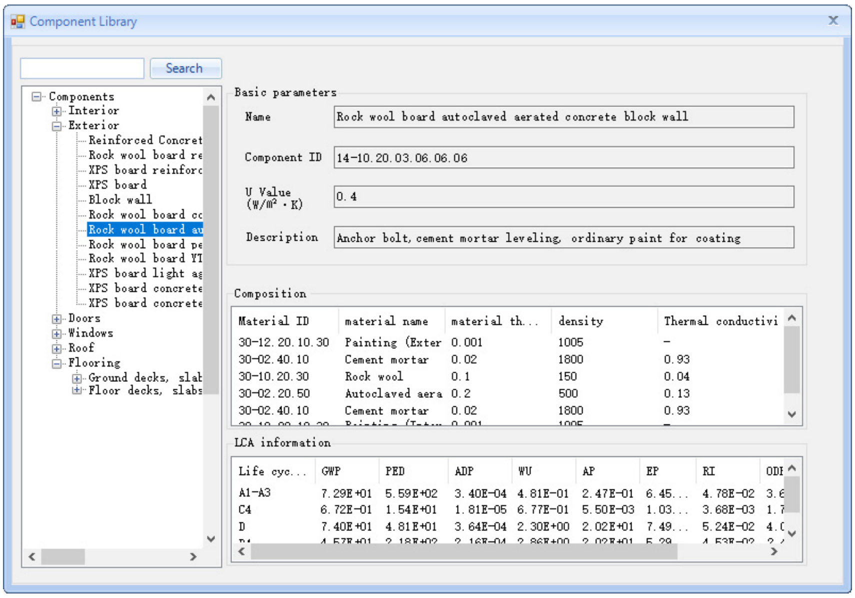


Figure 6. The interface of the building elements library in IBLAT.

Design developed stage: At this stage, the area, the layout, and the thickness of the materials in the construction design can be extracted since more details in the model are defined. The LCI data of components and materials can be mapped to the building information model with the progress of the project. For example, when looking at the walls, designers can refine the material option and the construction thickness with IBLAT, whereas, when designing the structures, they can still perform LCA or LCC on the element library.

Construction stage: At this stage, the majority of the materials have been determined, and the model information can be linked directly to the material library (Figure 7) to carry out a more detailed and precise calculation.

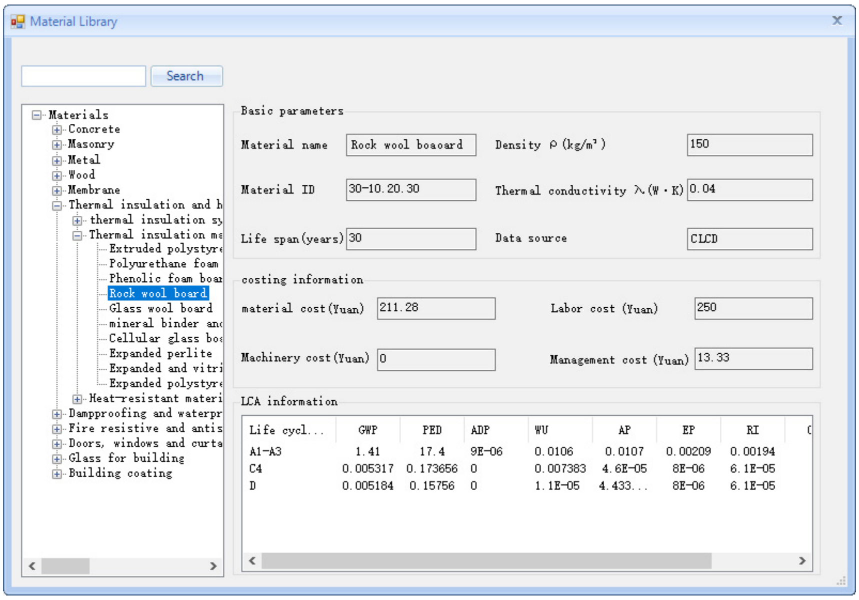


Figure 7. The interface of building material library.

4.5. Parameters Considered at the Respective Stage of the Green Building Design Process

It is important to avoid the simple accumulation of the 'green techniques' by taking the building's overall environmental and economic performance into consideration. Although the Assessment Standard for Green Building (GB50378-2019) [53] does not have the fully developed methods and benchmarks to assess the building's life cycle performances, criteria, and guidelines in the standard provided the lists of requirements of energy and resource conservation, environmental protection, and human health. Standard for Building Carbon Emission Calculation (GB/T 51366-2019) [42] issued the detailed calculation method for building life cycle GWP but did not mention the benchmarks. In terms of the Assessment Standard for Green Building (GB50378-2019) [53], nearly 20% of the terms were directly related to the life cycle environmental and economic performances of the building in a qualitative way. Building material and operational energy saving are the main concerns of the standard, which interact with each other and constitute the main factors affecting the performance of the building's life cycle.

Yang [63] classified the specific design parameters to be considered in the green building design process (Appendix A Table A1). Although the key parameters considered at each design stage show some differences between projects, the geometrical parameters (e.g., such as the site layout, general form, and space organization) are commonly defined at the early stage, followed by the floor plans, sections, façades, and types of the service system. Subsequently, the construction details and the exact equipment are defined. For the green building design, targets for energy performance or even for life cycle performances are specified from the beginning. On that basis, the passive design strategies of space organization and the general thermal conductivity and materialization of the construction are considered at the early design stage. Moreover, the material and dimensions of the building envelope take on a critical significance for operational energy consumption and embodied impacts. Accordingly, the above factors should be considered as early as possible and refined gradually at the later design stages.

Figure 8 summarizes the criteria in Assessment Standard for Green Building (GB50378-2019) [53]. The key parameters at each stage of the design process are extracted using the method of life cycle performance assessment, as well as the green building design process.

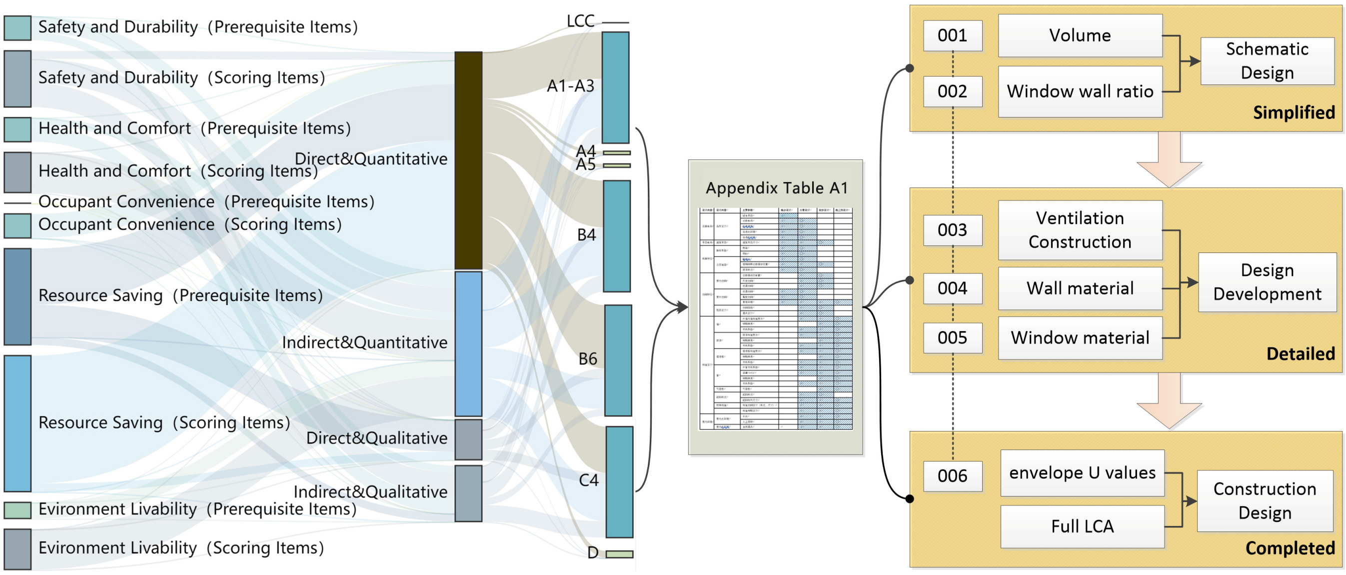


Figure 8. The application process of the BIM-enabled LCA/LCC method and tools at different design stages of the case study project.

