

# Sustainability Analytics and Modeling

## An Integrated HMCDM Framework for Assessing the Environmental Sustainability of Sports Mega-Event Host Cities

--Manuscript Draft--

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| <b>Abstract:</b>                                     | <p>Sports mega-events exert considerable environmental effects via emissions associated with transportation, energy, water usage, and waste creation. Nevertheless, there is very little scientific literature on this topic that utilizes a forward-looking perspective and a consistent evaluation tool for assessing the environmental sustainability of potential host cities before assigning them the event. This paper presents the Hierarchical Multi-Criteria Decision Making (HMCDM) method to evaluate the environmental sustainability of potential hosts of sports mega-events based on Super Bowl LIX (2025, New Orleans) as the benchmark event.</p> <p>The HMCDM framework consists of five key criteria: transportation emissions, energy use, water use, waste and materials, and grid carbon intensity. To establish weights of the criteria, a hybrid approach involving the Analytic Hierarchy Process (AHP), Entropy Weighting Process (EWP), and TOPSIS was utilized. The proposed method is then tested for both historical and future Super Bowl host cities, as well as for FIFA World Cup tournaments using an Extended HMCDM (E-HMCDM). The findings show that transportation emissions and grid carbon intensity are the two most important criteria contributing to environmental sustainability performance. The proposed framework contributes a systematic and adaptable decision-support tool for evaluating environmental sustainability of sports mega-events to advise host selection and long-term event planning.</p> |

# An Integrated HMCDM Framework for Assessing the Environmental Sustainability of Sports Mega-Event Host Cities

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## Abstract

Sports mega-events exert considerable environmental effects via emissions associated with transportation, energy, water usage, and waste creation. Nevertheless, there is very little scientific literature on this topic that utilizes a forward-looking perspective and a consistent evaluation tool for assessing the environmental sustainability of potential host cities before assigning them the event. This paper presents the Hierarchical Multi-Criteria Decision Making (HMCDM) method to evaluate the environmental sustainability of potential hosts of sports mega-events based on Super Bowl LIX (2025, New Orleans) as the benchmark event.

The HMCDM framework consists of five key criteria: transportation emissions, energy use, water use, waste and materials, and grid carbon intensity. To establish weights of the criteria, a hybrid approach involving the Analytic Hierarchy Process (AHP), Entropy Weighting Process (EWP), and TOPSIS was utilized. The proposed method is then tested for both historical and future Super Bowl host cities, as well as for FIFA World Cup tournaments using an Extended HMCDM (E-HMCDM). The findings show that transportation emissions and grid carbon intensity are the two most important criteria contributing to environmental sustainability performance. The proposed framework contributes a systematic and adaptable decision-support tool for evaluating environmental sustainability of sports mega-events to advise host selection and long-term event planning.

**Keywords:** sports mega-events; environmental sustainability; multi-criteria decision-making (MCDM); Analytic Hierarchy Process (AHP); TOPSIS; environmental footprint assessment; sustainable event planning; host city evaluation; Super Bowl; FIFA World Cup; hierarchical decision modeling; sustainability assessment framework

## 1. Introduction

Sports mega-events, such as the Super Bowl, FIFA World Cup, and Olympic Games, are considered some of the most resource-intensive short-term events. Often attracting hundreds of thousands of spectators across the world, they not only generate significant economic activity within their host cities but also carry considerable environmental impacts. This includes high levels of greenhouse gas emissions (GHGs), water consumption, as well as food and material waste. As sustainable development becomes a greater topic of conversation among event organizers, governing bodies, and host cities, minimizing these environmental footprints and shifting towards greener operational practices are to become a greater priority as well.

Even still, the current body of knowledge regarding sports mega-events has largely been concentrated on quantifying the environmental footprint of singular events using techniques like carbon accounting and life cycle analysis. Though this is useful to understand the environmental impacts of mega-sporting, this research is often event-specific and tends to be based on past events. Consequently, there is currently a lack of standardized frameworks that can be used to assess the environmental suitability of prospective host cities for mega-sporting events before they are awarded the privilege. Because of this, environmental factors often play little-to-no role in the decision-making process, with economic and logistical feasibility dominating instead.

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To address this, multi-criteria decision-making methods such as the Analytic Hierarchy Process (AHP) and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) have been increasingly adopted in various environmental and urban planning-related fields to evaluate complex systems through both quantitative and qualitative analyses. These methods allow for the synthesis of various criteria into a singular evaluation framework. A similar strategy could be applied to the evaluation of sustainability attributes of prospective host cities.

