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Study on Life-Cycle Carbon Footprints and an Uncertainty Analysis of Mega Sporting Events: An Analysis in China

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Abstract: This study proposes a model for the quantitative evaluation of the life-cycle carbon footprints of large sporting events and the uncertainties related to them. The model was used to analyze the case of a mega sporting event in Beijing, China. First, the quantitative model for the evaluation of the carbon footprints of mega sporting events includes a preparation stage, a holding stage, and an end stage. These stages consider the energy and resources used for construction, operation, transportation, catering, and accommodation. Second, this study proposes a prediction model using model-based and simulation-based methods to address the difficulty of obtaining traffic activity. Third, a semi-quantitative method that combines a data quality indicator and stochastic simulation is adopted for the uncertainty analysis of mega sporting events. Finally, a case study is used to indicate that the preparation stage of a mega sporting event accounts for the highest CO_2 emissions at 92.1%, followed by 7.5% in the holding stage and 0.4% in the end stage. The total life-cycle CO_2 emissions of a sustainable scenario of a mega sporting event in Beijing amount to 205,080.3 t CO_{2e}, and the per capita CO_2 emissions during the event's holding stage amount to 0.26 t CO_{2e}/person. The uncertainty in the input parameters is 0.0617, indicating that the uncertainty of the model is low, and the reliability of the results is high.

Keywords: carbon footprint; mega sporting events; life cycle; uncertainty analysis; environmental impact

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Citation: Wang, H.; Tian, J.; Li, Y.; Wang, Y.; Lu, Y.; Zhang, J.; Lei, C.; Li, C. Study on Life-Cycle Carbon Footprints and an Uncertainty Analysis of Mega Sporting Events: An Analysis in China. *Buildings* **2024**, *14*, 2510. https://doi.org/10.3390/buildings14082510

Academic Editor: Francesco Nocera

Received: 2 July 2024
Revised: 6 August 2024
Accepted: 12 August 2024
Published: 14 August 2024

1. Introduction

Given the economic and cultural developments worldwide, mega sporting events have become increasingly popular. However, high-density CO_2 emissions due to venue construction, venue operations, transportation, personnel accommodation, and catering during the preparation, holding, and end stages of such events generate negative impacts on the climate. In recent years, amid concerns about global warming, many countries have set targets for carbon peaking and carbon neutrality. In addition, experts and scholars have conducted a growing number of studies on quantifying greenhouse gas (GHG) emissions generated by various events.

A number of current studies have discussed the environmental impacts of various types of sporting, cultural, and commercial events. For instance, scholars have calculated the environmental impacts of event participants [1–3], solid waste disposal at events [4], event sites [5], trade fairs [6,7], religious events [8], event transportation [9,10], the location of infrastructure around events [6,11], and event tourism [12]. However, studies focusing on the carbon footprints of sporting events remain underdeveloped. Although a few experts [13,14] have studied the GHG emissions of sporting events with different boundaries, their research lacks portions of construction or venue operation, which are considered significant [15]. Meanwhile, no standardized and uniform carbon footprint calculation frameworks or methodologies exist.

The process of calculating the carbon footprint of mega sporting events is not consistent in terms of whether it should include various components, such as venue construction, post-event utilization, personnel transportation, and accommodation during the holding stage. Sara et al. [6] and Gallo et al. [7] argued that the preparation and assembly phases of events account for a larger share of emissions when quantifying their environmental impacts and cannot be ignored. Furthermore, Parkes et al. [16] asserted that the CO_2 emissions from the post-event utilization phase are much larger than those of the event's hosting stage. Therefore, sustainable management plans for events should focus on and incorporate the post-event utilization phase as part of their legacy. Pereira et al. [9] concluded that transportation accounted for 61% of the overall emissions by calculating the carbon footprint of Premier League clubs. In another study, Pereira et al. [17] found that transportation would be the largest source of CO_2 emissions by accounting for the CO_2 emissions of the 2030 FIFA World Cup, with tourism accommodation in second place.

Uniform protocols and approaches for assessing the carbon footprints of major sporting events have been established. In 2019, the Ministry of Ecology and Environment of the People's Republic of China published the "Implementation Guidelines for the Carbon Neutrality of Large-Scale Events" (for trial implementation) to regulate the execution of carbon neutrality for major events [18]. Although the standard provides some useful suggestions for organizers of mega sporting events, it does not provide CO_2 emission indicators. Collins et al. [19] adopted an ecological footprint analysis and environmental input–output modeling to conduct a comprehensive quantitative environmental impact assessment of mega sporting events. However, the input–output method is commonly used for macro-level studies, such as those of countries, industries, or upstream emissions over a life cycle [20,21]. In addition, it is not applicable to the calculation of the micro-scale carbon footprints of individual mega sporting events. A number of research works [6,22] adopted the process-based life-cycle approach to calculate CO_2 emissions. This approach has the advantage of identifying the specific types of energy and materials that contribute to emissions and facilitating the development of strategies for conserving energy and lowering carbon dioxide emissions.

In examining the CO_2 emissions associated with transportation during large-scale sporting events, researchers have utilized a range of methodologies. David M. Herold et al. [23] investigated the transportation choices of spectators at football matches in Austria to assess their carbon footprints. Data collection was conducted through online surveys and on-site questionnaires, targeting 19% of season ticket holders and home game spectators. Stavros Triantafyllidis et al. [24] examined the traveling behaviors and carbon dioxide emissions of participants in mass sporting events held in rapidly growing cities. They collected information via questionnaires, which included participants' postal codes, departure and return locations, and the modes of transportation used. Spinellis et al. [25] used the shortest arc of latitude and longitude between the origin and destination as the ideal route by air when computing the carbon footprint of transport. Desiere et al. [26] calculated the carbon footprint of academic conferences due to transportation by assuming transportation modes based on distance with a dividing line of 600 km. In addition, Dolf et al. [15] determined travel data, such as the mode of transport, distance, and occupancy rates, for an audience through questionnaires. However, the above methods are imprecise or difficult to replicate.

Life-cycle assessment (LCA) is a globally recognized method for quantitatively assessing environmental impacts. Considering a life-cycle approach, the stages of a mega sporting event encompass the preparation, execution, and conclusion phases. In the "Carbon Footprint Methodology for the Olympic Games", the IOC applied an LCA to calculate the GHG emissions for the Olympic Games. Ana Antunes et al. [27] employed LCA to analyze ten demolition strategies for buildings at their end of life. The results indicated that selective demolition and on-site treatment strategies have the least environmental impact, while transportation distance significantly affects the environmental footprint. Case studies were used to validate the findings, demonstrating that optimizing demolition strategies and treatment methods can substantially reduce the environmental impact of building waste. Similarly, Murat Kucukvar et al. [28] used LCA to analyze the stadiums of the FIFA World Cup in Qatar in 2022, focusing on the health impacts during the production, construction, operation, and end-of-life stages of container stadiums. The study compared temporary one-year operations with permanent 50-year operations, revealing that in the temporary scenario, circular design reduced the health impacts by 60%, significantly lowered material carbon footprints, and decreased dependence on imported construction materials. Lidia Piccerillo et al. [14] also utilized LCA to assess the environmental impact of the 75th Italian National University Championships and calculated the carbon footprint of participants during the event. The findings showed that transportation contributed the most to CO_2 emissions. Neugebauer et al. [29] used information that complied with the ISO 14040 [30] and ISO 14044 [31] standards and adopted the LCA approach for the first time to conduct a comprehensive evaluation of CO_2-equivalent emissions. The information came from four phases of an international conference: the preparation of the conference, conference execution, and the pre-/post-conference activities; the main influencing factors were identified, and future sustainable orientations were explored. However, few studies have applied LCA to the carbon footprints of mega sporting events for several reasons, such as the overly complex data collection and difficulty in establishing boundary conditions.

Table 1 summarizes the present research on CO_2 emissions from sporting events. While some research has partially addressed greenhouse gas (GHG) emissions for different event types, there remains a lack of comprehensive and standardized methodologies for analyzing the carbon footprints of large-scale sporting events.

Table 1. Summary of the literature on the environmental impacts of events.

Author	Year	Object	Stages	Content
David M. Herold [23]	2024	Sporting events' tourism	Undefined	The study used Austria's largest football club as a case study to investigate the transport mode choices of club supporters, systematically assessing the total greenhouse gas emissions produced by supporters at professional football matches.
Ville Uusitalo [3]	2024	Teams competing in a sporting event	Undefined	This study employed the life-cycle assessment method to analyze a case of carbon neutrality achieved by a Finnish professional ice hockey team. It details the carbon footprint assessment process and the greenhouse gas reduction measures implemented.
Cheng Zhang [5]	2022	2014 Nanjing Youth Olympics	Preparatory, hosting, after	This study applied methods such as the SCM and LMDI to investigate the impact of the 2014 Nanjing Youth Olympic Games on local CO_2 emissions at different stages.
Murat Kucukvar [28]	2021	FIFA World Cup Qatar 2022 RAA stadium	The raw material production, construction, operations, and end of life	This study conducted a full life-cycle analysis of the stadium, comparing the differences between two operational scenarios—short-term and long-term operations. The study indicated that circular design could reduce the impact on human health and decrease the use of building materials.
Cheng and Xinixn et al. [5]	2021	Location of major sporting events	Preparatory, hosting, and post-event stages	This investigation considered the CO_2 emissions associated with the preparation, execution, and post-event phases of major sporting events in their host locations.

Table 1. *Cont.*

Author	Year	Object	Stages	Content
Cooper et al. [12]	2021	Sporting events' tourism	Undefined	This study examined the environmental impacts caused by sporting event tourism and proposed a linear model accounting for the carbon footprint of transportation, food, waste, lodging, and stadium operations for fans and teams.
Gallo et al. [7]	2020	Large-scale events: World Fair	Office activities, construction of expo site and pavilions, operations, and decommissioning process	Full life-cycle GHG emissions were calculated on the basis of ISO 14064 [32] for events. The findings indicated an overall effect of approximately 1 ton of CO_2 equivalent per square meter of exhibition space and an average of 60 kg CO_2 equivalent per visitor.
Rodrigo Pinheiro Toffano Pereira et al. [17]	2020	World Cup's transportation and accommodation	Undefined	A scenario analysis approach was employed to evaluate the carbon footprint associated with transportation and accommodation for the 2030 FIFA World Cup as profits increased due to an increase in the number of participating teams. The study proved that the carbon footprint would increase by 24% due to transportation and accommodation alone.
Sabrina Neugebauer [29]	2020	International conference series in Europe	Preparation of the conference, conference execution, and further pre-/post-conference activities	The findings reveal that the travel activities of participants contribute most significantly to the overall environmental impact. The conference operations resulted in a carbon footprint of 455 tonnes of CO_2 equivalent, averaging 0.57 tonnes per participant. A scenario analysis indicated that changes in train travel, vegetarian options, and reductions in conference materials could significantly improve the environmental conditions of the conference.
Rodrigo Pinheiro Toffano Pereira et al. [9]	2019	Premier League Club's transportation	Undefined	An analysis of the carbon footprint of soccer clubs utilized the evaluation method proposed by the UK's Department for Environment, Food, and Rural Affairs (DEFRA) and determined that transportation emissions constituted 61% of the total carbon footprint.