5. Case Study

A primary school project was taken as an example to verify the effectiveness of the method and tool developed in this study. It is noteworthy that LCA and LCC were not employed for decision-making at the beginning of the design project since there was considerable uncertainty in the real design process, and it was selected for a case study once it was certain to be built in practice. Accordingly, a retrospective study was conducted to examine the life cycle performance of different solutions at the very beginning of the design to demonstrate how green building design in China can be improved using the BIM-enabled LCA and LCC methods. The life cycle processes considered in the study comprise the upstream and downstream flows of the building materials, transportation, construction, operational energy demand, demolition, and recycling of materials.

The site of the school is located in Tianjin in the cold climate zone of China, without any tall buildings nearby. The total floor area of the building is nearly 12,930 m^2. The project aimed to achieve the green building label (3 stars) in China (Figure 9).

5.1. The Reference Case and the Baseline Values of the Design Parameters

The reference case was defined as a basis for the comparison of different design solutions. The thermal quality of the envelope is equal to or better than the baselines in the national and local standards [60,64] for building energy efficiency (Table 4), which could meet the prerequisite terms in Assessment Standard for Green Building (GB50378-2019) [53]. The main structure is reinforced concrete. The reference life span of the building was set to be 50 years.

Design Builder was applied as the energy simulation tool throughout the whole design process. Parameters such as the heating and cooling schedules, the system efficiency, the airtightness, and the number of occupants were set according to the design standard for energy-efficient buildings [60,64] and Code for Design of School [65] (Table 4, Appendix A Table A2).

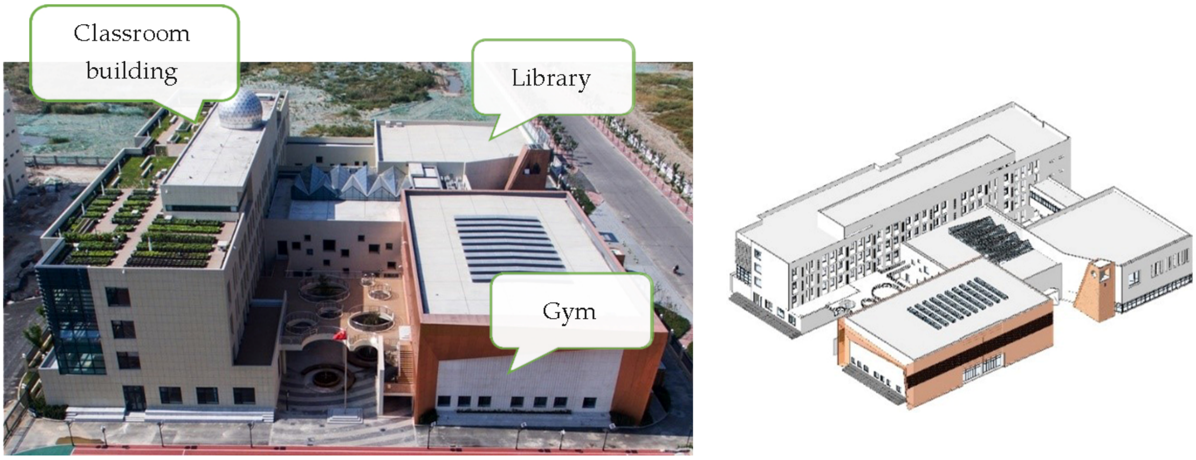


Figure 9. The case study building: a 36-class primary school building project located in Tianjin City in China.

Table 4. Thermal quality of the envelope defined in the reference case and baselines of the standards (W/m^2·K).

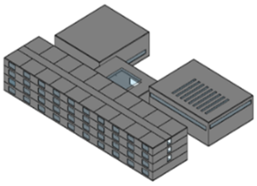
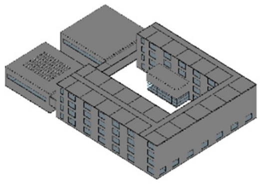
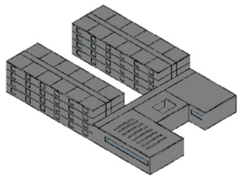
	National Standard [60]	**Local Standard [64]**	**Reference Case**	
Roof	0.40	0.35	0.35	Concrete board + EPS insulation + waterproof
External walls	0.5	0.45	0.4	AAC + EPS insulation
Window	2.5 (0.2 < *w*/*w* < 0.3) 2.0 (0.3 < *w*/*w* < 0.4) 1.9 (0.4 < *w*/*w* < 0.5)	2.0 (N) 2.3 (E, W) 2.5 (S)	2.0	6 Clear + 12 Air + 6 Low-E glass; thermal break aluminum frames
Skylight	2.4	2.3	2.2	

5.2. The Schematic Design Stage

In the case study project, the layout and volume of the building were conceptualized first, in which three schemes with different shape coefficients were considered. In addition, their window-to-wall ratios on the façade were also taken into account (Table 5). Since the windows on the southern façade are closely related to the solar gain, and since the north windows have great impacts on both the thermal and the lighting quality of the school building, different design options for the window-to-wall ratio were examined, especially for the north and south façades. The w/w ratio for the west and east orientation was set as 0.15. Figure 10 shows the component information in the schematic stage. At this point, designers selected the elements from the database and allocated them to each building part in a rough BIM model.

In the conventional green building design, the designers are inclined to select the solution with the minimum surface-to-volume ratio. Accordingly, Layout 1 at the s/v ratio of 0.20 was selected as the solution for the schematic design stage. The window/wall ratio of 0.35 (scenario 2-2) for both the south and the north façades was selected at the beginning of the design process. However, Layout 1 exhibited neither the best environmental performance nor the lowest life cycle cost, as indicated by the BIM–LCA/LCC results (Figure 11a); additionally, it did not have the lowest initial cost. Moreover, most of the major classrooms in this solution had a south orientation. As revealed by the simulation results, GWP and PED achieved the optimal life cycle environmental performance when scenario 2-2 was selected (Figure 11b), and the life cycle cost was also the lowest. The initial cost increased linearly with the increase in the window area.

Table 5. Three different scenarios for building shape and window-to-wall ratio.

	Layout 1	Layout 2	Layout 3
Revit model			
001 surface/ volume ratio	0.20	0.23	0.21
	Scenario 1	Scenario 2	Scenario 3
002 window/wall ratio (*w*/*w* ratio) of the south and north façades	0.25	0.35	0.45

