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An Exploration of Carbon Emissions Throughout the Entire Lifecycle of Kindergarten Buildings—Exemplified by a Kindergarten in China

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Abstract. This study used the IstructE tool to assess the carbon footprint of a kindergarten in China, in order to explore the uniqueness of the carbon footprint of children's education buildings in educational-type buildings. Based on the architectural drawings, the structural details such as beams, columns, floor slabs, interior and exterior walls, and doors and windows of this kindergarten were analyzed in detail. This research result provides a reference for the design of other such buildings that adopt sustainable design concepts. The assessment showed that the total life cycle carbon emissions of the A1-A5 modules were 275 tCO_2e/m^2, and the Scors rating was only a D grade. Through sensitivity analysis, it was found that replacing low-strength or precast concrete could effectively reduce the carbon content of the building.

Keywords: Carbon footprint; kindergarten buildings; embodied carbon; life cycle.

1. Introduction

Over the past decades, a series of environmental problems caused by the massive emission of greenhouse gases has been plaguing humanity. Studies show that the concentration of greenhouse gases will not decrease in the next hundred years [1].

The emission of carbon dioxide (also known as carbon emissions) among greenhouse gases has drawn worldwide attention. Some official institutions and even governments have taken measures to address the issue of carbon emissions. For instance, China has replaced traditional fossil fuels with clean energy and constructed the Three Gorges Dam. Its annual power generation capacity is equivalent to approximately 40 million tons of coal, thereby reducing a significant amount of carbon emissions [2]. Furthermore, the Paris Agreement aims to achieve a net-zero carbon emissions level within the next few decades, meaning that the amount of carbon dioxide emitted will be balanced by its absorption, and many countries have signed up to this [3].

Among all the human activities that cause carbon emissions, the construction industry holds a significant position. According to statistics, the construction industry accounts for as high as 37% of the global annual carbon emissions (United Nations Environment Programme [4]. Therefore, starting from the construction industry, reducing carbon emissions is a direction worth considering. This research will focus on kindergarten buildings among various building types. Taking a certain shopping mall building in China as an example, it will assess the carbon emissions throughout the entire life cycle of the building.

1.1. Embodied Carbon and Operational Carbon in Kindergarten Buildings

In the context of buildings, carbon emissions typically occur primarily during the construction and operation phases, which are also referred to as embodied carbon and operational carbon, respectively. Embodied carbon refers to the carbon dioxide emissions generated by buildings before and during the construction process [5], while operational carbon represents the carbon emissions produced during the building's operation phase [6, 7].

In addition, the proportion of carbon emissions between these two factors varies greatly depending on the building type, materials used, location, and age of the building. Over the entire life cycle, the proportion of embodied carbon can range from 2% to 80% [5]. Therefore, conducting research based on building type classification is of great significance.

However, most of the current research focuses on studying other attributes of buildings. For instance, conducting research on the embodied carbon content of building materials [8, 9]. Or it involves researching ways to reduce the carbon footprint by optimizing building layouts [10].

Furthermore, although many studies have begun to focus on the carbon emissions of educational buildings, both embodied carbon and operational carbon [11]. However, in fact, the appearance design, material usage, and architectural layout of kindergarten buildings also have their own particularities in terms of the carbon emissions they imply. Therefore, studying their embodied carbon emissions is of certain value for achieving the goal of reducing carbon emissions in buildings.

1.2. Life Cycle Study

In recent years, numerous studies have analyzed the carbon footprint of buildings throughout their entire lifecycle, from construction to demolition [12, 13].