The uncertainty of LCA quantification results has an important impact on the analysis of the carbon footprints of mega sporting events [33]. During the computation procedure, a lack of data, unrepresentative data, random sampling errors, measurement errors, misclassifications, missing data, incomplete system boundary settings, different scenario settings, model assumption errors, and other factors may produce uncertainty in the results [12]. Given that no unified standardized LCA and uncertainty analysis methods have been established, the results of GHG impacts estimated using LCA methods are only approximate values [34]. The same research question may yield different results [35] and may even lead to wrong decisions on environmental impacts [36]. Therefore, it is necessary to further study the uncertainty and possible value ranges based on the results of LCAs. Given the importance of uncertainty analysis, a number of experts and scholars have examined it in recent years. Researchers have discussed the sources of uncertainty [37], definitions [38–40], analysis methods [41,42], and so on. Some scholars have carried out research on uncertainty in LCAs. For example, some researchers carried out a study on the uncertainty in the whole life cycle of roadway drainage systems [42]. Certain scholars proposed a methodology incorporating sensitivity analyses and uncertainty analyses to address the uncertainties inherent in comparative building LCAs [43]. In general, parameters, scenarios, and model uncertainty are three common basic sources, among which parameter uncertainty is particularly significant because of the extensive data required in the computation process [37,44]. The authors of [37,44] stated that parameter uncertainty pertains to variability in a model's input data and the spread of outcomes resulting from its propagation within the model. Scenario uncertainty arises from variations in the settings of system boundary scopes, the values taken, etc. Model uncertainty stems from the selection of varying or imperfect parameters in the structure and model used for analysis. The most widely used uncertainty analysis methods are statistical analysis and the data quality indicator (DQI). Statistical analysis methods can produce accurate results when large sample data are available. However, the application of statistical analysis methods is constrained by the insufficient data gathered during events and the lack of a comprehensive database in China. Relying on data indicators and expert judgment, the DQI method offers a semi-quantitative solution that effectively addresses data scarcity. Moreover, it is applicable to situations in which the event or project has a fixed single scarcity of data. Experts have also used some other methods, such as sensitivity analysis [45] and scenario analysis [46]. Although numerous studies have been conducted on the calculation of CO_2 emissions, the investigation of associated uncertainties remains insufficient, particularly in the context of the life-cycle processes of mega sporting events [38]. Yingjie Chen [47] extended the traditional STIRPAT model by including seven driving factors, thereby creating a more practical approach for calculating energy consumption and CO_2 emissions in the construction of large public buildings. Ahmad Bin Thaneya [48] developed a framework for categorizing various types of uncertainties and systematically addressed these uncertainties using scenario-aware Monte Carlo simulation (MCS). Andreia Santos [49] proposed incorporating feature factor uncertainty into life-cycle assessments.

Assessing the impacts of carbon footprints generated by mega sporting events can contribute to the identification of important impact sources and mitigation strategies. However, the existing research on the carbon footprints of mega sporting events is still at the level of qualitative analysis, but a comprehensive quantitative model framework and methodology for uncertainty analysis is lacking. Therefore, the need for research on the analysis of the carbon footprints of mega sporting events has become urgent. This study presents the quantification and analysis of the carbon footprint and carbon removal associated with a mega sporting event in Beijing. Consequently, the current study undertook the following steps. (1) A qualifying model was built to assess the life-cycle carbon footprints of mega sporting events, including the processes of venue construction, basic operation, special operation, catering, accommodation, and transportation. This model was used to further develop a framework for approximating the carbon footprints of mega sporting events. (2) A predictive model for traffic activity was also built using the model and simulation-based methods to provide an approach to evaluating the CO_2 emissions of transportation. (3) This study analyzed the parameter uncertainties of the carbon footprints of mega sporting events by using a semi-quantitative method to quantify the uncertainties due to input parameters. (4) This study contributes to the knowledge of carbon assessments by assessing the carbon footprint of a case in Beijing. Moreover, this research proposes improvements in data collection. Scenario and model uncertainties were also investigated by using scenario analysis, and mitigation strategies were proposed. This study contributes to the refinement of existing methodologies, and the findings can be transferred to future events.

2. Method

2.1. Boundary and Scenario of the Life-Cycle Carbon Footprint Model for Mega Sporting Events

In this study, the research object was restricted to mega sporting events. On the basis of the number of participants, the types of events held, and the types of participants, mega sporting events were defined as sports-themed events, festivals, exhibitions, and other group social events with more than 1000 participants in a single session. Mega sporting events were divided into the preparation stage, the holding stage, and the end stage according to point in their life cycle. The preparation stage involves the construction or renovation of fixed or temporary facilities, the acquisition of event materials, and the activities of personnel and mechanical facilities, and it should be counted from the date of the successful project bid. The holding stage is the core of the event, which requires the consideration of the daily operation of the event venue, special operations, transportation, catering, accommodation, etc. This stage should be counted consistently from the first to the last day of the event. The end stage includes venue waste removal, transportation, and recycling, which should be counted from the end of the event until the removal is completed.

This study adopted scenario analysis to analyze the influencing factors of CO_2 emission by setting up multiple scenarios. Moreover, it provides a basis for carbon reduction and carbon neutrality. In addition, this study set up a general scenario and a sustainable scenario to analyze the carbon footprint. The general scenario was set as follows: the competition area of a mega sporting event does not adopt energy-saving and carbon-reduction measures, that is, no clean energy is used; the proportion of clean energy in primary energy consumption is 0; and the water recycling rate is 0. The sustainable scenario is set as follows: The competition area where a mega sporting event is held uses 100% non-fossil energy in primary energy consumption, and measures are adopted to bring the rate of water recovery and utilization to 100%.

2.2. Framework of the Model for the Life-Cycle Carbon Footprints of Mega Sporting Events

The comprehensive model for calculating the life-cycle carbon footprints of mega sporting events was built using a process-based method and uncertainty analysis. The model aimed to promote the study of sustainable sporting events by quantifying their CO_2 emissions. The process-based method was primarily applied to the micro-level, with Equation (1) explaining the core principles:

$$G = Q \times EF \tag{1}$$

where G is the CO_2 emissions (kg CO_2e); EF is materials, energy, and other CO_2 emission factors (kg CO_2e/unit); Q is activity data.

To ensure the complete quantification of CO_2 emissions, three stages were defined: the preparation stage, the holding stage, and the end stage. The model framework is shown in Figure 1.

The equation for calculating the life-cycle carbon footprint of mega sporting events is shown in Equation (2):

$$G_Z = G_{CB} + G_{JB} + G_{JS} \tag{2}$$

where G_Z is the carbon footprint over the life cycle (kg CO_2e); G_{CB} is the CO_2 emissions in the preparation stage (kg CO_2e); G_{JB} is the CO_2 emissions in the holding stage (kg CO_2e); G_{JS} is the CO_2 emissions in the end stage (kg CO_2e).

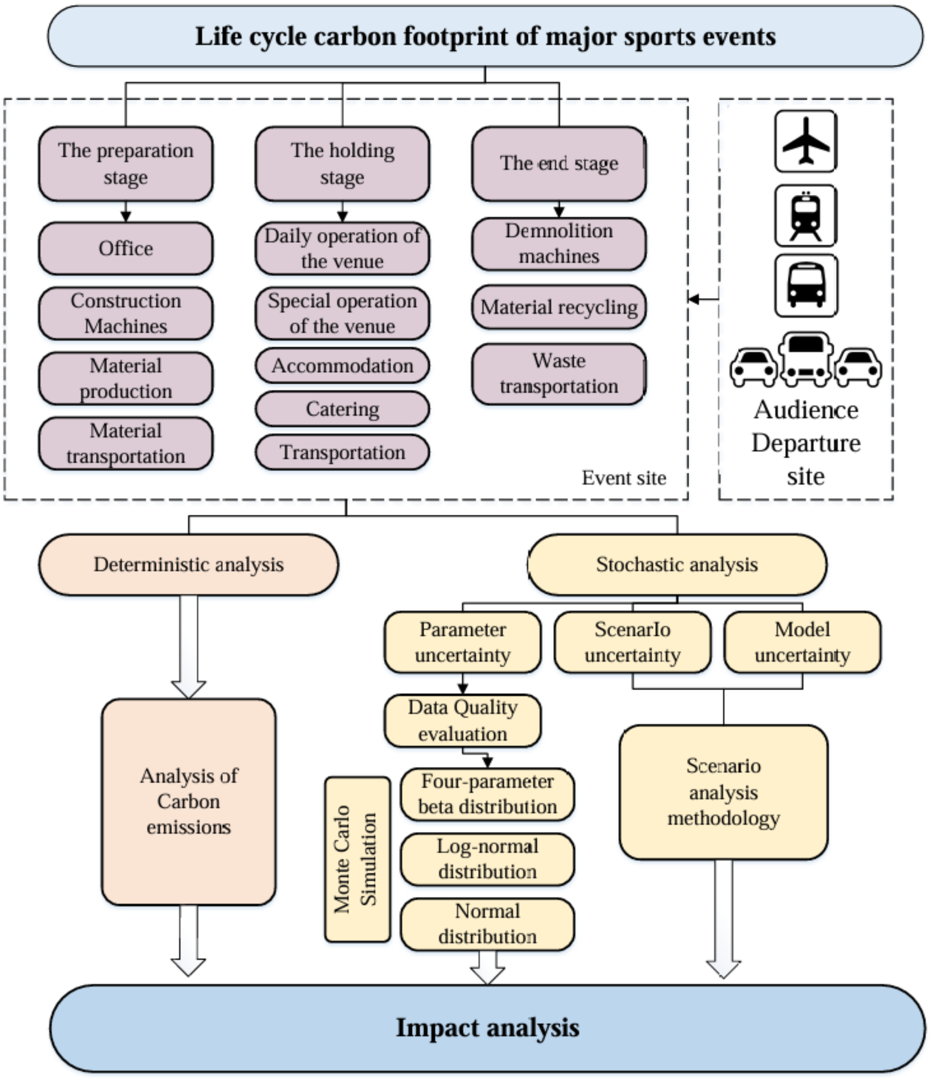


Figure 1. Framework for the calculation of the carbon emissions of mega sporting events.