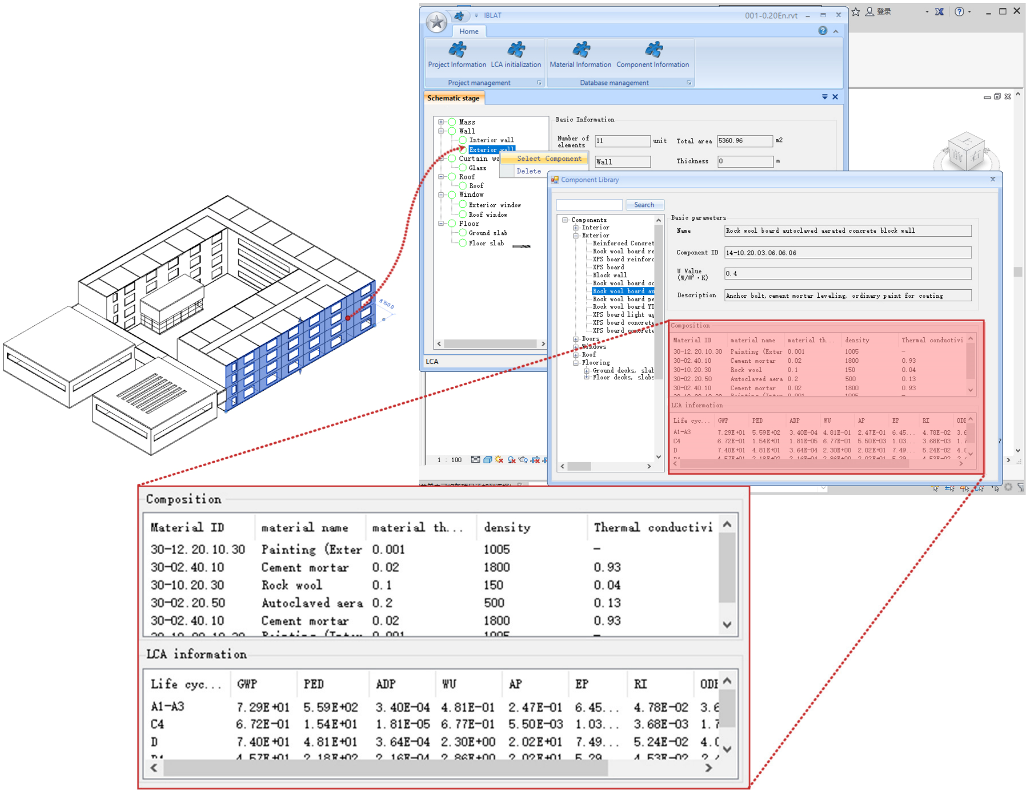
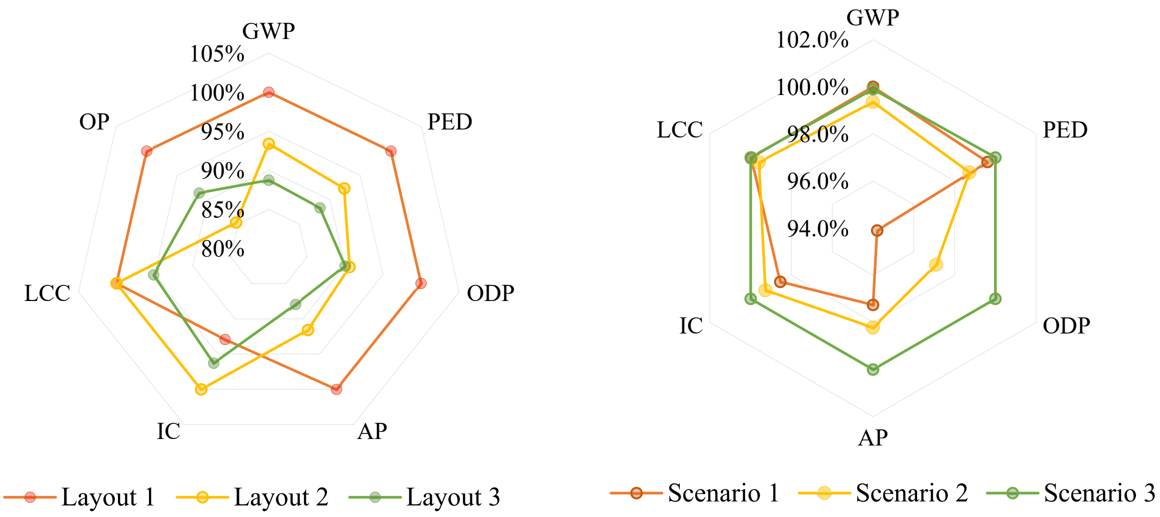


Figure 10. Matching the component data with the model information using IBLAT.

5.3. The Design Developed Stage

At the design development stage, the passive ventilation strategy, and the envelope materials including windows and walls were analyzed and compared on the basis of more available sophisticated project data. The material database was applied in a more detailed calculation for the above elements. The construction of the other elements of the building (e.g., the interior wall and the finishing), which were not key concerns at this stage, still mapped the data in the element database (Figure 12). Furthermore, it was also necessary to use default values for temporarily missing data to ensure the integrity of the LCA and LCC.



(**a**) 001 surface/volume ratio (**b**) 002 window/wall ratio

Figure 11. Environmental impacts and cost of three alternative layouts and three different scenarios of the window/wall ratio to the south.

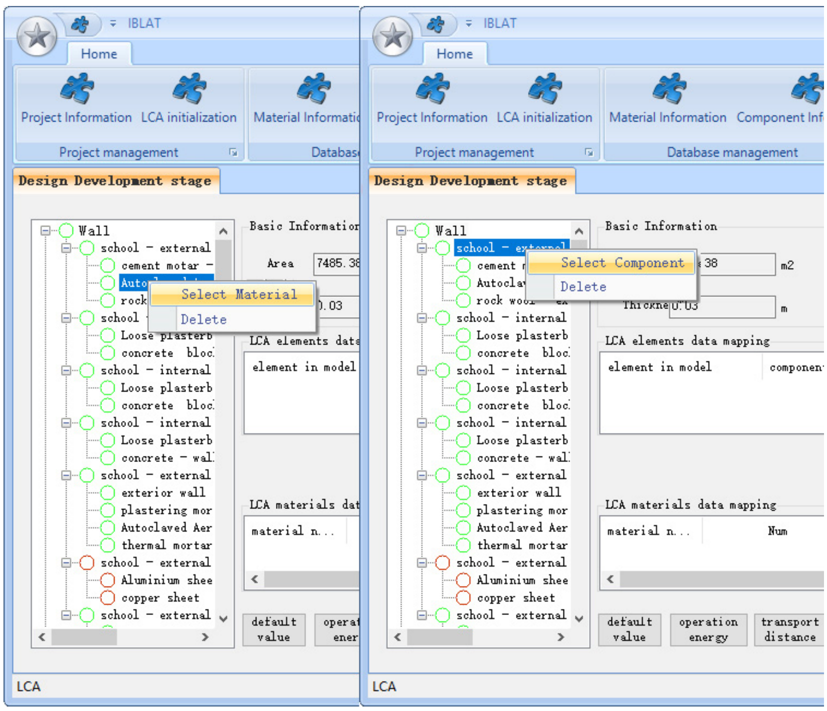


Figure 12. Designers can select the data they need in the elements or materials library.

First, the characteristic design of the building's envelope was explored (Table 6). In the architecture of the project, an additional layer was designed, which was attached to the basic construction of the exterior wall with a cavity space in between (Figure 13). This layer provided sun shading for the windows while accommodating the outdoor units of the air conditioners. Moreover, a passive ventilation construction was designed using the cavity space, which is conducive to introducing fresh air into the classrooms through the openings on the side walls and the small windows to the indoor spaces. At the same time, this additional wall panel attracts more building materials and greater cost at the manufacturing stage. The façade construction applied in the case study building is beneficial to ensure constant and sufficient air exchange in the transitional seasons. The annual energy saving potential was estimated at 9.7 MWh/a, thus accounting for a 26% reduction in ventilation energy consumption and 1.1% in total energy consumption. As revealed by the LCA and LCC results in Table 7 and Section 6.1, the reduction in operational energy can significantly compensate for the life cycle impacts and cost of the additional elements (e.g., the metal cover of the openings and the small window to the classroom) applied to the ventilation construction.

Table 6. Three different scenarios for the ventilation construction, wall material, and window material.

		Scenario 1 (Sc 1)	Scenario 2 (Sc 2)	Scenario 3 (Sc 3)
003 ventilation construction		With	Without	-
004 wall material		AAC	CMU	Concrete
005 window material	Material composition	Double Low-E glass: 5 + 9A + 5Low-E	Triple clear glass 5 + 9A + 5 + 9A + 5	Other windows: double Low-E glass 5 + 9A + 5 Low-E Southern windows: triple clear glass 5 + 9A + 5 + 9A + 5