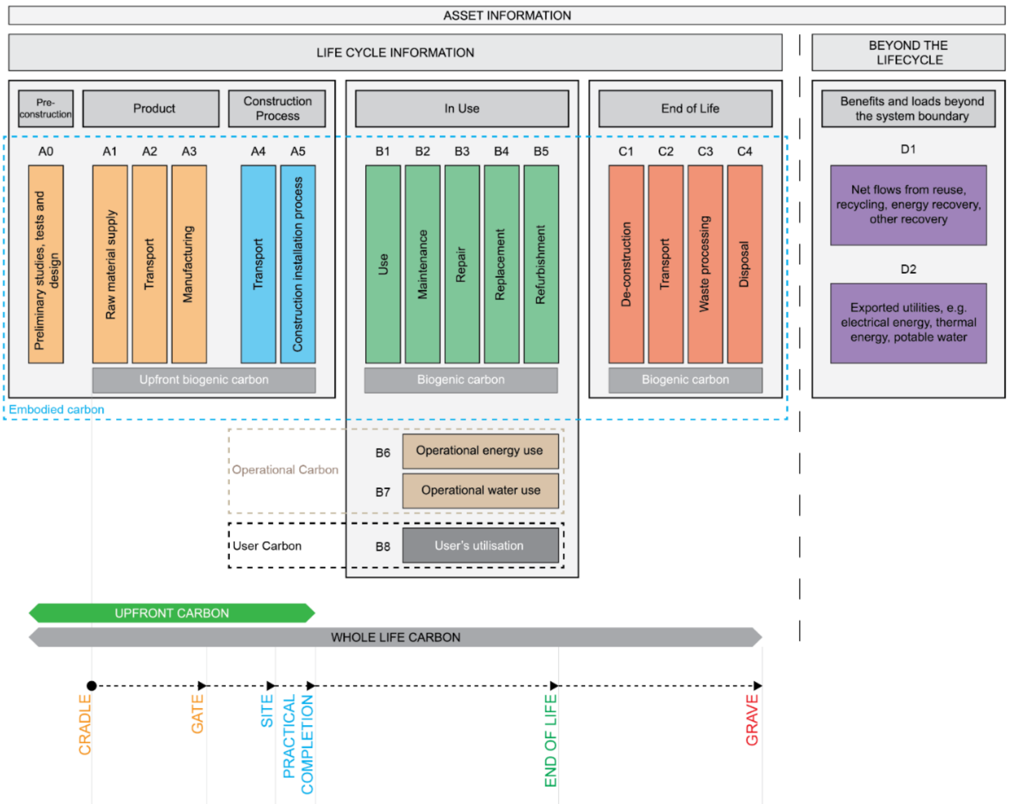

Figure 1. Lifecycle stage [15]

For the research on carbon emissions of buildings, life cycle studies require the carbon emission factors for each stage. Its definition is "a representative value that attempts to link the amount of pollutants emitted into the atmosphere with the activities associated with the emission of such pollutants [14]." The lifecycle of a building is typically divided into A1 - C4 stages (in energy and carbon emission studies, the carbon emission data of modules A1 - A5, B1 - B5, and C1 - C4 are usually selected, as shown in Figure 1). The stages outside the lifecycle range are defined as stage D. The general standard unit for carbon factors is "$kgCO_2e/kg$", but the unit (such as kg, m^2, or m^3) can also be appropriately modified according to the specific carbon data selected. The material carbon emission parameters support conversion between different measurement units [15].

A1-A3: The production stage is also known as the "from cradle to gate" stage. It refers to the equivalent amount of carbon dioxide ($kgCO_2e$) generated during the extraction, processing, and manufacturing of building materials. This is the stage from when the materials are transported out of the factory until they finally leave the factory gate.

A4 and A5: Transportation of materials and products to the site, as well as carbon dioxide generated during the construction process.

B1-B5: The carbon dioxide emissions during the usage phase of buildings, including activities such as daily use, maintenance, repair, and renovation.

C1-C4: Corresponding to the final stage of the building's life cycle, including the stages of demolition, waste transportation, and waste disposal, etc., carbon dioxide is generated during these processes.