2.2.1. Carbon Emission Factors of the Model

Currently, no unified authoritative study of CO_2 emission factors for energy and materials has been conducted in China. Hence, a set of CO_2 emission factors applicable to the case city (Beijing) was determined through standards, database comparisons, and calculations.

The official electricity factors currently released in China are all for CO_2 emissions and do not include GHG emissions of N_2O, CH_4, etc. For example, the Ministry of Ecology and Environment of the People's Republic of China announced the national average emission factor of 0.5810 t CO_2/MWh for power grids in the "Methodology and Reporting Guidelines for Corporate Greenhouse Gas Emissions Accounting for Power Generation Facilities (Revised Version 2022)". In addition, DB11/T 1420-2017 "Technical Guidelines for Assessment of Low-Carbon Building Operation" [50] in Beijing set the value of the CO_2 emission factor for electricity to 1.06 kg CO_2/kWh. Therefore, considering the temporal and regional requirements, this study adopted the energy balance sheet method (physical volume summary table) from the China Building Energy Consumption Research Report 2018 for the calculation of the electricity factor. The data source was the local statistical yearbook, Beijing Statistical Yearbook 2021; Equation (3) was used for the calculation:

$$EF_e = {}^{G_f}/(E_f + E_r) \tag{3}$$

where EF_e is the electricity emission factor (kg CO_2e/kW h); G_f is the CO_2 emissions from thermal power generation (kg CO_2e); E_f represents thermal power generation (kW h); E_r represents renewable energy generation (kW h).

Similarly, for the thermal emission factor, a calculation method including GHGs such as CO_2, N_2O, and CH_4 is necessary:

$$EF_h = {}^{G_h}/E_h \tag{4}$$

where EF_h is the thermal emission factor (kg CO_2e/GJ); G_h is the total CO_2 emissions of all types of energy for heating (kg CO_2e); E_h is the total heat production (GJ).

2.2.2. The Calculation Method for the Carbon Footprint in the Preparation Stage

The event preparation stage involves the construction of permanent infrastructure (building of venues and associated infrastructure, etc.) and the construction of temporary facilities. The accounting of construction activities should encompass the entire sequence from raw material extraction through production, transportation, and on-site assembly to completion. This sequence is typically segmented into material production, transportation, and construction phases. Activity level data, such as the consumption of building materials, energy consumption during transportation, and the energy consumption in each construction shift, needed to be collected. The data on materials and energy consumed in the preparation stage of the project were obtained from the bill of quantities in this study.

Carbon emissions from the construction of infrastructure such as venues were calculated according to Equation (5):

$$\begin{gathered} G_{CB} = G_{SC} + G_{YS} + G_{SG} \\ \textstyle\sum_{i=1}^{n} Q_{mi} \times EF_{mi} + \sum_{i=1}^{n} Q_{oi} \times EF_{oi} \times k_{oi} + \sum_{i=1}^{n} Q_{ei} \times EF_{ei} \end{gathered} \tag{5}$$

where G_{CB} represents the total CO_2 emissions in the preparation stage (kg CO_2e); G_{SC} represents the CO_2 emissions in the material production stage (kg CO_2e); G_{YS} represents the CO_2 emissions in the material transportation stage (kg CO_2e); G_{SG} represents the CO_2 emissions in the construction stage (kg CO_2e); Q_{mi} represents the consumption of the ith material (kg CO_2e); EF_{mi} is the CO_2 emission factor of the ith material k(g CO_2e/unit); Q_{oi} is the fuel consumption of the ith vehicle in 100 km (kg/100 km); EF_{oi} is the emission factor of the ith vehicle (kg CO_2e/kg); k_{oi} is the distance traveled by the ith vehicle (100 km); Q_{ei} is the consumption of the ith energy (kg); EF_{ei} is the emission factor of the ith energy (kg CO_2e/unit).

2.2.3. The Calculation Method for the Carbon Footprint in the Holding Stage

The holding stage is the most complex stage in the whole life cycle. The basic operations of the venue, special operations, transportation, catering, and accommodation were considered in this study. The formula is shown in Equation (6):

$$\begin{gathered} G_{SG} = G_{JY} + G_{TY} + G_{JT} + G_{CY} + G_{ZS} = \\ \textstyle\sum EF_i \times Q_{JYi} + \sum EF_i \times Q_{TYi} + \sum\sum V_{i,j} \times S_{i,j} \times C_{i,j} \times EF_i + \sum EF_i \times Q_{CYi} + \sum EF_i \times Q_{ZSi} \end{gathered} \tag{6}$$

where G_{JB}, G_{JY}, G_{TY}, G_{JT}, G_{CY}, and G_{ZS} represent the CO_2 emissions in the hosting stage, basic operation of the venue, special operation, transportation, catering, and accommodation, respectively (kg CO_2e); EF_i is the emission factor of energy, material, and food consumed (kg CO_2e/kg); Q_i represents the amount of energy, material, and food consumed (kg); $V_{i,j}$ is the number of people or vehicles using the jth energy with the ith vehicle type; $S_{i,j}$ is the distance traveled using the jth energy with the ith vehicle type (km); $C_{i,j}$ represents the energy consumption per unit distance using the jth energy with the ith vehicle type (kg); EF_j is the emission factor of the jth energy (kg CO_2e/kg).

The boundary scope of the basic operation of the venue was limited to the process of daily use, i.e., the energy consumption of the operation of HVAC, lighting, elevators, and electrical equipment, as well as the processes of maintenance and renovation. However, a growing number of scholars have recently argued that the maintenance and renovation processes are difficult to measure. Therefore, other studies have omitted them.

Special operations refer to the CO_2 emissions generated through additional energy consumption due to the special characteristics of events. For example, the ice-making and ice-repairing processes of ice venues and the snowmaking and maintenance processes of ski venues should be considered.

Figure 2 shows the methodology developed to estimate the CO_2 emissions generated from the transportation of spectators, staff, and athletes who participated in the event and logistics. The estimation of the CO_2 emissions due to passenger movement was divided into the internal and external parts of the event venue. Different methods were adopted for the estimation of the emissions of each part. While the internal part referred to travel within the area of the event venue, all trips from the departure point of the spectators to the event venue were included in the external part. The mode of transportation outside the event area could be by airplane, train, bus, private car, etc., while the mode of transportation inside the event area was mainly ferry or cable car. Note that the departure point of spectators could be outside or inside the city of the event venue. Therefore, the external part was further divided into two parts according to the transportation modes used. For example, using an airplane to travel inside a city is rare. The carbon emissions from logistics were also divided into two parts: outside and inside the city of the event venue. The supplies to be transported included agricultural products, drinking water, epidemic prevention supplies needed during the event, solid waste and garbage removal, etc. The total CO_2 emissions were estimated using the total demand and transportation distance.

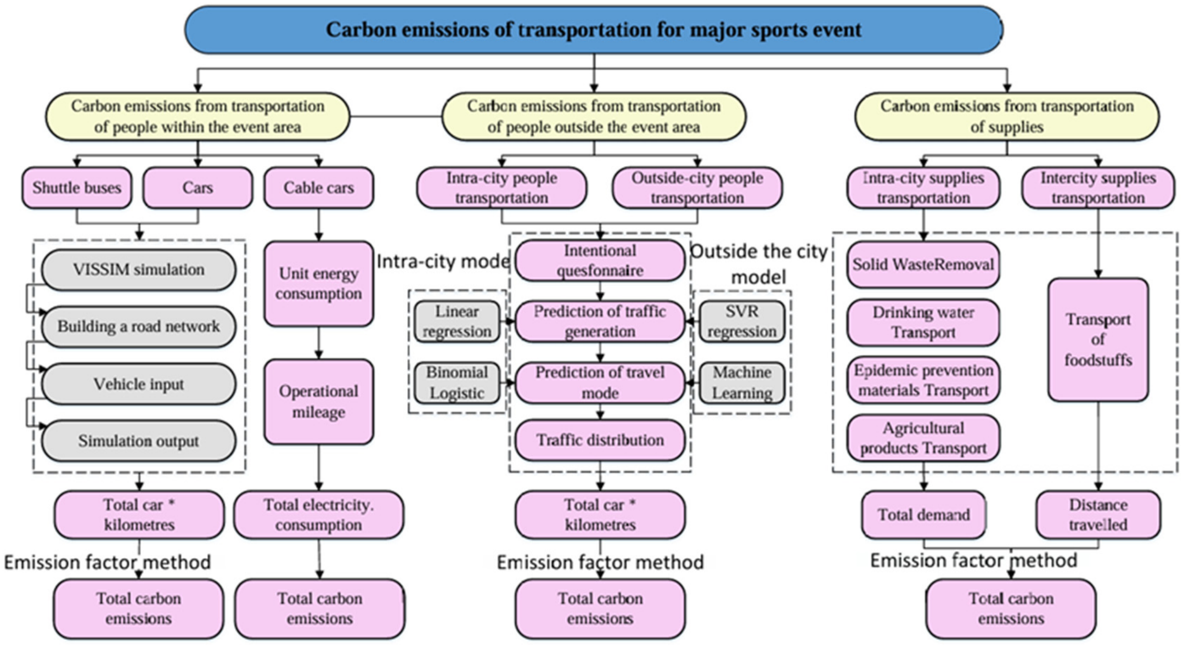


Figure 2. Methodology for calculating the CO_2 emissions of transportation.

In this study, data on individuals' travel activities were primarily obtained through two methods: model-based and simulation-based approaches.

For the internal part, a set of simulations for the journeys using different modes of transportation was conducted in the VISSIM simulation environment. As depicted in Figure 3, the specific steps for simulating individuals' travel within the event area using VISSIM were as follows: (1) the basic simulation parameters within the event area, including the simulation time length, step length, and other parameters, were defined. (2) The overall layout of the competition area was imported as a background image, and its scale and position were adjusted to match the simulation area. (3) A road network was established, and the number, directions, and types of lanes within the event area were specified. (4) The traffic demand data, such as the number of vehicles employed and modal share, were input. (5) Simulations were executed, and traffic operations were recorded. (6) The simulation results were provided as output, focusing on traffic volume and travel distance, to facilitate subsequent calculations.