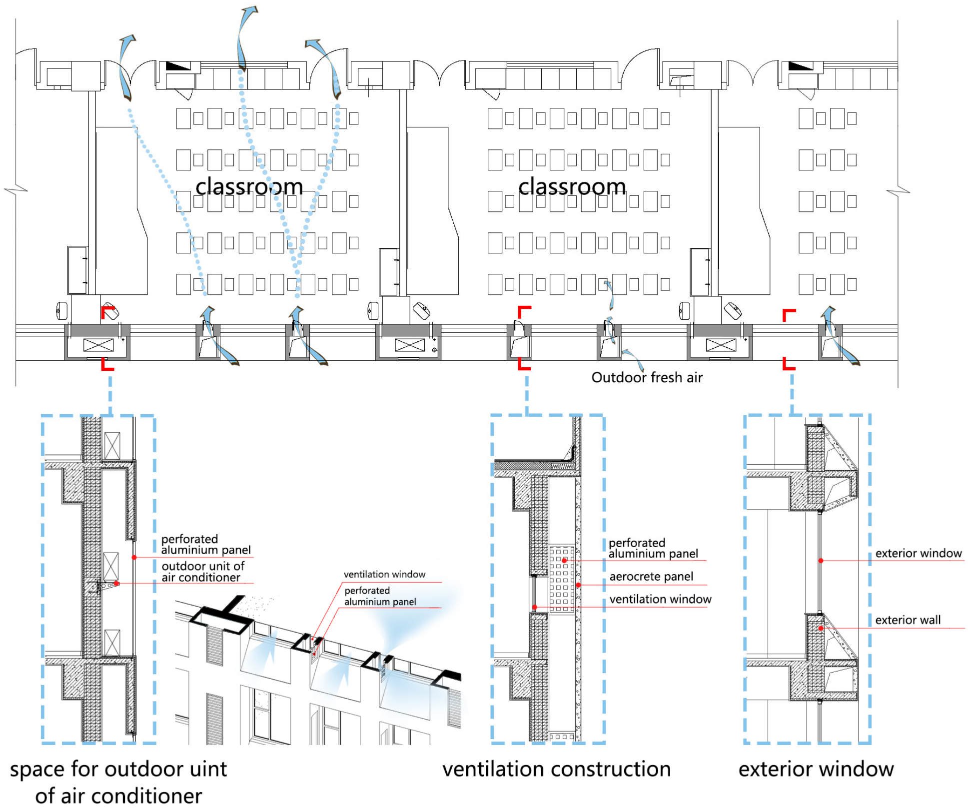
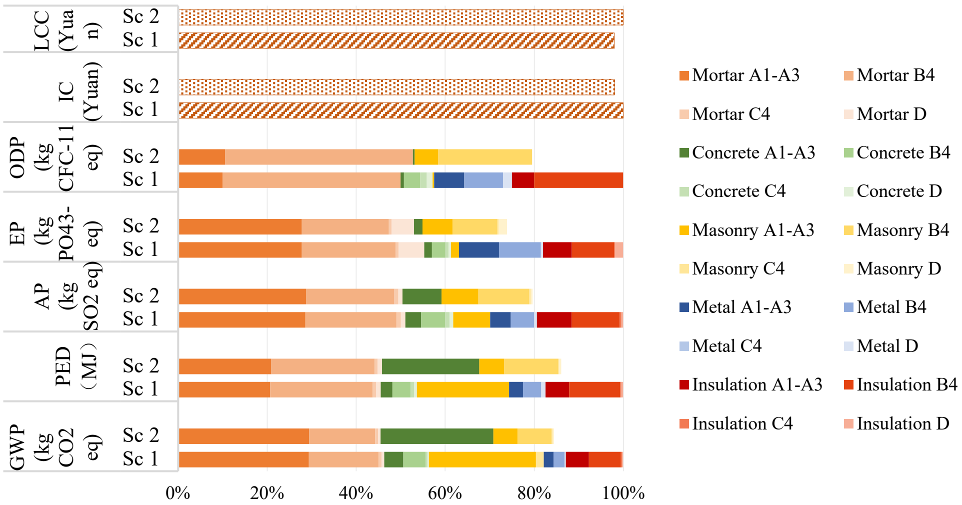
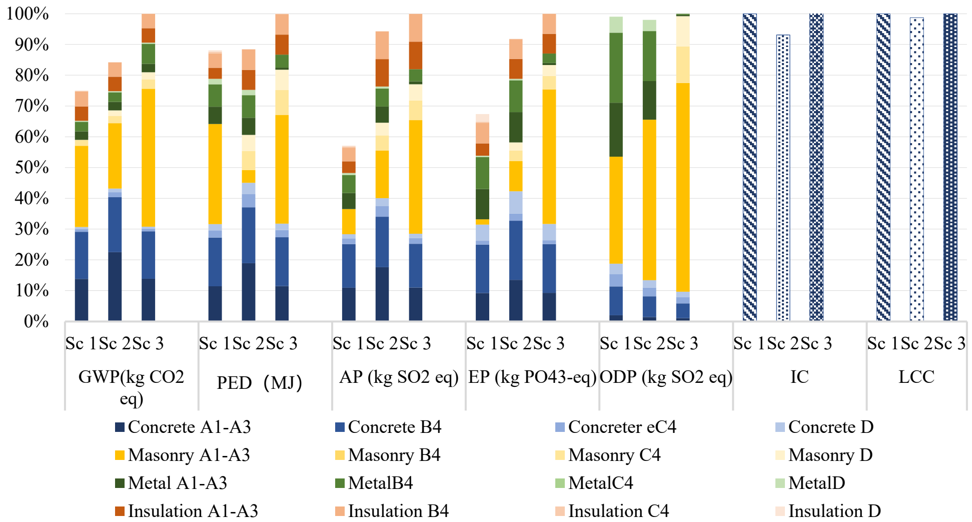
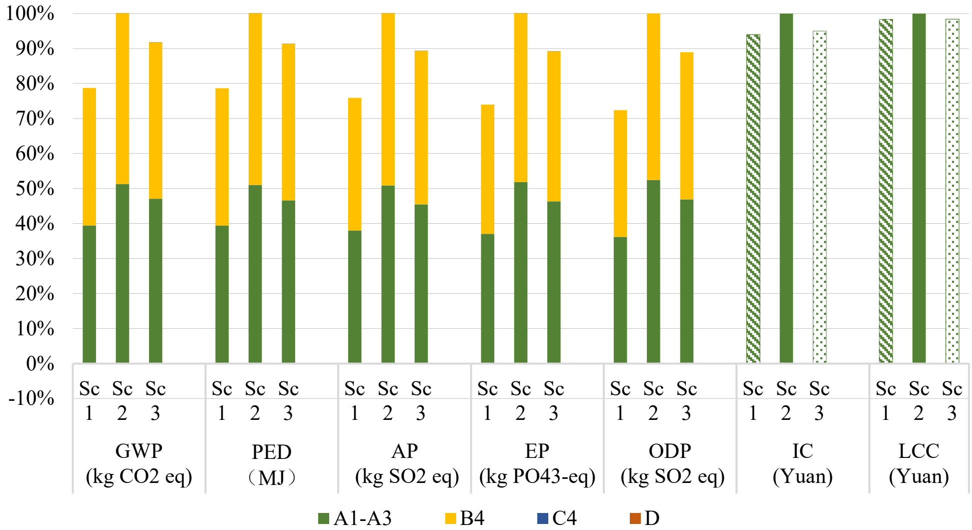


Figure 13. Plan and section drawings of the ventilation construction.

Table 7. Environmental impacts and cost of different design parameters at the design development stage (only related parameters are counted).

<table>
<tr><th>Design Parameters</th><th>Results</th></tr>
<tr><td>003 ventilation construction</td><td>
</td></tr>
<tr><td>004 wall material</td><td>
</td></tr>
<tr><td>005 window material</td><td>
</td></tr>
</table>

The materials of the main external walls were then compared (Table 6). It can be seen from the results (Table 7) that the exterior walls of AAC materials had obvious advantages in terms of environmental performance. In the design of the exterior window materials of the building, scenario 3 (Sc 3) with better environmental performance and the moderate cost was selected. The lower g value of the low-E glazing reduced the direct solar gain from the south orientation, although it could prevent excessive solar radiation in summer and heat loss in winter. An alternative for double low-E glass with the same U-value is triple clear glazing (Table 6). The results in Section 6.1 show that the solution with clear glass to the south orientation and low-E glass to the other orientations had the optimal life cycle environmental and economic performances.

5.4. The Construction Design Stage

The construction design stage provides more detailed information about specific building elements, such as the foundation, the refined façade construction, and the interior and exterior finishing. Designers used the BIM–LCA/LCC tool to refine material details and to calculate the overall performance of the project. The results can assist in the application for a Green Building Certificate. For the case study project, three different levels of thermal performance were studied, i.e., the reference case and two alternative scenarios with 20% or 30% improved U-values (Table 8). The scenarios were defined referring to the scoring items in China's Assessment Standard for Green Building (GB50378-2019) [53] and building products available on the local market. Their life cycle performances were analyzed and compared (Figure 14).