2. Case study and Methodology

2.1. Calculation principle of the IstructE tool

This study obtained the material usage based on the architectural drawings and specifications and made reasonable estimations for some structures to calculate the carbon footprint of the building. The research focused on the main frame structure, load-bearing structure, and some decorative structures, including beams, columns, floor slabs, walls, windows, and doors. The methodology was based on the 2025 edition of "Structural Engineers' Society Guidelines" by the British Society of Structural Engineers. The calculation aid tool used was the IstructE software developed by this society, which is specifically designed to provide calculation support for engineers. The calculation process strictly followed the methodology proposed in the 2025 publication "How to Calculate Carbon Footprint (Third Edition)" by the British Society of Structural Engineers. The flowchart of the calculation process is Figure 2:

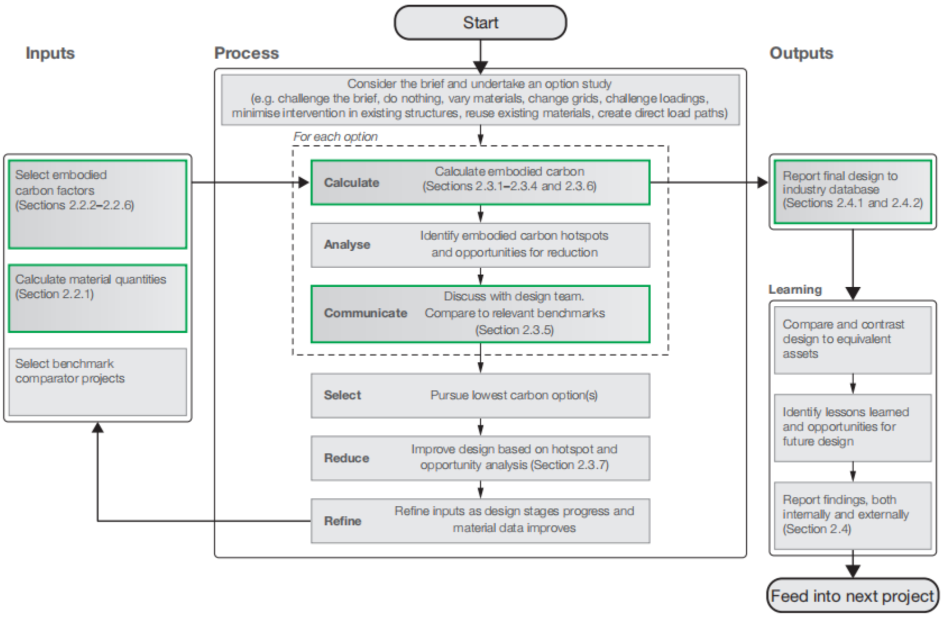

Figure 2. The IstructE tool calculates the program flowchart [15]

The calculation method for the carbon footprint of building materials is to multiply the amount of materials by their carbon factor. This method can determine the total carbon footprint of the materials used in construction. (The units of this formula can be calculated based on density, such as $kgCO_2e/m^2$, $kgCO_2e/m^3$, etc.)

$$\text{material quantity (kg)} \times \text{carbon factor (kgCO2e/kg)} = \text{embodied carbon (kgCO2e)} \quad (1)$$

The information that needs to be filled in includes project information, and for each building component, corresponding data such as material properties and quantities should be selected. In addition, this tool also has a comparison function, which can simultaneously fill in six different material options and display the comparison results in the lower interface, which can be used for sensitivity analysis.

This section presents the research results on the carbon footprint of the main components of the target building (floor slabs, beams, columns, and walls). According to the methodology requirements, we conducted detailed studies on floors 1 to 4 in sequence, compared the differences among different floors, and simultaneously recorded the carbon footprint data of the building components in a tabular form. Since the first floor has already been used as an example in the methodology section, in this part, I will start from the second floor.

2.2. Data collection

This study mainly focuses on the assessment of the embodied carbon in the structure of a kindergarten building in Hohhot City, Inner Mongolia Autonomous Region, China. The main structure of this building consists of four floors, with a partial third floor. It is a common reinforced concrete frame structure building. Its exterior walls are made of 300mm thick terracotta concrete block walls, and the interior walls are 200mm thick terracotta concrete block walls. The total building area is 1882.4 square meters.