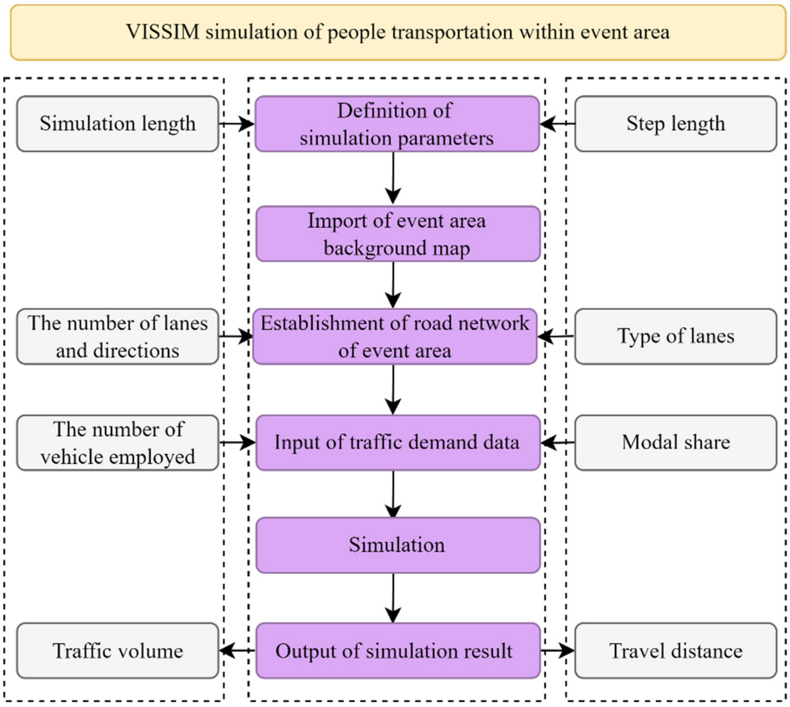


Figure 3. The simulation process for the transportation of individuals within the event area.

On the other hand, trip generation, mode choices, and route assignments were involved in the estimation of travel activity based on a survey for the external part. A linear model and a binomial logit model were established to estimate the trips and the travel modes to be adopted for the travel activities starting from each traffic zone to the event venue inside the city. However, the trip generation and mode choices were realized by developing a support vector regression (SVR) model and an XGBoost model for travel activities outside the city. This study assumed that the shortest path in terms of travel time was adopted for each trip. The detailed calculation procedure is shown in Figure 2.

The catering of the event refers to the food and beverages consumed by athletes, staff, and spectators at the venue during the event. Meanwhile, accommodation refers to the lodging of these participants. The data were derived in part from values recommended by the IOC in the “Carbon Footprint Methodology for the Olympic Games”. Based on the assumptions, athletes/staff visitors were calculated to have an average of two meals and 1 L of non-alcoholic beverages or 0.5 L of non-alcoholic beverages per day. Press and broadcast members/spectators were calculated to have an average of one cold meal or hot snack and 0.5 L of non-alcoholic beverages per day. The athletes and staff were assumed to be accommodated in hotels in the event area. The spectators’ accommodations were divided into four- to five-star hotels, two- to three-star hotels, and single nights in bed-and-breakfast hotels outside the event area. The calculation was based on the daily quantities of consumption of electricity, fuel for hot water, breakfast, waste, and water. Table 2 summarizes the consumption.

Table 2. Summary of accommodation-related data.

Types of Hotel	Parameter	Value (per Night and per Person)
One night in a luxury hotel (four- to five-star hotel)	Electricity	30 kW h
	Fuel for hot water	10 MJ
	Water	450 L
	Waste (municipal waste)	1.5 kg
	Breakfast	1 gourmet breakfast
One night in a medium hotel (two- to three-star hotel)	Electricity	20 kW h
	Fuel for hot water	7 MJ
	Water	300 L
	Waste (municipal waste)	1 kg
	Breakfast	1 standard breakfast
One night in a bed and breakfast (B&B)	Electricity	10 kW h
	Fuel for hot water	3.5 MJ
	Water	150 L
	Waste (municipal waste)	0.5 kg
	Breakfast	1 standard breakfast

2.2.4. The Calculation Method for the Carbon Footprint of the End Stage

The final stage encompassed the dismantling of both permanent and temporary facilities at the venue, during which CO_2 emissions primarily arose from the energy consumption associated with the operation of construction machinery. The calculation formula is presented in Equation (7). If processes such as reuse and reprocessing of renewable materials occur, carbon reduction can be calculated with Equation (8).

$$G_{JS} = \sum EF_i \times Q_{JXi} - G_{CL} \tag{7}$$

Here, G_{JS} represents the CO_2 emissions of the end stage (kg CO_2e); Q_{JXi} represents the energy consumption of construction machinery in the end stage (kg).

$$G_{CL} = \sum (EF_{mi} - EF_{ZC}) \times Q_{JCi} \times \sum \eta_{JS} \tag{8}$$

Here, G_{CL} is the amount of carbon reduction from recycling of materials in the end stage (kg CO_2e); Q_{JCi} is the amount of material consumed in the end stage (kg); η_{JS} is the material recyclability factor; EF_{mi} is the CO_2 emission factor for the production of recyclable materials (kg CO_2e/t); EF_{ZC} is the CO_2 emission factor for the reprocessing of recyclable materials (kg CO_2e/t).

2.3. Uncertainty Analysis of the Model for the Life-Cycle Carbon Footprint of Mega Sporting Events

Uncertainty factors are common in the CO_2 emission process. However, data on mega sporting events are usually so inaccessible that their uncertainty is difficult to quantify. According to its sources and classifications, this study divided uncertainties into parameter, scenario, and model uncertainties. Parameter uncertainty is mainly studied due to uncertainties arising from a lack of data, lack of representative data, random sampling error, measurement error, classification error, and data loss. A combination of the DQI and stochastic analysis was applied, and the main processes of CO_2 emissions were identified by quantifying the following three aspects: the level of contribution to total CO_2 emissions, the coefficient of variation, and the impact on the uncertainty of the results. Scenario and model uncertainties were used to analyze the uncertainty caused by the incomplete boundary settings of the system, different scenario settings, and model assumption errors through scenario analysis with various scenario models.

2.3.1. Parameter Uncertainty

The stochastic analysis method based on data quality is a semi-deterministic method that combines the qualitative evaluation of data through expert judgments with a quantitative evaluation through numerical simulation, compensating for the inadequacy when one of these is used alone. The DQI translates data quality scores that are quantified using descriptive indicators into the empirical distribution of the input parameters. The selection of the descriptive indicators is crucial. Combined with a data evaluation matrix proposed in a previous study, the current study assessed the uncertainty of input data in five aspects—the data source, sample completeness, technical relevance, geographical relevance, and temporal relevance—according to the data characteristics of mega sporting events [51]. Table 3 presents these aspects.

Table 3. Data quality pedigree matrix [52].

Data Quality Score	Data Quality Indicator				
	Data Source	Sample Completeness	Technical Correlation	Geographic Correlation	Temporal Correlation
1	Unknown	Unknown and inadequate data from small ranges and short periods	Related processes, different technologies, and producers	International data or unknown	>15 years
2	Unvalidated data from non-relevant enterprises	Representative data from a small range and period or data from an adequate range and period	Related processes, same technology, different producers	National data	≤15 years
3	Unvalidated data from relevant researchers	Representative data from a suitable range but slightly shorter period	Same process and producer, different technologies	Regional data	≤10 years
4	Validated data from relevant producers	Representative data from a slightly smaller range but for the right period	Same process and technology, different producers	Data from other regions with similar production conditions	≤6 years
5	Validated data from independent sources	Adequate sample, appropriate period	Same process, technology, and production	Field research data	≤3 years

To translate the quality indicator scores into probability distribution functions, certain transformation relationships needed to be determined. The most commonly used distribution functions are the normal distribution, lognormal distribution, four-parameter beta distribution, and triangular distribution functions. The four-parameter beta distribution was adopted because of its flexible form, strong adaptability, and positive-only values. Its probability density function is shown in Equation (9).

For random sampling, commonly used methods, such as Monte Carlo simulation and Latin hypercube sampling, are applied to randomize the quantitative random numbers from the probability distribution determined using the data quality score of the initial input data. In this study, a Monte Carlo simulation was applied to generate 10,000 sets of data with Python software 3.10.2 through the probability density function generated using the DQI.

The expression of the probability density function of the four-parameter beta distribution is given in Equation (9).

$$f(x,\alpha,\beta,a,b) = \frac{(x-a)^{\alpha-1}(b-x)^{\beta-1}}{(b-a)^{\alpha+\beta-1}} \times \frac{F(\alpha+\beta)}{F(\alpha)\times F(\beta)}; (a \le x \le b) \tag{9}$$

The transformations of shape and position parameters α, β, a, and b derived from the expert empirical evaluation and the synthesized score of data quality are shown in Equations (10) and (11), respectively.

$$(\alpha,\beta)= max[int(2-5,1]\times(1,1) \tag{10}$$

$$(a,b)=u\times\left[0.4+0.05\,int\,(2S_{DQI}),1.6-0.05\,int\,(2S_{DQI})\right] \tag{11}$$

Here, S_{DQ} is the synthesized score of the data quality; u is a representative value of the data, and it was adopted as the average value in this study.

2.3.2. Scenario Uncertainty

In this study, scenario analysis was conducted to investigate the scenario uncertainty caused by incomplete system boundaries and different parameter values due to technological progress factors. On the basis of the quantification of the different influencing factors of the above two scenarios, the scenarios were calculated and analyzed separately. As shown in Table 4, the baseline scenario refers to all material, energy, and resource consumption processes within the calculation boundary set in this study, and the corresponding CO_2 emission factors were taken from the values determined in this research. In the system boundary scenario, the calculation boundary was set to consider only the process of the consumption of the main materials and energy resources to explore the feasibility of simplifying complicated calculations by reducing the unit process. In the technological progress scenario, the CO_2 emission factor of materials, energy, and resources was set to a value of 10% reduction to determine the possibility of CO_2 emission reductions brought about by future technological progress. The unit process with the greatest potential for CO_2 emission reduction was determined through a sensitivity analysis.