Table 8. Three different scenarios for the thermal performance, material, and construction of the envelope.

006 U-Values of Building Envelope	Reference Scenario (Scenario 1)	−20% (Scenario 2)	−30% (Scenario 3)
Roof	0.35	0.28	0.25
	Reinforced fine aggregate concrete: 40 mm Mortar: 20 mm XPS: 85 mm Expanded perlite cement: 30 mm Reinforced concrete: 120 mm Mortar and painting: 10 mm	Reinforced fine aggregate concrete: 40 mm Mortar: 20 mm XPS: 95 mm Expanded perlite cement: 30 mm Reinforced concrete: 120 mm Mortar and painting: 10 mm	Reinforced fine aggregate concrete: 40 mm Mortar: 20 mm XPS: 110 mm Expanded perlite cement: 30 mm Reinforced concrete: 120 mm Mortar and painting: 10 mm
Exterior wall	0.40	0.32	0.28
Description	Exterior mortar: 15 mm AAC: 200 mm Rock wool insulation board: 40 mm Mortar and painting: 10 mm	Exterior mortar: 15 mm AAC: 200 mm Rock wool insulation board: 80 mm Mortar and painting: 10 mm	Exterior mortar: 15 mm AAC: 200 mm Rock wool insulation board: 110 mm Mortar and painting: 10 mm
Window (south)	2.20	1.78	1.51
	Ug = 1.9; Uf = 2.2 Triple clear glass: 5 + 9A + 5 + 9A + 5, Frame: insulated aluminum alloy, 75 mm	Ug = 1.5; Uf = 2.0 Quadric clear glass: 4 + 9A + 4 + 9A + 4 + 9A + 4 Frame: insulated aluminum alloy, 85 mm	Ug = 1.1; Uf = 2.0 Triple low-E glass: 5 + 9Ar + 5 Low-E + 9Ar + 5 Low-E Frame: bridge-cut heat insulation aluminum alloy frame, 75 mm
Window (north, east, west) Skylight	2.20	1.78	1.51
	Ug = 1.9; Uf = 2.2 Double glass: 5 + 9A + 5Low-E Frame: insulated aluminum alloy, 65 mm	Ug = 1.5; Uf = 2.0 Triple glass: 5 + 9A + 5 + 9A + 5Low-E Frame: insulated aluminum alloy, 75 mm	Ug = 1.1; Uf = 2.0 Triple glass: 5 + 9Ar + 5 Low-E + 9Ar + 5 Low-E Frame: bridge-cut heat insulated aluminum alloy, 75 mm

As demonstrated in Figures 14 and 15, the combination of the glazing and the wall of the '−20%' scenario could lead to nearly optimal results for environmental performance with a moderate increase in initial cost (4%) but slightly lower (1%) LCC. This proportion could be further reduced if the costs for the foundation and service system were taken into account. Thus, it was selected as the solution for the thermal performance of the envelope.

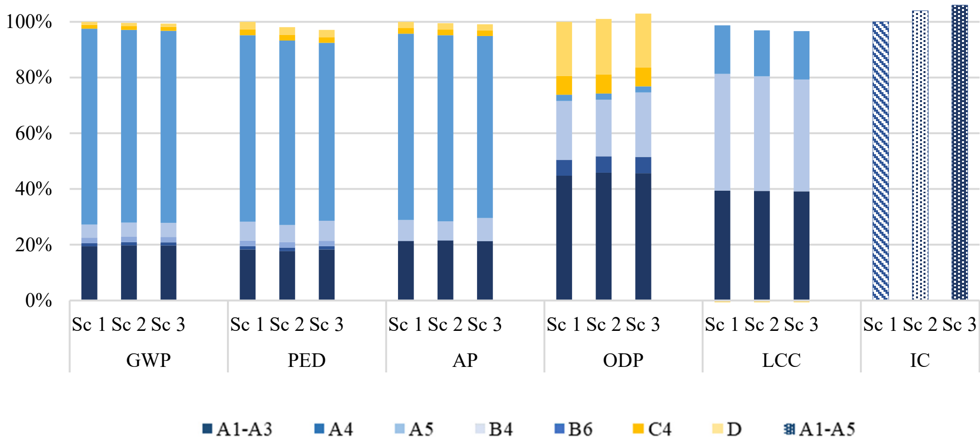


Figure 14. Embodied impacts of exterior walls, roofs, and windows of three different U-values (only relevant elements are counted).

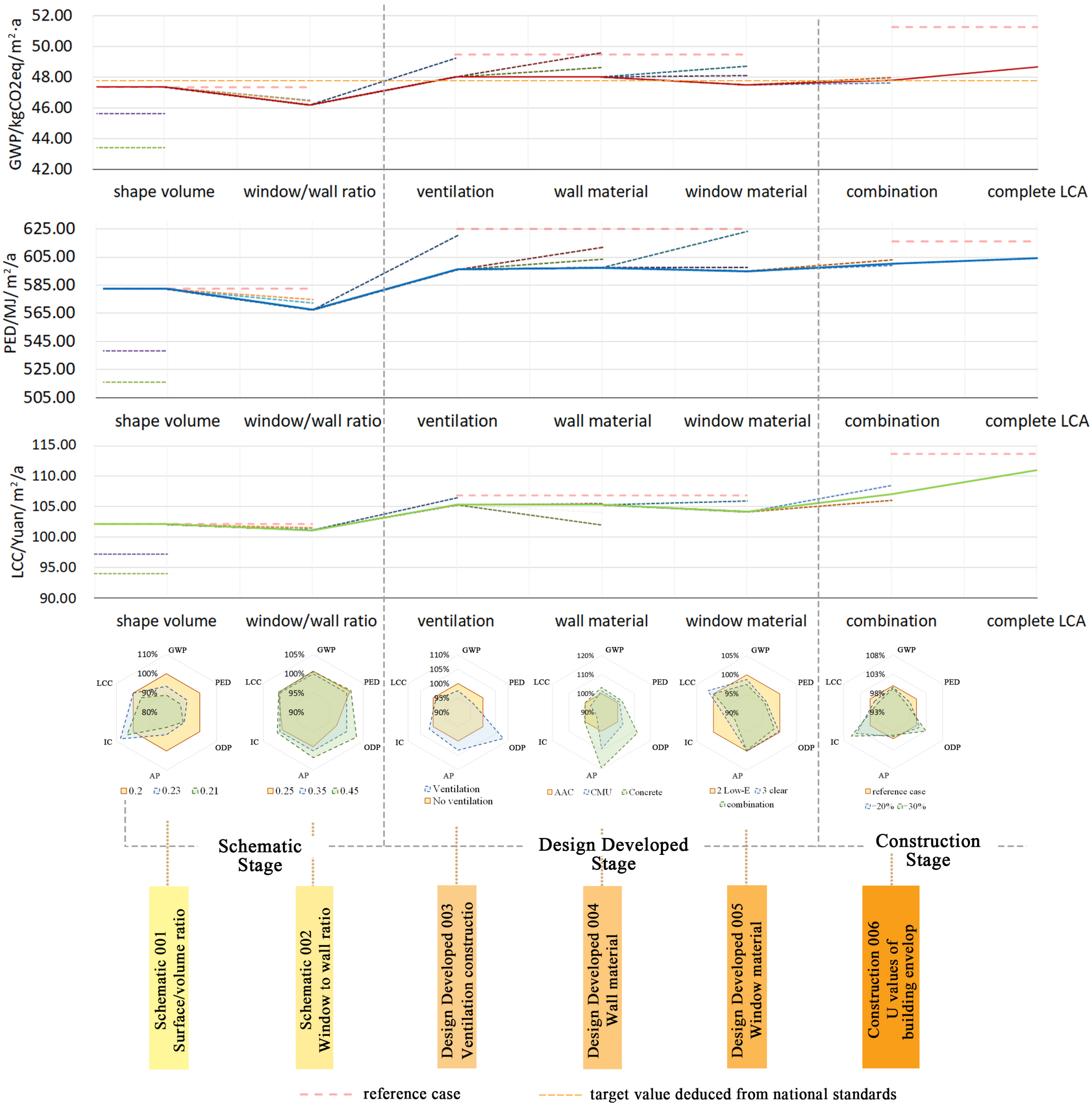


Figure 15. The LCA and LCC results and their comparison throughout the design process.