The detailed objective of the first stage is to obtain information. This study will combine the architectural drawings with on-site inspections to obtain the structural and architectural information of the building. Structural information includes the layout of the dimensions of beams, columns, and floor slabs, the selection and quantity of materials, and reinforcement details. The building information includes the quantities and types of materials used for the interior and exterior walls, as well as the usage of windows and other components.

2.3. Drawing analysis

Level 1

Beams: Based on the reinforcement plan of the frame beam layer, the detailed information of the beam is estimated as follows in Table 1.

Table 1. Level 1 beams collection table

SIZE	200*300	240*350	250*400	250*450	300*400	300*450	300*500	300*680
AREA (M^2)	0.06	0.08	0.10	0.11	0.12	0.14	0.15	0.20
LENGTH (M)	5.70	1.50	79.80	5.70	13.80	29.40	73.20	71.10
VOLUME (M^3)	0.34	0.13	7.98	0.64	1.66	3.97	10.98	14.50
MATERIAL	C30	C30	C30	C30	C30	C30	C30	C30

Columns: Based on the layout diagram of the frame columns, the detailed information of the columns is estimated as follows in Table 2.

Table 2. Level 1 columns collection table

C30	450*450
AREA	0.2
HEIGHT	2.9
NUMBER	24
VOLUME	14.09
MATERIAL	C30

Slabs: According to the contents of the building structure drawings, the thickness of the floor slab is 120mm, and its area is the floor area minus the area between the stairs and the elevator. The statistics of the floor slab materials for level 1 are shown in Table 3.

Table 3. Level 1 slabs collection table

THICKNESS	120
AREA	337.07
VOLUME	40.45

Walls: According to the architectural floor plan, the details of the wall design are as follows in Table 4.

Table 4. Level 1 walls collection table

	OUTER WALL	INTERIOR WALL
THICKNESS	300	200
LENGTH	92.9	142.86
HEIGHT	2.9	2.9
AREA	269.41	414.29
AREA (REMOVE THE DOORS AND WINDOWS)	192.19	361.73
VOLUME	57.66	72.35
MATERIAL	C30	C30

Windows and doors: The list of doors and windows shown in the architectural drawings is as depicted in the figure. The thickness of the window is estimated at 3 cm, and it is made of glass. The thickness of the door is estimated at 5 cm, and it is made of fire-resistant steel. The statistics of all the doors and windows on each floor are shown in Table 5.

Table 5. Building doors and windows collection table

	WINDOW				DOOR			
	AREA	THICKNESS	VOLUME	MATERIAL	AREA	THICKNESS	VOLUME	MATERIAL
LEVEL 1	63.3	0.03	1.90	GLASS	68.69	0.05	3.43	STEEL
LEVEL 2	34.91	0.03	1.05	GLASS	52.8	0.05	2.64	STEEL
LEVEL 3	51.11	0.03	1.53	GLASS	49.2	0.05	2.46	STEEL
LEVEL 4	29.63	0.03	0.89	GLASS	30.73	0.05	1.54	STEEL

Level 2

Beams: Based on the reinforcement plan of the frame beam layer, the detailed information of the beam is estimated as follows in Table 6.

Table 6. Level 2 beams collection table

SIZE	200*300	240*350	250*400	250*450	300*400	300*450	300*500	300*680
AREA (M2)	0.06	0.08	0.10	0.11	0.12	0.14	0.15	0.20
LENGTH (M)	5.70	1.50	79.80	5.70	13.80	29.40	73.20	71.10
VOLUME (M3)	0.34	0.13	7.98	0.64	1.66	3.97	10.98	14.50
MATERIAL	C30	C30	C30	C30	C30	C30	C30	C30

Columns Based on the layout diagram of the frame columns, the detailed information of the columns is estimated as follows in Table 7.