This study proposes a Hierarchical Multi-Criteria Decision Model (HMCDM) used to measure and compare the sustainability of hosting cities in terms of environmental footprint. Treating Super Bowl LIX (2025, New Orleans) as the baseline case for this research, the quantification of the environmental footprint of the Super Bowl in terms of its various impact domains will be rigorously assessed. This will be done by creating a structured decision-making process incorporating quantitative and qualitative aspects to measure the sustainability of hosting cities. This approach will be applied to a set of past Super Bowl hosting cities to ensure consistency in terms of hosting patterns. In addition, the approach will be extended to prospective hosting cities and tournament contexts, namely, tournament-style events such as the World Cup.

By providing a systematic and adaptable framework for evaluating environmental performance, this study contributes to the growing body of research on sustainable event planning and offers a practical tool for decision-makers seeking to incorporate environmental considerations into host selection processes. Ultimately, the framework represents how integrated, data-driven approaches can stimulate sustainable planning in an era of increasing environmental accountability.

## 2. Literature Review

### 2.1 Sustainability and Environmental Challenges in Sports Mega-Events

Sustainability has increasingly gained importance in the planning and management of sports mega-events over the past few decades. Conventionally, mega sporting events, including Olympic games, FIFA World Cup, and Super Bowl, have been measured in terms of their economic implications, tourism potential, and infrastructure legacies [1]. Nevertheless, the increasing concerns regarding climate change, resource depletion, and environmental degradation have caused scholars to focus more on the environmental implications of mega sporting events [2].

Sports mega-events are extremely environmentally intensive events owing to their high transportation needs, creation of new infrastructure, energy usage, and pollution. According to the current literature, transportation, especially long-distance air transport by fans, players, and staff, is among the leading causes of emission of greenhouse gases in sports mega-events. Dolf and Teehan noted that transportation accounts for the biggest portion of carbon footprint from mega sporting events, calling for transportation-based sustainability solutions in sports management [3]. Indeed, recent studies on mega-event sustainability found that transportation, building, and operation processes of sports venues contribute significantly to carbon emissions and energy consumption [4].

In addition to emissions from transportation, researchers have also brought into focus the environmental implications of the intensive use of resources in managing stadium operations and constructing temporary infrastructures [4]. Sports stadiums consume large amounts of energy and water for lighting, air conditioning, sanitation facilities, and food services; event-related construction, on the other hand, often leaves behind ecological footprints due to the transformation of the land used and embedded carbon emissions [1]. The problem of waste management, specifically that produced by single-use food packaging and food concessions, is another important consideration. Studies done during the Birmingham 2022 Commonwealth Games have shown surprising levels of particulate matter air pollution created not through transportation but through catering services at sports games [5].

With this emerging understanding of the dynamics of sports mega-events, sustainability in sports mega-events is now viewed as a multifaceted challenge that goes beyond carbon accounting [2]. Current studies recognize the interactive relationship between governance, infrastructural development, transportation, and institutional responsibility in determining the long-term environmental sustainability of sporting events [6]. As such, environmental sustainability has gone from being an afterthought to a key factor in event management and evaluation policies.

Though significant advancements have been made within this field due to the increasing amount of literature on environmental impacts, a considerable proportion of such works are still backward looking, specifically pertaining to events already held and assessing the impact thereafter. This poses a restriction in being able to use these conclusions for selecting host cities in advance as well as making sustainable decisions for them. There continues to be a requirement for models to assess the environmental fitness of prospective host cities.

### 2.2 Sustainability Governance and Evaluation Frameworks in Sports Events

To tackle growing environmental problems, several sporting bodies and organizations have implemented various sustainability-related governance models with the aim of better event management. One of the most significant models in this respect is ISO 20121. This model represents an international standard of sustainability management applied to events [7–9]. As such, it includes elements that may be used by organizations in

planning their activities in accordance with the environmental, socio-economic, and other sustainability principles.

The use of sustainable governance models has become widespread after the introduction of various programs that were launched in connection with the London 2012 Olympics. According to literature, sustainability governance models might help in reducing the amount of energy consumed, resources used, and waste produced. In addition, there are suggestions that this type of governance leads to increased accountability. The International Olympic Committee and FIFA are among sporting bodies that have made sustainable development one of the criteria for hosting major sporting events [10,11].