Table 4. Scenario settings for determining the scenario uncertainty.

Scenario Model	Scenario Number	Scenario Description
Baseline scenario	——	All material, energy, and resource consumption within the boundary range is considered; the CO_2 emission factor is taken as the existing value; the four-parameter beta distribution is chosen as the probability distribution function; the “temporal relevance” quality score evaluation index is selected as the actual value.
System boundary	1	The boundary range is defined to consider the main material, energy, and resource consumption processes.
Technological progress	2	Carbon emission factors of materials, energy, and resources are decreased by 10%.

Although uncertainty analysis and sensitivity analysis belong to two different disciplines, they are closely related. Sensitivity analysis can be used to evaluate the contributions of input factors to changes in the system output and determine which measures have the greatest impact on CO_2 emissions under existing influencing factors. The formula is shown in Equation (12).

$$\varepsilon_m=(G-G_m{}')/G\times 100\% \tag{12}$$

Here, ε_m is the sensitivity coefficient; m refers to the mth measure taken; $G_m{}'$ represents the CO_2 emissions of the mth technology.

2.3.3. Model Uncertainty

In the process of CO_2 emission calculation, model assumptions are involved. However, model assumptions cannot simulate real systems completely and accurately. Therefore, this study set up Scenarios 3–9 to investigate the model uncertainty. As many common probability density functions exist, the probability density function that best reflected the real situation needed to be selected. Scenarios 3 and 4 examined the impacts of different distribution forms on the CO_2 emission results; they mainly focused on the function definition domain, function value domain, shape, and data calculation process for a comprehensive analysis. In the calculation and collection process, given the national development of technology, the temporal correlations of emission factors had an important impact on the calculation results. Scenarios 5–9 explored the impacts of the temporal correlations of the input parameters on the CO_2 emission results. The model uncertainty analysis scenarios were set up as shown in Table 5.

Table 5. Scenario settings for the model uncertainty analysis.

Scenario Model	Scenario Number	Scenario Description
Distribution form	3–4	Scenario 3 used a normal distribution; Scenario 4 used a lognormal distribution form
Time dependence	5–9	The quality indicator scores of "time dependence" were 1–5 for Scenarios 5–9, respectively.

3. Case

3.1. Boundary of the Case

In this study, a mega sporting event in Beijing was used as a case. The sporting event primarily took place in a local skating center that hosted ice sporting events and a ski center that hosted a series of ski events. The life cycle of the case included the following: the preparation stage from 2018 to the eve of the event in 2021, which covered the production of materials, transportation, and the venue construction process; the hosting stage in 2022, which covered CO_2 emissions from basic operations such as venue heating and lighting, special operations such as ice making and snowmaking, catering and accommodation for staff and athletes, and transportation of spectators and materials; the end stage. During the event period, the total number of people in this skating center amounted to about 6660, including athletes, staff members, and spectators. There were about 8030 people in the ski center, including athletes, staff members, and spectators.

3.2. The CO_2 Emission Factors of the Case

The CO_2 emission factors of the case were calculated using the data and formulas described in Section 2.2.1. The factors of electricity and heat were taken from the emission data of Beijing 2020 using Equation (3). The emission factors of materials were mainly taken from the GBT 51366-2019 [53] National Standard for Building Carbon Emission Calculation, Emission Factor Database of the IPCC, GaBi Databases, and previous studies. The energy, such as diesel and gasoline, was obtained from official published information. Table 6 presents the details of the factors.

Table 6. Summary of the emission factors.

Emission Factor	Value	Unit	Source
Electricity (2020)	0.4579	t CO_2/MWh	Author calculation [a]
Purchased heat	60.6	kg CO_2e/GJ	Author calculation [a]
Crude oil	3.0274	t CO_2e/t	Author calculation [b]
Gasoline	2.9355	t CO_2e/t	Author calculation [b]
Aviation gasoline	2.9665	t CO_2e/t	Author calculation [b]
Kerosene	3.0439	t CO_2e/t	Author calculation [b]
Diesel oil	3.1063	t CO_2e/t	Author calculation [b]
Fuel oil	3.1806	t CO_2e/t	Author calculation [b]
Petroleum asphalt	3.0871	t CO_2e/t	Author calculation [b]
Petroleum coke	2.3037	t CO_2e/t	Author calculation [b]
Liquefied petroleum gas	3.1041	t CO_2e/t	Author calculation [b]
Refinery dry gas	3.0144	t CO_2e/t	Author calculation [b]
Natural gas	21.6714	t CO_2e/104 m^3	Author calculation [b]
Liquefied natural gas	3.1817	t CO_2e/t	Author calculation [b]

Table 6. *Cont.*

Emission Factor	Value	Unit	Source
Other petroleum products	2.9551	t CO_2e/t	Author calculation [b]
Wood (wood formwork, etc.)	178	kg CO_2e/t	Reference [52]
Rebar	2340	kg CO_2e/t	GBT 51366-2019 [53]
Concrete	295	kg CO_2e/m^3	GBT 51366-2019
Construction mortar	170	kg CO_2e/m^3	Reference [54]
Gravel	2.18	kg CO_2e/t	GBT 51366-2019
Cement	735	kg CO_2e/t	GBT 51366-2019
Sand	2.51	kg CO_2e/t	GBT 51366-2019
Tap water	0.21	kg CO_2e/t	GBT 2589-2020 [55]
Steel pipe	2530	kg CO_2e/t	GBT 51366-2019
Steel plate	2400	kg CO_2e/t	GBT 51366-2019
Stone	0.011	t CO_2e/t	GaBi Database
Dust-proof green mesh	1.99	t CO_2e/t	GaBi Database
Waterproof membrane	2.56	kg CO_2e/kg	GaBi Database
Coating	6.49	t CO_2e/t	Reference [56]
Aluminum profile	28500	kg CO_2e/t	GBT 51366-2019
Fine stone	2.18	kg CO_2e/t	GBT 51366-2019
Fine sand	0.004	t CO_2e/t	Reference [57]

[a] Adapted from Equations (3) and (4). [b] The values were derived from the formula recommended by the IPCC: $EF_e = (C_c R_o \times \frac{44}{12} + 27.9 \times C_m + 273 \times C_n) \times C_v \times 10^{-6}$, where *Cc*, *Ro*, and *Cv* correspond to the carbon content (tC/TJ), oxidation rate, and heating value (MJ) from the Guidelines for the Preparation of Provincial Greenhouse Gas Inventories and General Principles for the Calculation of Total Production Energy Consumption. *EFe* is the CO_2 emission factor (tCO_2e/ unit); 27.9 and 273 are the greenhouse gas potentials of CH_4 and N_2O from IPCC2022. *Cm* and *Cn* are the default emissions of CH_4 and N_2O (t/TJ).

3.3. Calculation of the Carbon Emissions of the Case

(1) The preparation stage

In the Beijing case, we collected the number of CO_2-emitting activities in the preparation stage through the design and construction documents, as shown in Table 7.

Table 7. Summary of the bill of quantities in the preparation stage.

Item	Value	Unit
Electricity	2379.608	mwh
Gasoline	756.1908	t
Diesel oil	1522.898	t
Wood (wood formwork, etc.)	348.7	m^3
Rebar	38,918.5	t
Concrete	192,021.5	m^3
Construction mortar	47,973.2	m^3
Gravel	10,942.4	t
Cement	3280.4	t
Sand	4979	t
Tap water	111,463.5	t
Steel pipe	21.59	t
Steel plate	2800	t
Stone	918	t
Dust-proof green mesh	122	t
Waterproof membrane	964.15	m^3
Coating	107.9	t
Aluminum profile	277	t
Fine stone	11,086	t
Fine sand	690	t

Using the emission factors in Table 6 and the number of activities in Table 7, the CO_2 emissions in the preparation stage of the Beijing case were calculated using Equation (5). The total CO_2 emissions in the preparation stage of the case were 201,857.2 t CO_2e.

(2) The holding stage

The boundary scope of the holding stage included the CO_2 emissions due to energy, material, and food consumed, as well as travel. In this study, the data on the venue operation and special operation in the holding stage were taken from the venue filling statistics, as shown in Table 8. Catering and accommodation data were calculated on the basis of the values recommended by the IOC in the Carbon Footprint Methodology for the Olympic Games and the actual number of people. The CO_2 emissions of the case in the holding stage were calculated using Equation (6), and the data in Table 6 were used for the CO_2 emission factors. The total CO_2 emissions in the holding stage of the case were 16,363.9 t CO_2e.

Table 8. Inventory of the consumption of the operations in the holding stage.

Item	Value	Unit
Electricity for ice-making	219,476	kwh
Electricity for snowmaking	18,493,216	kwh
Other electricity	1,304,504	kwh
Electricity for cable cars	433,387	kwh
Gasoline	7048	L
Diesel oil	27,752	L
Copy paper	2335.73	kg

The transportation CO_2 emissions represented a significant source of CO_2 emissions during the hosting phase. This study employed the transportation CO_2 emission model established in Section 2.2.3 to calculate these emissions for the Beijing case.

Obviously, transporting people and supplies to the event venue during the holding stage would inevitably produce CO_2 emissions. Following the procedures outlined in Section 2.2.3, the estimation of the CO_2 emissions resulting from transporting people and supplies was carried out as follows.

The CO_2 emissions were estimated for passenger transportation by decomposing it into two parts—those internal and external to the event venue—and two different methodologies were adopted to calculate the CO_2 emissions of these two parts.

A micro-simulation was performed with the road network (i.e., eight roads, including the segment connecting to the outside) inside of the event venue to estimate the travel activities for the two major travel means, namely, shuttle buses and cars, during the whole holding stage (the equivalent of 47 competitions). Shuttle buses were the main means of transportation for the spectators, staff, and athletes in general while organizing officers or invited guests used cars to travel within the venue. On the other hand, it was straightforward to estimate the CO_2 emissions for the cable cars that were used to transport passengers up the hill, as they were operated in fixed periods and routes during the holding stage. The detailed simulation settings and results can be found in our previous work [58].