Table 7. Level 2 columns collection table

C30	450*450
AREA	0.2
HEIGHT	2.9
NUMBER	24
VOLUME	14.09
MATERIAL	C30

Slabs

The statistics of the floor slab materials for level 2 are shown in Table 8.

Table 8. Level 2 slabs collection table

THICKNESS	120
AREA	337.07
VOLUME	40.45

Walls

According to the architectural floor plan, the details of the wall design are as follows in Table 9.

Table 9. Level 2 walls collection table

	OUTER WALL	INTERIOR WALL
THICKNESS	300	200
LENGTH	92.9	117.01
HEIGHT	2.9	2.9
AREA	269.41	339.33
AREA (REMOVE THE DOORS AND WINDOWS)	234.07	286.96
VOLUME	70.22	57.39
MATERIAL	C30	C30

Level 3

Beams: Based on the reinforcement plan of the frame beam layer, the detailed information of the beam is estimated as follows in Table 10.

Table 10. Level 3 beams collection table

SIZE	200*300	240*350	250*400	250*450	300*400	300*450	300*500	300*680
AREA (M2)	0.06	0.08	0.10	0.11	0.12	0.14	0.15	0.20
LENGTH (M)	5.70	1.50	79.80	5.70	13.80	29.40	73.20	71.10
VOLUME (M3)	0.34	0.13	7.98	0.64	1.66	3.97	10.98	14.50
MATERIAL	C30	C30	C30	C30	C30	C30	C30	C30

Columns Based on the layout diagram of the frame columns, the detailed information of the columns is estimated as follows in Table 11.

Table 11. Level 3 columns collection table

C30	450*450
AREA	0.2
HEIGHT	2.9
NUMBER	24
VOLUME	14.09
MATERIAL	C30

Slabs

The statistics of the floor slab materials for level 3 are shown in Table 12.

Table 12. Level 3 slabs collection table

THICKNESS	120
AREA	337.07
VOLUME	40.45

Walls

According to the architectural floor plan, the details of the wall design are as follows in Table 13.

Table 13. Level 3 walls collection table

	OUTER WALL	INTERIOR WALL
THICKNESS	300	200
LENGTH	92.9	117.01
HEIGHT	2.9	2.9
AREA	269.41	339.33
AREA (REMOVE THE DOORS AND WINDOWS)	234.07	274.36
VOLUME	70.22	54.87
MATERIAL	C30	C30

Level 4

Based on the reinforcement plan of the frame beam layer, the detailed information of the beam is estimated as follows in Table 14.

Table 14. Level 4 beams collection table

SIZE	200*300	240*350	250*400	250*450	300*400	300*450	300*500	300*680
AREA (M2)	0.06	0.08	0.10	0.11	0.12	0.14	0.15	0.20
LENGTH (M)	5.70	1.50	79.80	5.70	5.4	29.40	73.20	65.4
VOLUME (M3)	0.34	0.12	7.98	0.63	0.65	4.12	10.98	13.08
MATERIAL	C30	C30	C30	C30	C30	C30	C30	C30

Columns Based on the layout diagram of the frame columns, the detailed information of the columns is estimated as follows in Table 15.

Table 15. Level 4 columns collection table

C30	450*450
AREA	0.2
HEIGHT	2.9
NUMBER	22
VOLUME	12.92
MATERIAL	C30

Slabs

The statistics of the floor slab materials for level 4 are shown in Table 16.

Table 16. Level 4 slabs collection table

THICKNESS	120
AREA	313.13
VOLUME	37.58

Wall

According to the architectural floor plan, the details of the wall design are as follows in Table 17.

Table 17. Level 4 walls collection table

	OUTER WALL	INTERIOR WALL
THICKNESS	300	200
LENGTH	84.5	92.7
HEIGHT	2.9	2.9
AREA	245.05	268.83
AREA (REMOVE THE DOORS AND WINDOWS)	205.98	247.54
VOLUME	61.79	49.51
MATERIAL	C30	C30

Roof

The roofing project is estimated to be 120mm thick reinforced concrete, which is consistent with the floor slabs of the 1st to 4th floors. Roof statistics are shown in Table 18.