6. Discussion

6.1. Summary of the Results with the Implementation of the Method in the Design Process

Using the proposed method and IBLAT tool, the primary school was compared and optimized with the key parameters throughout the whole design process. At each stage, real-time feedback on design decisions can help designers to improve their solutions continuously. The performances of different options at each stage of the designing process are shown in Figure 15, including the life cycle GWP, PED, ODP, AP, LCC, and IC. The results at each design stage are presented in Table 9.

Table 9. The major performance indicators of the reference, improved, and final solution at different design stages.

		Operational Energy	Life Cycle GWP	Life Cycle Primary Energy Consumption	LCC	Initial Cost
		Kwh electr. e/m^2/a	Kg CO_2 e. m^2/a	MJ/m^2/a	Yuan/m^2	Yuan/m^2
Schematic	Initial	46.5	47.4	582.37	5237.3	2022.4
	Improved	46.1	46.2	567.62	5185.7	2024.4
Design Development	Reference	47.3	49.5	625.25	5566.1	2024.42
	Improved	45.4	47.5	595.06	5340.9	2101.35
Construction Design	Reference	45.1	51.3	616.26	5715.0	2132.3
	Final	44.2	48.7	604.18	5577.5	2244.5
Deduced benchmarks	Baseline value	59.4	55.8	-	-	8400
	Target value	47.9	47.8	-	-	6300

At the schematic stage, the model exhibits a high level of granularity. Even so, designers can still obtain relatively complete LCA/LCC results with the assistance of the element database and default values in IBLAT. The first layout and form defined in the schematic stage significantly affect the life cycle performances, as indicated by the LCA and LCC results in the design process. It will take more effort to achieve lower impacts in the later design stages.

At the design development stage, the floor and façade areas of the building are determined step by step. Moreover, more detailed materialization tends to replace the information on the general components of the building. Furthermore, the model has high accuracy to support the optimization of material details in the vital elements. The construction details for natural ventilation on the façade can improve the indoor air quality while reducing the electricity consumption of the mechanical system for air exchange in transitional seasons. They also facilitate the improvement of life cycle environmental and economic performances with minimal material and money input.

In the construction design stage, more detailed information could be acquired with further progress of the scheme. The copper–aluminum composite decorative wall panels were applied to the external wall, and the overall environmental impacts and cost slightly increased. In this case study, it is noteworthy that lower U-values did not always lead to better LCA or LCC results. The cumulative chart of LCC clearly shows the significantly increased replacement costs in the 30th and 40th years of the building's lifetime, since most of the insulation material would need to be replaced in approximately 30 years, while the windows and doors would reach their service life in approximately 40 years. The initial construction and replacement processes accounted for major parts (40% and 33%) in the LCC, respectively. Although the operational stage accounted for 81.1% of the building's life cycle GWP, it accounted for only 17.4% of the life cycle costs (Figure 16).

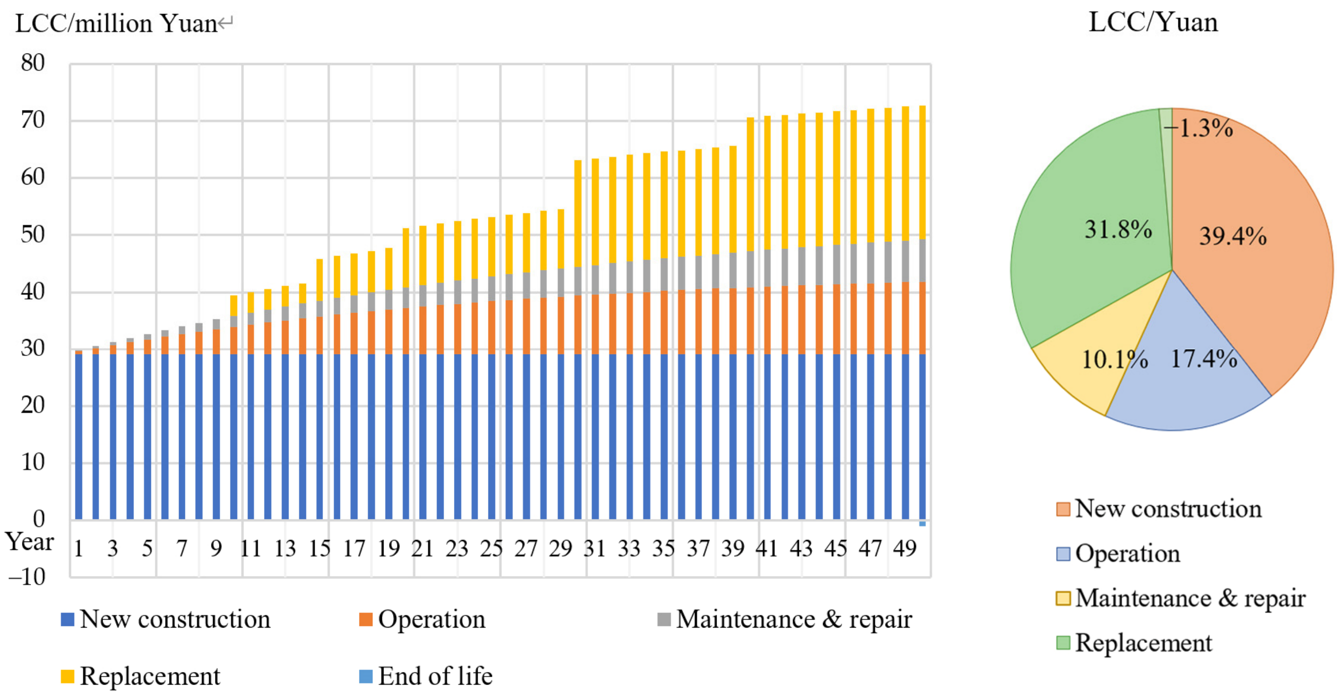


Figure 16. Accumulative life cycle costs and LCC proportions of the case study building.

At the schematic stage, the model exhibits a high level of granularity. Even so, designers can still obtain relatively complete LCA/LCC results with the assistance of the default values. As revealed by the results, there was a deviation of less than 10% between the early design results and the final results. With the efforts to select the key parameters with better performance, the life cycle performances of the building were gradually improved. The final results show 5% and 2.4% decreases in GWP and LCC, respectively compared with the reference case, although the initial cost was increased slightly (Table 9). Meanwhile, the final results conformed to the requirements of more than a 7 $kgCO_2/(m^2 \cdot a)$ reduction in carbon emission intensity and a 20% reduction in operational energy according to the 2016 energy efficient standard, as specified in the recently issued General Code for Energy Efficiency and Renewable Energy Application in Buildings (GB 55015-2021) [60].

6.2. Differences between the Results at Different Design Stages

There were two sudden increases in the LCA and LCC results across the schematic, design developed, and construction design stages. The main reason for the changes is that more elements were added to the building information model with the development of the design process. For instance, the additional façade layers and the partition walls were built into the model at the design development stage. The refined building volume and interior partitions also led to increased operational energy demand at the beginning of this stage. At the construction design stage, the foundation, the copper–aluminum cladding, and more precise structural data were incorporated into the model.

The line chart in Figure 15 presents the sensitivity of each parameter. The layout and form, the material options, and the corresponding thermal quality of the exterior windows had a major influence on both the LCA and the LCC results. The construction details for passive ventilation and the window-to-wall ratio also significantly affected the LCA results, but not so much the LCC results. The service system, which can also have an important impact on the life cycle performance, was not elaborated on in the contribution, because the case study concentrated on passive design strategies, whereby the service system was not considered as the design variable, but according to the values from the template at the beginning.

6.3. Discussion of Uncertainties in the LCA/LCC Parameters

The LCA and LCC results are affected by a wide variety of uncertainties. The uncertainties due to the LCI data sources, as well as the time-associated parameters such as the lifespan of the building, the price index, and the discounting rate, are discussed below.

6.3.1. The Effect of National/Regionalized Database on LCA Result

The LCI data are closely correlated with the national or regional context. To explore the influence of different data sources on the calculation results, the inventory data for the building materials and electricity in the CLCD database integrated with the IBLAT tool were compared with those in the GaBi database integrated into the Tally software, as well as with the LCA results of the case study building using two different data sources.