As stated in Section 2.2.3, a number of models were developed as a basis for estimating the journeys made for the intra- and inter-city trips, which were the fundamental data for the estimation of the CO_2 emissions resulting from transportation from outside the event venue. Note that only local spectators were allowed to attend the events due to the protection policy for the COVID-19 pandemic. As a result, no inter-city trips were generated, and there were no CO_2 emissions for this part. To calibrate the parameters for the models of the intra-city trips, we conducted a survey to collect corresponding data. Due to space limitations, we omitted the description of the details of the model calibration, which was also beyond the scope of this study. However, the results of the number of spectators at the event venue estimated for each district and the modal share are summarized in Table 9.

Based on the occupancy rate (i.e., 3.36 persons per car on average) obtained from the survey, the number of cars used was converted from the number of spectators who would have liked to take private cars to the event venues. The distances traveled from each district to the event venue were estimated following the assumption that the shortest paths in terms of distances with free-flow traffic status were taken. This assumption generally held, which was mainly due to the fact that the period of the holding stage covered the period of the Spring Festival, during which most non-local workers returned to their hometowns, resulting in a light traffic load. According to the 2021 Beijing Transport Development Annual Report [59], the percentages for fossil-fuel-powered and new-energy cars were 92.42% and 7.58%, respectively. Based on the data reported by AUTOHOME [60], the average energy consumption for new-energy cars was 15.22 kWh/100 km. On the other hand, the fuel consumption for fossil-fuel-powered cars was estimated to be 9 L/100 km by averaging the comprehensive fuel consumption over a number of cars. In addition, the emission factors for these two types of cars are shown in Table 6.

Table 9. The results estimated for intra-city trips.

District	Number of Spectators Estimated (Person)	Modal Share	
		Private Cars	Public Transportation
Changping	24.5948	0.7709	0.2291
Chaoyang	103.2351	0.7904	0.2096
Daxing	24.3080	0.8825	0.1175
Dongcheng	37.6123	0.7413	0.2587
Fangshan	25.1982	0.8642	0.1358
Fengtai	30.8991	0.3161	0.6839
Haidian	62.7802	0.6941	0.3059
Huairou	14.1169	0.8444	0.1556
Mentougou	10.4423	0.7644	0.2356
Miyun	17.5966	0.8913	0.1087
Pinggu	14.7424	0.9040	0.0960
Shijingshan	18.6296	0.7126	0.2874
Shunyi	24.7715	0.8176	0.1824
Tongzhou	15.4790	0.8762	0.1238
Xicheng	27.7368	0.7015	0.2985
Yanqing	14.4403	0.8867	0.1133

The CO_2 emissions resulting from the transportation of supplies during the holding stage could be divided into two distinct segments, namely, intra- and inter-city transportation. Intra-city transportation specifically refers to the transportation segment from a supply distribution center in Beijing to the event venue. The estimation took various types of supplies, including agricultural products, drinking water, and epidemic prevention supplies, into account, in addition to the operational aspect related to solid waste management during the holding stage. On the other hand, inter-city transportation comprised the transportation of supplies between different cities. The primary focus of the calculation was the transportation of agricultural products, as these supplies required the most transportation effort. The daily consumption of agricultural products, including grains, cooking oils, dairy products, and drinking water was estimated to be 0.9 kg, 0.0688 kg, 0.1096 kg, and 2 L for each person based on a survey. Furthermore, it was estimated that there were about 16,000 people, including athletes, staff members, spectators, and volunteers, during the holding stage. Note that this number estimated for the provision of supplies was slightly larger than the number of people (i.e., 14,690 in total), as described in Section 3.1, to ensure that there were adequate supplies for the event. The amounts of various epidemic prevention materials were estimated according to the data provided by the organizer of the Beijing case. The solid wastes produced during the holding stage were estimated to be 190.72 t for domestic garbage and 1.1 t for medical waste, respectively, according to the data suggested by the organizer of the Beijing case. Table 10 summarizes the amounts estimated for the various types of supplies.

Table 10. The amounts estimated for supplies.

Zone	Category	Type	Demand (t)
Inter-city	Grains	-	79.2
	Total		79.2
Intra-city	Agricultural Product	Grains	79.2
		Cooking oils	6.05
		Dairy products	9.64
	Drinking Water	-	176
	Epidemic prevention materials	Disposable medical protective clothing	0.17
		Mask and protective screen	169.67
		Disinfectant	48.89
	Solid waste	Domestic waste	190.72
		Medical waste	1.1
	Total		681.44

Table 11 summarizes the travel activities in terms of the mileage estimated for the transportation of people and supplies based on the data stated above and the procedure outlined in Section 2.2.3. Based on the emission factors summarized in Table 6, we obtained the estimations of CO_2 emissions for transportation during the holding stage, as shown in Table 12, and the total CO_2 emissions estimated for transportation during the holding stage were 242.06 t CO_2e.

Table 11. The results of the travel activities estimated for the holding stage.

Type	Type	Item	Mileage (Car × 100 km)
Passenger transportation	Internal segment of the event venue	Shuttle buses	219.424
		Cars	31.091
		Cable cars (8 h/d)	1.008
	External segment of the event venue	Fossil-fuel-powered cars 92.42%	156.951
		New-energy cars 7.58%	1909.196
	External segment of the event venue	Public transportation	178,268.300
Freight	Intra-city	Grain	7.912207
	Inter-city	915 kg electric truck	3809.305
		12 t medium truck	287.067

Table 12. The CO_2 emissions estimated for transportation during the holding stage.

Type	Part	Mode/Type of Transport	Carbon Emissions (t)
Passenger transportation	Internal segment of the event venue	Cars	0.446
		Shuttle buses	11.465
		Cable cars	0.428
		Total	12.170
	External segment of the event venue	Fuel-powered cars	50.440
		New-energy cars	1.380
		Public transport	0.013
		Total	51.830
Freight	Inter-city	Agricultural products	5.470
		Total	5.470
	Intra-city	Agricultural products	69.050
		Drinking water	88.120
		Epidemic prevention	8.550
		Waste removal	1.400
		Total	172.590

(3) The end stage

Referring to the data of the AIJ-LCA, the demolition phase accounts for about 10% of a new construction process. Hence, the end stage in this study was calculated as 10% of the mechanical energy consumption in the preparation stage. The total CO_2 emissions in the end stage of the case were 855 t CO_2e.

4. Results

4.1. Deterministic Analysis of the CO_2 Emission Results for the Life Cycle of Mega Sporting Events

Based on the proposed framework for the calculation of CO_2 emissions for mega sporting events, the deterministic results of the case were analyzed. The calculation results showed that the CO_2 emissions over the whole life cycle of the event were 219,076.1 t CO_2e. Figure 4 shows the proportion of CO_2 emissions in each stage. The preparation stage occupied a major position in the life cycle of the event, amounting to 92.1%, followed by 7.5% in the holding stage and 0.4% in the end stage. The CO_2 emissions from the production of materials used in the processes at the venue, such as steel, concrete, construction mortar, aluminum profiles, steel plates, and diesel oil, occupied a larger proportion than the electricity consumption in the construction process and the fuel consumption in the transportation process. This amount was followed by the holding stage, with a share of 7.5%. Special operations had the highest proportion in the holding stage due to the high power consumption of snowmaking and maintenance processes in the ski venue, which involved snowmaking guns, pumps, snowmobiles, and other special equipment. This covered the snowmaking process in the trial operation phase. Next were the daily operations, food, accommodation, and transportation for the venue. Unlike previous results [15,22] where transportation accounted for a larger share of CO_2 emissions, the event in this case was limited by the novel coronavirus epidemic, with spectators only coming from within Beijing and no travel taking place from outside Beijing. Thus, the transportation of spectators and logistics had a relatively small share of CO_2 emissions. The end stage of the event accounted for the smallest proportion. Considering the post-event conversion and utilization plan of the venue, only a small number of temporary buildings had to be demolished. The deterministic results presented three conclusions. First, the CO_2 emissions were 12 times higher in the preparation stage than in the holding stage. Thus, to reduce the environmental impact of new venues, a post-event utilization plan needed to be fully designed. Venues should be arranged to be used reasonably. It is necessary to extend the service life of venues and reduce the construction of new venues—for example, by conducting public events in venues, reusing venues to host large-scale events, and so on. Second, the production of steel, concrete, construction mortar, and other materials accounted for a larger proportion of the emissions in the preparation stage. Organizers of mega sporting events can achieve energy conservation and emission reductions by reducing the use of the above materials or opting for alternative low-carbon materials. Thirdly, organizers should pay attention to events with high CO_2 emissions during the hosting phase. They can reduce CO_2 emissions by adopting water-saving and energy-saving measures, using green energy, etc.

Table 13 presents the results of the comparative analysis between the general scenario and the sustainable scenario. The life-cycle CO_2 emissions in the sustainable scenario were 205,080.3 t CO_2e, with an emission reduction ratio of 6.4%. The highest emission reduction ratio was 76.66% in the holding stage. The main energy consumed during the holding stage for venue operation, special operation, and accommodation was electricity. Hence, the use of clean energy could further reduce CO_2 emissions. At the same time, the adoption of a water recycling rate of 100% reduced the water consumptionof 3045 m^3 during the holding stage. Therefore, the adoption of clean energy and water recycling measures is an important way to reduce CO_2 emissions. However, given the use of other materials and energy, such measures need to be taken in parallel with other carbon-neutral means.

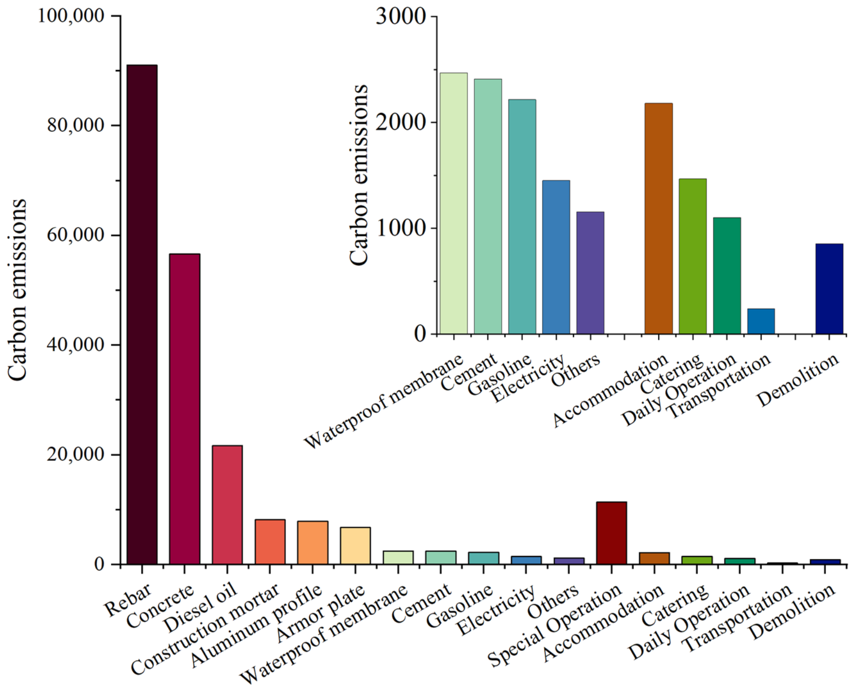


Figure 4. Deterministic results for CO_2 emissions from the event.