Table 18. Roof detail table

THICKNESS	120
AREA	337.07
VOLUME	40.45

Foundation

Foundation statistics are shown in Table 19.

Table 19. Foundation detail Table

	COLUMN SIZE	VOLUME
DJ-1	0.45*0.45	1.42
DJ-2	0.45*0.45	2.07
DJ-3	0.45*0.45	2.67
DJ-4	0.45*0.45	3.09
DJ-5	0.45*0.45	4.00

2.4. Input and Calculation in IstructE tool

Due to the lack of information such as investment in buildings and local soil density, they were estimated reasonably based on the suggestions of the IstructE tool. The specific values are shown in Table 20.

Table 20. IstructE tool - Building Details List

PROJECT INFORMATION	
PROJECT NUMBER	1
PROJECT NAME	KINDERGARDEN
TYPOLOGY	EDUCATION
DESIGN STAGE	AS BUILT
PROJECT VALUE (£)	£1,000,000
SECONDARY FUNCTIONAL UNIT	
IS THIS PROJECT ON AN EMPTY SITE?	NO
ASSUMPTIONS	
AVERAGE DISTANCE TO LANDFILL (KM)	50
REINFORCEMENT	STEEL - REBAR - GLOBAL AVG
PERCENTAGE EXCAVATION REMOVED FROM SITE	100%
SOIL DENSITY (KG/M3)	1600
DESIGN LIFE (YEARS)	50

3. Result and analysis

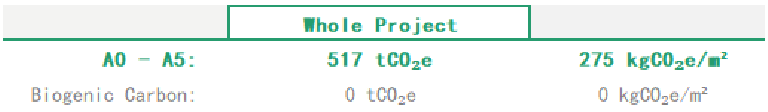

Figure 3. Total Embodied Carbon

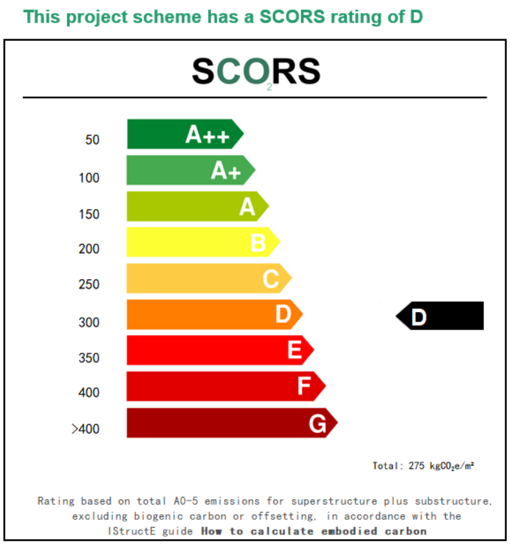

Figure 4. SCORS GRADE

After inputting the various material information of the kindergarten building into the IstructE tool, the calculated results are shown in the figure below. During the A0-A5 stages of the life cycle (i.e., before the usage stage), the total carbon emissions were 517 tCO_2e, and the carbon emissions per square meter were 275 tCO_2e. The IstructE tool assigned a carbon emission score of D based on Figure 4, indicating that the design of this building in terms of embodied carbon emissions was not ideal.

4. Sensitivity analysis

Based on the classification of various building components, the aim is to explore the embodied carbon emission proportions of each component in kindergarten buildings among educational buildings.