The embodied impacts calculated with Tally and with IBLAT showed some differences, as Tally applies generic global data for most of the building materials. The LCA data for Chinese grid electricity is available in the database, which does not consider the difference between different regions (Table 10). As the EPD data for Chinese building materials and products have been insufficient thus far, the data integrated into IBLAT were quoted from different sources (e.g., the CLCD database and literature on the LCA of specific building products). Some of the data for material disposal and recycling were quoted from the generic data (e.g., Ecoinvent-GLO) since the data for end-of-life processes of Chinese building materials are not always available.

Table 10. Comparison of the LCI data of the major materials (from cradle to gate) between Chinese and Tally databases.

Material/Energy	Description	Unit	Data Source	GWP	PED	ODP	AP
				Kg CO_2 e.	MJ	Kg CFC-11 e.	Kg SO_2 e.
Concrete	C30	1 m^3	Gabi	324.97	2068.88	1.86×10^{-6}	1.41
			CLCD	295.3	2296	3.77×10^{-6}	0.87
	C80	1 m^3	Gabi	470.65	2532.75	3.78×10^{-6}	2.08
			CLCD	511.15	3445	3.94×10^{-6}	1.27
Steel	Hot rolled steel; reinforcing rod	1 Kg	Gabi	1.22	17.01	6.17×10^{-9}	0.01
			CLCD	1.64	27.11	2.45×10^{-8}	0.01
Glass	Double low-E glass	1 Kg	Gabi	1.44	20.7	5.47×10^{-13}	0.01
	Float glass	1 Kg	CLCD	1.08	12.5	1.34×10^{-9}	0.02
Aluminum	Thermal break window frame	1 Kg	Gabi	4.25	66.91	6.82×10^{-9}	0.02
			CLCD	7.95	142	1.72×10^{-6}	0.06
Electricity	China average	1 Kwh	Gabi	0.86	10.4	1.70×10^{-9}	3.56×10^{-3}
	Northeast China	1 Kwh	CLCD	0.94	13.36	1.10×10^{-9}	6.05×10^{-3}
Natural gas	China average	1 Kwh	Gabi	0.26	4.39	1.11×10^{-17}	3.11×10^{-4}
		1 Kwh	CLCD	0.19	3.48	1.75×10^{-9}	8.42×10^{-4}

The difference in the results calculated using the Chinese (national or regional) and the generic (global) LCI data at the final stage reveals how the data source affected the results of life cycle impacts (Tables 10 and 11). The values calculated using Chinese data were higher in terms of embodied impact. Moreover, the proportions of the impacts at different stages were not similar for the results from different data sources. This result had a certain effect on the comparison results between different design solutions, thus decreasing the validity of applying the LCA and LCC methods in the decision-making of the design process. As ultralow-energy-consumption buildings and nearly zero-energy buildings have been popularized in China, the proportion of the impacts regarding the building elements and materials in the whole life cycle will increase dramatically. The development of China's LCI database for buildings, thus, takes on fundamental significance in achieving the goal of energy conservation and emission reduction.

Table 11. LCA results from Tally and from IBLAT.

Impact Category		GWP	PED	ODP	AP
Unit		Kg CO_2 e./m^2/a	MJ/m^2/a	Kg CFC-11 e./m^2/a	Kg SO_2 e./m^2/a
Embodied impacts	Tally	9.9	87.08	6.26×10^{-8}	0.04
	Chinese data	14.67	211.64	1.20×10^{-6}	0.09
Impacts from operational energy	Tally	34.91	408.85	3.86×10^{-8}	0.10
	Chinese data	32.93	392.54	3.51×10^{-8}	0.14
Total	Tally	44.82	495.97	1.01×10^{-7}	0.14
	Chinese data	48.67	604.18	1.23×10^{-6}	0.23

6.3.2. The Influence of Different Building Lifespan on LCA/LCC Results

The lifetime of the building can be input into the IBLAT as a parameter. The reference value of building lifespan was set as a scenario of 50 years (50) for the case study building, in accordance with the standard [42]. However, the LCA and LCC results were significantly different when the building lifespan was shorter (scenario 30 years) or longer (scenario 70 years). As depicted in Figure 17, the annual average life cycle GWP and LCC were lowest for a lifetime of 70 years, with LCC declining significantly compared to 50 years, along with a 4% reduction in life cycle GWP. China's current building lifespan is generally short. Accordingly, increasing the service life of buildings is of critical significance for achieving the strict national targets of energy saving and carbon emission reduction. Notably, when the lifespan of the building is set to 70 years, more rigorous requirements would be raised for the durability of the building materials, construction techniques, and maintenance strategies.

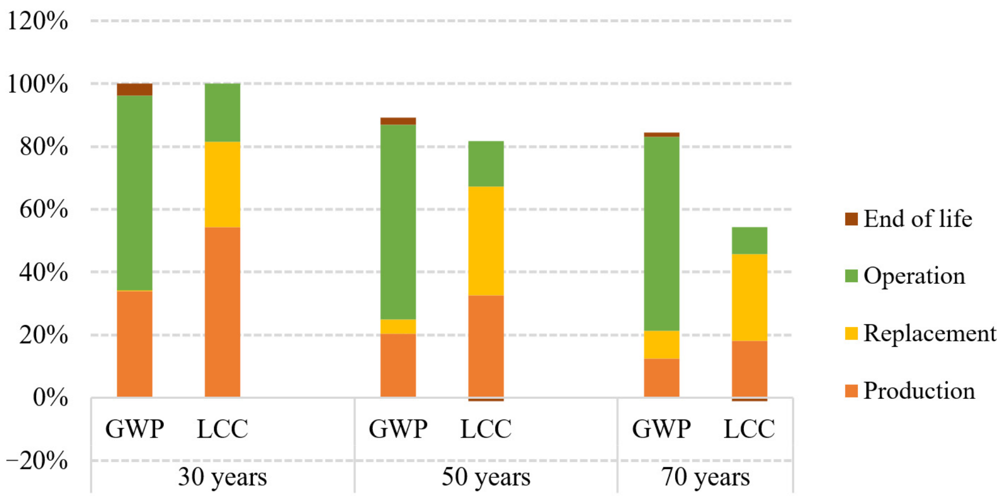


Figure 17. The per square meter per annual life cycle GWP and LCC results for the case study building with lifetimes of 30, 50, and 70 years.

6.3.3. The Influence of Different Scenario Definitions on LCA/LCC Results

The case study assumed the price index and discounting rate for building elements and energy products according to the statistical data over the past few years [66]. In addition, the LCC of the other four scenarios (Table 12) was explored according to the range of market changes in the past decade. The increase in labor costs partly compromised the possible reduction in material costs. The energy price is stable under government control to a certain extent. However, if the energy price rises more quickly than the building products in the future, the operational process will account for a more crucial part of the LCC (Figure 18). In IBLAT, the designers can customize the above basic parameters before performing LCC.

Table 12. Scenario definition of the discounting rate and price indices.

	Sc1	Sc2	Sc3	Sc4	Sc5
Price index of energy product	0.18%	1.18% (+1%)	1.68% (+1.5%)	0.18%	3.18% (+3%)
Price index of building product	2.94%	2.94%	1.44% (−1.5%)	2.94%	2.94%
Discounting rate	4.35%	4.35%	4.35%	2.85% (−1.5%)	2.85% (−1.5%)

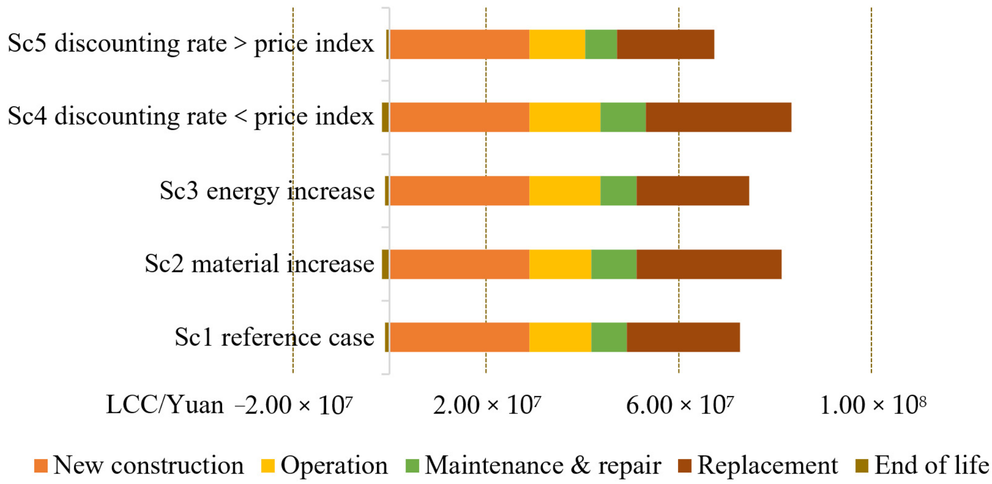


Figure 18. LCC results under different discounting rates and price indices.