Nevertheless, contemporary sustainability frameworks still suffer from several critical deficiencies. First, most frameworks concentrate on managing operational processes and producing reports after the event, while environmental evaluation before choosing the host city is hardly ever included in any framework. Second, the sustainability programs usually rely on mitigation techniques at the stage of event implementation but provide insufficient means for measuring the environmental efficiency of potential host cities [12]. Finally, academic literature points out contradictions between sustainability rhetoric and observable results achieved by the governing bodies of sports events.

Recently, scholars have stressed the importance of developing consistent sustainability assessment frameworks based on statistical measures. They also highlight the necessity to use quantitative indicators to facilitate environmental evaluation and develop adequate policies [1,2].

### *2.3 Multi-Criteria Decision-Making in Sustainability Assessment*

Growing complexity in evaluating sustainability has played its role in the emergence of such MCDM methods in environmental planning and sustainability studies. As the issues related to sustainability require considering many criteria such as environmental performance, economic viability, governance level, infrastructure, etc., traditional one-indicator evaluation becomes inappropriate in assessing the complex nature of decision-making in sustainability [13,14].

Some of the most popular MCDM methods used today are AHP (the Analytic Hierarchy Process) introduced by Saaty, and TOPSIS (the Technique for Order Preference by Similarity to Ideal Solution) proposed by Hwang and Yoon. AHP is useful when it comes to the determination of the weights of the criteria, and, at the same time, TOPSIS can be used for ranking alternatives. Namely, to rank structural materials in terms of sustainability, to evaluate the sustainability of coastal urban underground space, and to evaluate redevelopment in old residential projects [15–17].

Literature indicates that hybrid MCDM approaches have been successful in various sustainability-related applications, ranging from infrastructure planning, sustainable construction, healthcare evaluations, to environmental management [18–20]. The researchers have also suggested that hybrid methods are superior to simple models in terms of increasing the reliability of analysis since they combine subjective expertise-based weights as well as objective data-based structures [13]. It should be noted that in the existing literature on sustainability assessment, various approaches are used, such as entropy-based weighting techniques and hierarchical analysis approaches [14].

While MCDM has gained significant traction in environmental research, very few scholars apply the approach to the topic of mega-sports events. While many research papers consider environmental impacts of sports events separately or focus on discussing the policies related to the matter at hand, few articles consider combining an evaluation of the environmental footprints with evaluating the cities bidding for the event. Moreover, even fewer studies consider hierarchical weights or comparison analysis when assessing mega-sports events.

### *2.4 Research Gap and Contribution*

The existing literature indicates various shortcomings associated with the environmental evaluation of sports mega-events. Firstly, most environmental impact assessments are retrospective and sport event-specific, concentrating mostly on the calculations of emissions and resource usage following the completion of the sport event. Although these works are useful for estimating the effects of mega-sports events on the environment, they are limited in terms of their applicability in advance when selecting host cities.

Secondly, despite the importance of sustainability governance systems, such as ISO 20121, they lack standardized quantitative metrics for assessing the environmental feasibility of potential host cities before allocating the event. Consequently, the existing sustainability governance systems are more managerial than analytical.

Thirdly, while the Multi-Criteria Decision-Making technique has been widely used in sustainability and infrastructure development research, its application in the field of sustainable sports mega-events is under-developed. Previous research fails to utilize environmental foot printing estimates, hierarchical weight assessment, ranking comparisons, and robustness testing to evaluate the environmental viability of host cities.

The current research attempts to overcome these shortcomings by offering a Hierarchical Multi-Criteria Decision-Making (HMCDM) approach for assessing environmental sustainability of potential host cities for sports mega events. As a basis of the environmental footprint model used in this approach, Super Bowl LIX is chosen, along with the key criteria which include transport emission, energy use in stadiums, water use and solid waste production. Using this model as a base, this research integrates AHP, EWM and TOPSIS methods into a single analytical approach that allows systematic evaluation and prioritization of potential host cities based on their environmental sustainability.

As opposed to previous research which emphasizes retrospective analysis and/or the evaluation of sustainability on the grounds of one indicator only, the offered approach represents a prospective decision-making model. Additionally, due to incorporating robustness and sensitivity analysis, this research enhances the validity of its results as the robustness analysis enables an assessment of the stability of rankings across different weights schemes. Thus, this study makes a theoretical contribution to the burgeoning body of knowledge on sports sustainability in two ways: environmental footprint assessment and HMCDM analysis.