Table 13. Comparison of CO_2 emission results for different scenarios.

Stage	The Emissions in the General Scenario (t CO_2e)	The Emissions in the Sustainable Scenario (t CO_2e)	Emission Reduction (t CO_2e)
The preparation stage	201,857.2	200,405.3	−1451.9
The holding stage	16,363.9	3819.9	−12,544.0
The end stage	855	855	0

In the general scenario, the per capita CO_2 emissions over the event's life cycle reached 14.91 t/person, and the per capita CO_2 emissions of the event's holding stage reached 1.11 t/person. In the sustainable scenario, the CO_2 emissions per capita for the life cycle of the event amounted to 13.96 t/person and 0.26 t/person during the event's hosting stage. Wicker et al. [1] calculated the annual CO_2 emissions per capita due to sporting events to be 844 kg CO_2e. The CO_2 emissions from participating in the event were about 0.3 times that of a year's worth of daily sporting events. The average CO_2 emissions of Rio 2016, including those of construction, organization, and demolition, were 0.42 t CO_2e/visitor, and they were 0.64 t CO_2e/visitor for FIFA 2018 in Russia [7]. This result was less than the life-cycle CO_2 emissions per capita in the case of Beijing because the venues were new buildings, and the preparation phase accounted for a significant proportion of CO_2 emissions.

4.2. Parameter Uncertainty Analysis

A stochastic simulation of the case was conducted through Python, and the result is shown in Figure 5. After 10,000 sets of Monte Carlo simulations, the mean and standard deviation of the stochastic analysis of the CO_2 emissions over the whole life cycle were 218,535 t CO_2e and 12,945 t CO_2e, respectively, which were 0.14% different from the deterministic results. The coefficient of variation was 0.0617, and the range of minimum and maximum values was (−15.97%, 16.67%). The mean values of the deterministic results in each stage were similar to the results of the stochastic analysis. Hence, the above stochastic model can be effectively applied to the stochastic simulation of CO_2 emissions in mega sporting events. As shown in Figure 5, after the calculation and analysis of dozens of sub-processes, the coefficients of the variations in the end stage and the accommodation and catering processes in the hosting stage were high and contributed greatly to the uncertainty in the data quality of the output. The real activity data in this project were difficult to obtain, and the information recommended by the IOC was partially used in the calculations. Thus, a larger data sampling error and imputation error may have occurred. To sum up, in the calculation of life-cycle CO_2 emissions, the process of data collection for the end stage and the accommodation and catering processes in the holding stage should be noted so that the quality of the emission inventory can be improved, and the uncertainty can be reduced with better results.

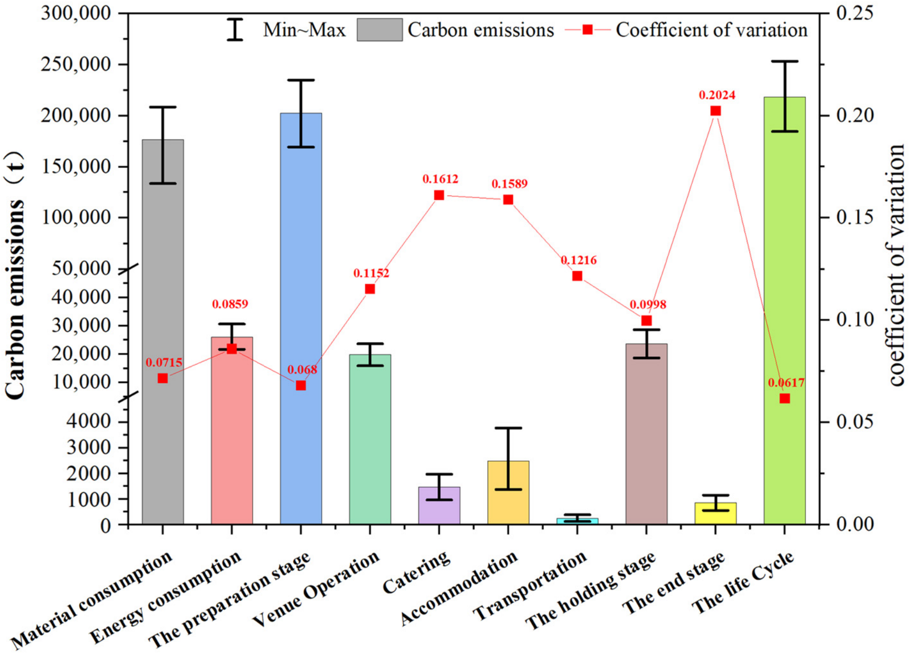


Figure 5. Parameter uncertainty results for CO_2 emissions.

4.3. Scenario Uncertainty Analysis

Given that no unified norm specifies the boundary settings for mega sporting events, the impact on the CO_2 emission results could be studied by setting different system boundaries. According to Scenario 1, this study analyzed the influence of the integrity of the system boundaries on CO_2 emissions. The boundary conditions in Scenario 1 were set by removing the consumption processes for which it was difficult to collect data or that were uncommon, and only 18 major processes, including the use of materials such as steel, concrete, and construction mortar, special operations, catering, accommodation, transportation, and other major processes, were considered. Figure 6 shows the CO_2 emission results for Scenario 1 compared with those of the baseline scenario. The total CO_2 emissions in Scenario 1 were 196,056 t CO_2e with a standard deviation of 12,768 t CO_2e, which amounted to CO_2 emission reductions of 13.5% and 0.6% compared with the baseline scenario, respectively. Thus, a change in the system boundary will change the CO_2 emission results to a certain extent, and the system boundaries should be set according to the actual situation, such as the data collection and result accuracy requirements in the calculation process.

Scenario 2 considered the impact of a reduction in the emission factors for each material and type of energy due to future technological developments. Assuming a 10% reduction in the emission factors of each energy and material due to future technological advancements, the CO_2 emission simulation and sensitivity calculation were re-executed. Figure 7 shows the CO_2 emissions represented by the mean values and sensitivity when each energy and material emission factor was reduced by 10%. Steel had the largest sensitivity of 0.4, followed by concrete and electricity with 0.3 and 0.08, respectively. The CO_2 emissions were reduced by 8937.2 t CO_2e, 5769.9 t CO_2e, and 2225.3 t CO_2e, respectively. The results indicated that the uncertainty in the input data for the steel, concrete, and electricity emission factors contributed the most to the uncertainty in the results. It can be concluded that steel bars, concrete, and electricity were highly sensitive, and the reduction in their CO_2 emission factors contributed to a reduction in emissions. The carbon reduction effect of steel bars was the most significant, and prioritizing low-carbon materials had a significant impact on the CO_2 emissions of activities.

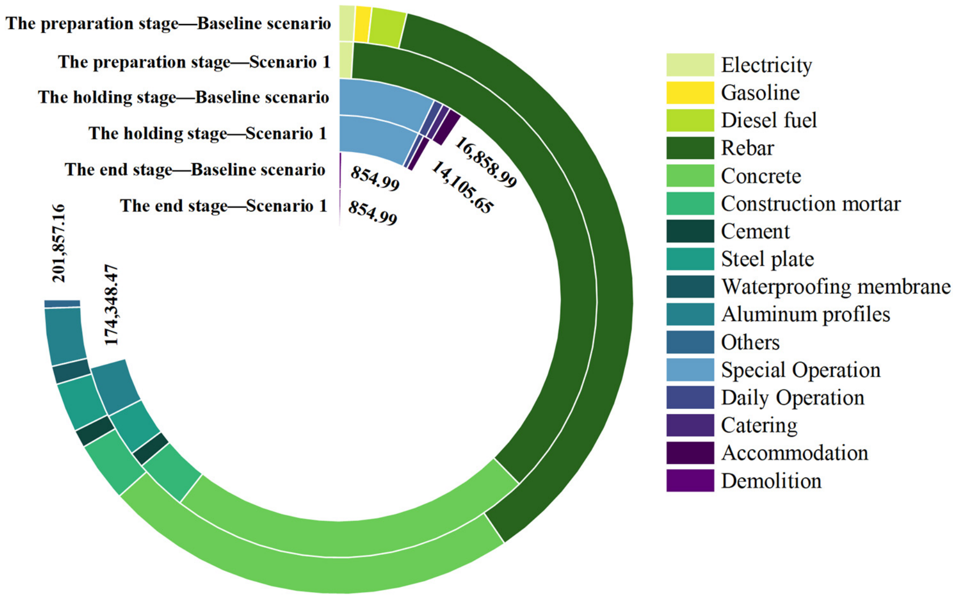


Figure 6. Carbon emissions in Scenario 1.