7. Conclusions

A BIM–LCA/LCC method that assists in the green building designing process in the Chinese context was proposed following a review of the existing BIM-based LCA/LCC methods and tools. Moreover, a tool related to this method was developed. Through the case study of a primary school building, some conclusions can be drawn.

Different scenarios for the case study indicated that the parameters defined at the early design stages significantly affected the final performance of the buildings. Thus, the life cycle performances should be investigated from the beginning of the design process to the more defined stages to optimize the design scheme. The scalable database developed in combination with the tool established in the study was based on Chinese national LCA data, and the database structure was built in accordance with the BIM coding system, thus facilitating the matching of LCA/LCC data to the building elements and materials.

The proposed method integrates the objectives and standards of the green building assessment system in China, as well as summarizes the design parameters that should be focused on and optimized at different design stages. The current version of the Assessment Standard for Green Building (GB50378-2019) [53] needs to introduce more comprehensive indicators and benchmarks to assess life cycle performances.

It is necessary to develop standards and benchmarks for life cycle performances to provide baselines and target values for design optimization and assessment. Benchmarks should be deduced using both the top-down method according to national targets and standards and the bottom-up method according to the statistical data and sampling data from building practice.

A wide variety of data sources for the LCI of building materials and energy products can lead to different LCA results. Accordingly, it is imperative to apply local, or at least national, data. Furthermore, due to the long lifespan of buildings, the LCA and LCC results can be affected by time-associated parameters (e.g., the lifetime of the building and the elements, the LCI data for material and energy products, the price index, and the discounting rate). Thus, the major uncertainties in the LCA and LCC results should be analyzed from a dynamic perspective.

Author Contributions: Q.L., conceptualization, methodology, software, data curation, and writing—original draft preparation; W.Y., supervision, conceptualization, methodology, and writing—review and editing; Z.S., software; J.L., software, simulation parameter setting, and data curation; H.Y., data curation; L.Y., conceptualization; J.R., resources; L.L., data curation; N.K., conceptualization and methodology. All authors have read and agreed to the published version of the manuscript.

Funding: The authors acknowledge the National Natural Science Foundation of China for the financial support given to this research under process numbers 51878436 and 51478294.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: This contribution is the further exploration based on previous findings on the relevant topics that had been published in a journal article [59] and a conference paper [38] by the same authors.

Acknowledgments: TENIO Architectural Design Institute provided the information on the case study project. Wang Li-Xiong, Xu Zhen, Liu Kui-xing, and Zhou Ting at Tianjin University, Long Wei-ding at Tongji University, and Chief Engineers Zhu Jie, Li Fei-peng, Yan Xiangyu, and Song at the Design Institute of Tianjin University gave valuable advice and information for the study. The discussion with Yan Wei at Texas A&M was helpful for the study.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

ADPE	Abiotic depletion potential for fossil fuels
ADPM	Abiotic depletion potential of materials
AIA	American Institute of Architects
AP	Acidification potential
API	Application programming interface
BIM	Building information model
CFCS	Chlorofluorocarbons
CLCD	China Life Cycle Database
DGNB	German Sustainable Building Council
EP	Eutrophication potential
EPD	Environmental product declaration
GWP	Global warming potential
IBLAT	Integrated building life cycle assessment tool
IC	Initial cost
ICE	Inventory of carbon and energy
ISO	International standardization organization
KBOB	Life cycle assessment data in the construction sector
LCA	Life cycle assessment
LCC	Life cycle cost
LCP	Environmental life cycle performance
LOD	Levels of development
NRE	Nonrenewable energy
ODP	Ozone depletion potential
PED	Primary energy demand
PE-nr	Primary energy, renewable part
PENRT	Total nonrenewable primary energy
PM	Particulate matter
POCP	Photochemical ozone creation potential
RE	Renewable energy
SDEV	Standard deviation
SFP	Smog formation potential
SQL	Structured Query Language
UBP	Eco points
W/w	Window to wall

Appendix A

Table A1. Specific design parameters to be considered in the green building design process.

Content		Main Parameters	Conceptual Design	Schematic Design	Design Development	Construction Design
Overall layout	Site design	Urban interface	√			
		Function layout	√	○		
		Withdraw building line	√	○		
		Light environment in site	√	○		
		Air environment in site	√	○		
Floor plan	Building plane	Plane dimensions	√	√	○	
Form characteristics	Surface/volume ratio	Floor height	√	○		
		Orientation	√	○		
	Facade modeling	Window-to-wall ratio	√	○		
		Location of functional modules	√	√	○	
		Roof form	√	○		
Spatial characteristics	Interior space	Arrangement of functional modules		√	○	
		Open space		√	○	
		Traffic space		√	○	
	Outdoor space	Traffic space	√	○		
		Distributed space	√	○		
		Landscape environment	√	√	√	○
	Section design	Spatial line of sight		√	○	
		Ventilated design		√	○	
Construction details design	Wall	Construction layers of exterior and interior walls		√	√	○
		Material thickness			√	○
		Heat transfer coefficient		√	√	○
	Roof	Roof tectonic hierarchy		√	√	○
		Material thickness			√	○
		Heat transfer coefficient		√	√	○
	Floor	Construction layer of floor		√	√	○
		Material thickness			√	○
		Heat transfer coefficient		√	√	○
	Window	Heat transfer coefficient of exterior windows		√	√	○
		Glass SHGC		√	√	○
		Material thickness			√	○
		Heat transfer coefficient		√	√	○
	Airtightness	Airtightness			√	○
	Shading form	Shading form		√	○	
		Shading component dimensions		√	√	○
	Special construction	Design of structure space (form, size)		√	√	○
		Material design of construction		√	√	○
Indoor environment	Indoor light environment	Daylight		√	√	○
		Artificial lighting		√	√	○
	Indoor air environment	Natural ventilation		√	√	○
		Mechanical ventilation		√	√	○
Building structure	Size determination	Forms and sizes of the foundation, beams, slabs, and columns		√	√	○
	Calculation of materials	Steel bar ratio and concrete dosage			√	○

Table A1. *Cont.*

Content		Main Parameters	Conceptual Design	Schematic Design	Design Development	Construction Design
Equipment system	Heating	Heating form	√	√	○	
		Equipment system parameters	√	√	○	
	Cooling	Cooling form	√	√	○	
		Equipment system parameters	√	√	○	
	Lighting	Lighting layout	√	√	○	
		Lamp selection	√	√	○	
	Hot water	Hot water system form	√	√	○	

√ The parameter at this stage was considered; ○ the parameter at this stage was completed. Repaired according to Yang [63]. The cells with background shading show the points and the durations of time that the parameters need to be considered during the whole design process.

Table A2. Energy simulation parameters defined according to the standards [65,67].

Parameter	Description	Values
Heating system	Natural gas district heating	Transfer: 92%
Cooling system	Split air conditioning	SEER = 4.0
Airtightness	Infiltration	0.6 ach
Ventilation	Fresh air	30 m^3/h/person
	Heat recovery	65%
Occupants	Average area per person 960 students + 120 staff	8 m^2/person
Office equipment	7:00 a.m.–6:00 p.m., school days	5 w/m^2
Illumination	Lights turned on when day lighting <300 lx	8 w/m^2
Day lighting	Window-to-floor ratio of classrooms	1:5

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