In this study, the beams, columns, floor slabs, walls, and doors and windows of the building were all included in the IstructE for calculation. The comparison results are as follows：

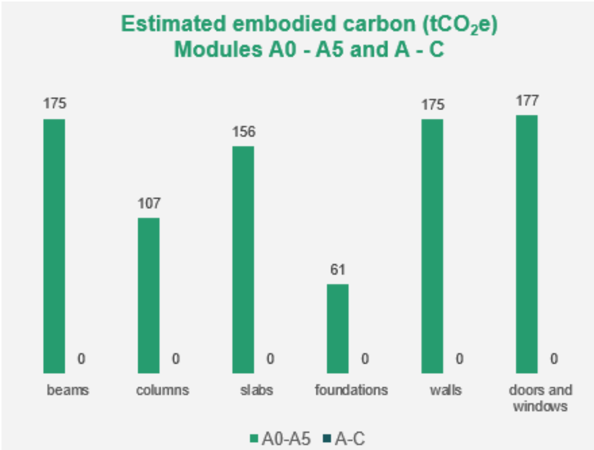

Figure 5. Bar chart of carbon emissions for each component

As can be seen from the chart, the hidden carbon emissions from doors and windows are the highest, reaching 177 tCO_2e. The possible reason for this is that educational buildings like kindergartens require good ventilation and lighting, which leads to a large usage of doors and windows. Furthermore, since there are many children involved in activities in such buildings, for safety reasons, the materials used for doors and windows will be of higher quality and more abundant. Therefore, for kindergarten buildings, one possible approach is to try using doors and windows made of low-emission and environmentally friendly materials to reduce carbon emissions.

In addition, the carbon emissions from the walls cannot be ignored. This might be because kindergarten buildings require a large number of activity rooms, which results in many interior walls. Additionally, such buildings need strong sound insulation capabilities, hence the use of thicker exterior and interior walls. From this, it can be concluded that using low-carbon materials to construct walls may have a significant positive impact on the carbon emissions of buildings.

Regarding the structure of this building, namely the beams, columns, and floor slabs. From this bar chart, it can be seen that the carbon emissions of beams account for the largest proportion, followed by slabs, and the least is that of foundations. and the design load is low, so the use of structural columns is less, and the thickness and area of the floor slabs are also relatively smaller. The building is relatively short, so the design of the foundation did not use a lot of concrete. This has led to the carbon emissions from the roof beams accounting for a relatively large proportion of the total.

	Whole Project	
A0 – A5:	510 tCO_2e	271 $kgCO_2e/m^2$
Biogenic Carbon:	0 tCO_2e	0 $kgCO_2e/m^2$

Figure 6. The entire embodied carbon of using low-grade concrete

	Whole Project	
A0 – A5:	503 tCO_2e	267 $kgCO_2e/m^2$
Biogenic Carbon:	0 tCO_2e	0 $kgCO_2e/m^2$

Figure 7. The total embodied carbon of using precast concrete columns

The figures above show the carbon emission results under two scenarios: using concrete with lower strength and using precast concrete columns. It can be seen that the embodied carbon in the building has been reduced. Therefore, for these types of buildings, optimizing the structure, using concrete with lower bearing capacity, or switching to precast concrete components can all help reduce carbon emissions.

5. Conclusion

The study on the carbon footprint of kindergarten buildings vividly demonstrates the profound impact of architectural practices on global carbon emissions. This research utilized the life cycle assessment tool (IstructE tool) to systematically analyze the carbon emissions of the library during the production stage and construction process (modules A0-A5), and conducted an assessment of its entire life cycle. Through the study of data from the architectural construction drawings, combined with reasonable assumptions to fill in the missing data in the construction drawings, the final calculation showed that the total carbon emissions of modules A0-A5 reached 517 tons of carbon dioxide equivalent, with unit area carbon emissions of 275 kilograms of carbon dioxide equivalent per square meter, all of which obtained SCORS D-level certification. The research results indicate that the carbon emissions of this library are considerable. However, it should be noted that this study only calculated the carbon emissions for structural components such as floor slabs, beams and columns, foundations, walls, and doors, and the actual overall carbon emissions may be higher. For reducing the carbon emissions of this type of buildings, the following methods are worth considering: using low-carbon materials for doors and windows, and optimizing the main structure.

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