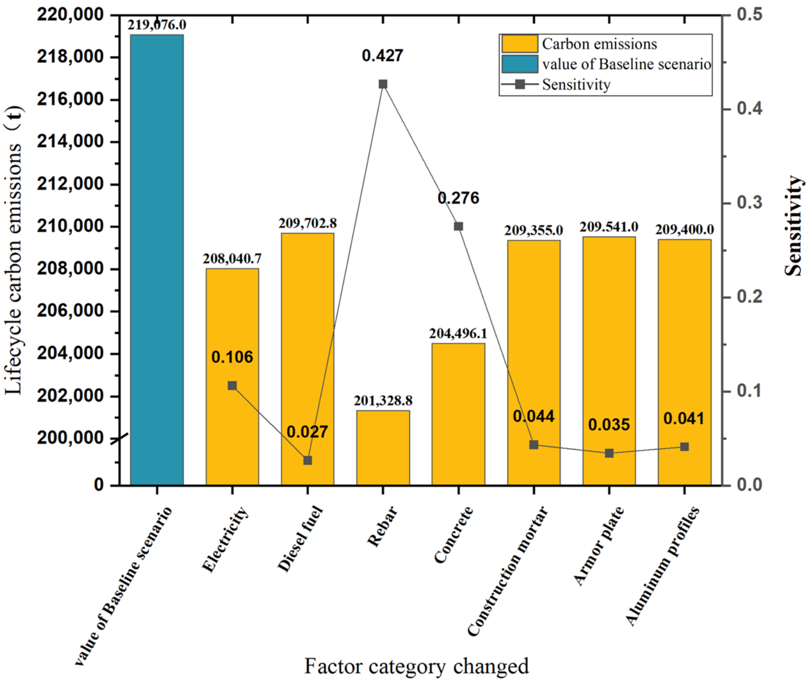
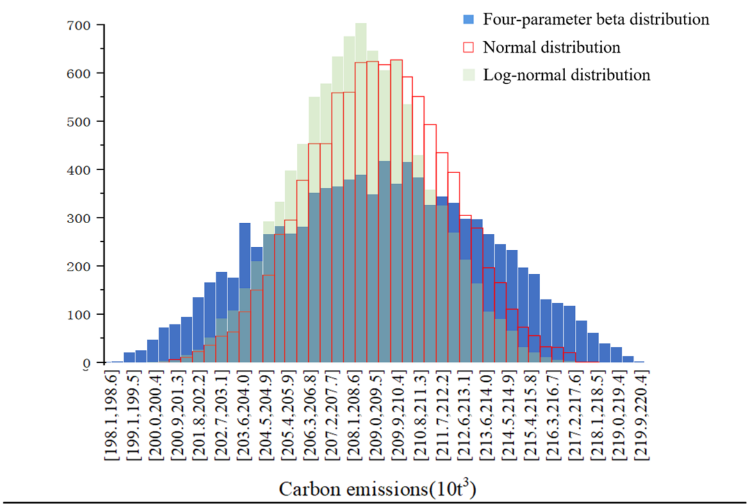


Figure 7. Carbon emission and sensitivity results for Scenario 2.

4.4. Model Uncertainty Analysis

Given that different features characterized each probability distribution form, this study used Scenarios 3 and 4 to analyze the impacts of different distribution forms on the calculation results to reduce the uncertainty due to model assumptions. The four-parameter beta distribution of the baseline scenario was flexible in form and had many parameters. Scenario 3 had a normal distribution, which is most suitable for cases with a small range of uncertainty and symmetry. Scenario 4 had a log-normal distribution with evident asymmetric characteristics, which is suitable for non-negative values with high uncertainty. Figure 8 shows the mean, coefficient of variation, and distribution of the simulated values of CO_2 emissions for each distribution form after the simulation. The sample means in each scenario were close to those of the base scenario, while the dispersions of Scenarios 3 and 4 were smaller. The coefficients of variation were slightly smaller than those of the base scenario, as they were 0.0139, 0.0141, and 0.0617, respectively. Therefore, the mean value of CO_2 emissions calculated with the three different distribution forms of 222,598 t CO_2e could be used as the final calculation result (the coefficient of variation was 0.0299) to reduce the impact of uncertainty brought by different distribution forms.



Distribution form	**Mean**	**Coefficient of variation**	**Range of results**
Four-parameter beta distribution	219,390	0.0617	(−15.97%,16.67%)
Normal distribution	229,149	0.0139	(−5.41%,5.40%)
Log-normal distribution	219,255	0.0141	(−5.39%, 6.34%)

Figure 8. Carbon emissions when using different distribution forms.

An uncertainty analysis of temporal correlations in the model was performed according to Scenarios 5 to 9 to explore the effects of data timeliness on CO_2 emissions. Based on the model described above, the coefficients of the variations in CO_2 emissions when the data quality of the temporal correlations ranged from 1 to 5 were calculated. The coefficients of variation were smaller at values of 5, 4, and 3; that is, they were 0.061, 0.0615, and 0.062, respectively. Meanwhile, the coefficients of variation were larger at values of 1 and 2; that is, they were 0.077 and 0.0764, respectively. The uncertainty in CO_2 emissions was smallest at a value of 5, with high reliability. As the temporal correlation score gradually decreased, the uncertainty slowly increased with a growth rate of 0.87% until the value significantly increased with a growth rate of 23.37% at four points. Therefore, in the subsequent collection of data, data beyond 10 years should be minimized to reduce uncertainty.

5. Discussion

Through the assessment and analysis of the carbon footprint of a case, this study investigated the characteristics of mega sporting events to expand the understanding of their carbon footprints.

Through this case analysis, we hope to put forward suggestions and policies for the reduction of the emissions of mega sporting events and the improvement of data accuracy. In addition to the measures mentioned above, there are some important points that we should address here.

5.1. In the Preparation Stage

The organizer should reduce the construction of new venues. Existing venues can be used or renovated. If a mega sporting event requires a new stadium, the carbon footprint of the preparation phase will be high. Therefore, the cost and benefits should be fully considered when selecting the destination for an event. Reducing the number of new stadiums, using existing venues, or adapting to existing venues can reduce CO_2 emissions. When new stadiums have to be built, measures should be taken to reduce CO_2 emissions. Firstly, a low-carbon performance design should be adopted to ensure that less energy and resources are consumed in the subsequent use of the venue—for example, a reasonable building orientation design and reasonable design of the interior environment. Secondly, low-carbon building materials should be chosen to minimize CO_2 emissions in the production and transportation of building materials. Thirdly, low-carbon management in construction should be strengthened. The introduction of industrialized prefabricated-assembly construction materials and the use of prefabricated concrete, staircases, floors, and other components can reduce CO_2 emissions during the construction process. CO_2 emissions during construction can also be reduced by saving on energy consumption, water consumption, and material consumption and using energy-saving equipment.

5.2. In the Holding Stage

This holding stage is also a phase in which energy consumption and CO_2 emissions are concentrated. Therefore, low-carbon management should be carried out during the holding stage. During the holding stage, there are some measures for energy conservation and emission reduction that can be taken. (1) Clean energy, such as green electricity and solar energy, should be adopted. (2) The catering industry should promote vegetarian food, reduce the packaging of consumables, and give priority to local suppliers. (3) Vehicles that run on clean energy, such as ferries, should be used within the competition area. (4) An intelligent carbon management platform should be set up to monitor, manage, and analyze real-time energy consumption and water consumption for waste classification, HVAC, lighting, sports equipment, and facilities.

5.3. In the Post-Event Stage

The post-event stage also has an impact on the carbon footprint of the event. However, it was not included in the scope of this research. Since this stage involves the demolition of temporary buildings, the reuse of venues, and other situations, the scope of carbon footprint analysis and calculation is difficult to uniformly define. There is not a widely used international method for calculating CO_2 emissions in the post-event stage. In the future, it is necessary to explore relevant carbon footprint calculation methods. Considering the results of the carbon footprint analysis of the Beijing case, we suggest that reasonable post-event usage plans be set up. (1) The event venue can be developed into a place for promoting sports knowledge for the public and providing high-quality sports infrastructure and services. (2) The advantages of the venue can be used, full-season operation modes can be explored, and sporting events and mass entertainment events can be undertaken in various seasons. (3) Cultural heritage can be developed, distinctive cultural brands can be built, full use can be made of explicit and implicit cultural heritage, sports and culture tourism can be planned, the characteristic regional culture can be publicized, and the economic development of surrounding shops can be promoted.

5.4. The Assumptions and Limitations of the Model

The CO_2 emission data from the end stage of mega sporting events depends on the usage of venues after the events. Therefore, when analyzing the Beijing case, referring to the data from the AIJ-LCA, the demolition phase accounted for about 10% of the new construction process. This calculation method was not precise enough.

The COVID-19 pandemic protection policy only permitted locals from Beijing to attend the events, thereby limiting the estimation of CO_2 emissions within the host city. Due to the lack of detailed information, we assumed that there was only one supply distribution center in the host city for the estimation of supply transportation, which may have caused bias in the estimation of CO_2 emissions resulting from supply transportation.

6. Conclusions and Future Work

(1) A quantitative model for assessing the carbon footprint over the entire life cycle of a mega sporting event was built in this study. The model was shown to ensure the accuracy of calculations through an uncertainty analysis, thus improving the precision of carbon footprint research for mega sporting events. This laid the foundation for quantitative low-carbon evaluations of mega sporting events.

(2) This work also proposed a method for quantifying CO_2 emissions from transportation for people and logistics, particularly by obtaining traffic volumes. The estimation was evaluated using model-based and simulation-based methods, including a VISSIM simulation, a support vector, a regression (SVR) model, and an XGBoost model. The proposed method is an optimal solution to the difficulty of collecting and quantifying traffic volumes.

(3) The case study indicated that the preparation stage of a mega sporting event accounts for the highest CO_2 emissions at 92.1%, followed by 7.5% in the holding stage and 0.4% in the end stage. The total life-cycle CO_2 emissions of a sustainable scenario of the mega sporting event in Beijing were 205,080.3 t CO_{2e}, and the per capita CO_2 emissions during the event's holding stage amounted to 0.26 t CO_{2e}/person.

(4) This study adopted a combination of data quality evaluations and Monte Carlo simulations to collect and compare data on typical carbon footprint emission processes and to determine the uncertainty of various data and results. Using scenario analysis, the impacts of system boundaries, parameter selections, probability distribution forms, and temporal correlations on carbon footprint were investigated. Based on an uncertainty analysis of 10,000 sets of Monte Carlo simulation data using this model, it was concluded that the uncertainty caused by the uncertainty in the input parameters was 0.0617, indicating that the uncertainty of the model was low, and the reliability of the results was high.

The quantitative low-carbon evaluation of large-scale sporting events is an important direction for future work. On the one hand, due to the complexity of large-scale sporting events, the principles for each stage are not unified. On the other hand, further improvement is needed to quantitatively calculate the carbon footprints of mega sporting events using the model proposed in this study.

Author Contributions: Conceptualization, H.W.; methodology, H.W. and Y.W.; formal analysis, J.T., H.W., Y.L. (Yao Lu), and C.L. (Chentong Lei); data curation, Y.L. (Yanfeng Li) and J.Z.; writing—original draft preparation, J.T., H.W., and Y.L. (Yao Lu); writing—review and editing, J.T. and H.W.; visualization, J.T. and C.L. (Chong Li). All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by National Key Research and Development Program, grant number 2020YFF0305505.

Data Availability Statement: The authors confirm that the data supporting the findings of this study are available within the article.

Acknowledgments: The authors of this research acknowledge the BEJOC for providing the data.

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

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