### 3. Materials and Methods

#### 3.1 System Boundary

This study evaluates the environmental impact of sports mega-events within a defined operational system boundary. The analysis includes major short-term sources of environmental impact associated with event execution, specifically:

- Spectator and team transportation (air and ground travel)
- Stadium energy consumption during event operations
- Accommodation-related energy and water use
- Food production and consumption
- Waste generation and disposal

Long-term and indirect impacts, such as stadium construction, infrastructure development, and broadcast production outside the host city, are excluded due to limited data availability and the focus on short-term, event-week impacts. This boundary ensures consistency across host city comparisons while capturing the primary contributors to environmental footprint.

#### 3.2 Data Collection and Assumptions

Data for Super Bowl LIX (2025, New Orleans) and comparative host cities were collected from a combination of publicly available datasets, government reports, and secondary literature. These include transportation statistics, stadium specifications, energy consumption estimates, and environmental performance indicators.

Where direct measurements were unavailable, reasonable assumptions were made based on existing literature and comparable events. These include estimates of average travel distances, modal splits for transportation, per-capita food consumption, and waste generation rates. All assumptions were applied consistently across cities to ensure comparability.

**Assumption 1: Several metrics are generalizable between cities.** All assessed host cities are assumed to have constant hotel electricity costs per room-night, average room occupancy, meal-related GHG intensity, per-attendee waste generation, and stadium event electricity load.

**Justification:** Instead of using city-specific measurements, these figures are based on national benchmarks for lodging and event sustainability. This presumption prevents bias from being introduced by missing or inconsistently reported data and enables consistent comparison across cities.

**Assumption 2: Environmental impacts scale linearly and independently across categories.** The model treats each environmental pathway: Travel, Energy, Water, Waste, and Grid Carbon Intensity as independent, and the overall impacts scale linearly with attendance or activity levels.

**Justification:** This standard assumption in event-sustainability modeling, that per-capita resource intensity remains approximately constant for major athletic events, allows the model to sum impacts at each stage without requiring interaction terms between categories.

**Assumption 3: 2025 Super Bowl ticket sales and attendance patterns are representative of future events.** The analysis assumes that the 2025 Super Bowl's demand, ticket distribution, and overall attendance scale are typical of Super Bowl events.

**Justification:** The most recent and significant is Super Bowl LIX. It represents reasonable standards for the number of spectators at major sporting events.

**Assumption 4: Geographic distance and BTS mode-share statistics approximate actual spectator travel behavior.** There is a location centroid where much of the US population resides, as travel patterns are concentrated around large metro areas. The distance to the U.S. population centroid is estimated using the Haversine distance formula for spectator origins, and BTS distance-band flight-car mode-share curves are used to determine mode choice.

**Justification:** BTS travel-behavior statistics offer a nationally representative and validated relationship between trip distance and the likelihood of choosing air travel over road travel in the absence of ticket-holder origin datasets. When comparing host cities, this method guarantees uniformity and equity.

### 3.3 Hierarchical Multi-Criteria Decision Model (HMCDM)

To evaluate and compare the sustainability performance of host cities, a Hierarchical Multi-Criteria Decision Model (HMCDDM) is developed. The model integrates both quantitative environmental indicators and qualitative measures of infrastructure and policy readiness.

The framework is structured into multiple criteria representing key dimensions of sustainability, including:

- Transportation efficiency
- Energy and emissions profile
- Waste management performance
- Water usage
- Infrastructure and policy factors

Each criterion is then into 25 sub-factors, with 20 being common among all host cities, and 5 being dependent upon geographic factors. This is because the environmental footprints of various host cities differ due to factors like: distance to population centers (affecting air and road travel), local grid carbon intensity (changing stadium and hotel electricity emissions), climate (affecting HVAC energy and water demand), transportation infrastructure (influencing mode choice), and local waste or energy regulations (determining diversion rates and upstream efficiencies). Thus, while the structure of the Super Bowl itself remains constant, its environmental performance is dependent upon a multitude of geographical tendencies. Table 1 shows the 5 criteria along with the corresponding 25 sub-criteria.

**Table 1.** Criteria, Sub-Criteria, and Factors for Super Bowl Host Sustainability Evaluation

| Criteria & Sub-Criteria & Factors                 | Type         | Units/Scale                        | Justification                                                                                                          |
|---------------------------------------------------|--------------|------------------------------------|------------------------------------------------------------------------------------------------------------------------|
| Criterion #1: Travel Emissions                    |              |                                    |                                                                                                                        |
| (a) Total travel CO <sub>2</sub> e (air and road) | Quantitative | kg CO <sub>2</sub> e per spectator | Main contributor to total footprint. Air and road emissions are combined.                                              |
| (b) Distance to population centroid               | Quantitative | miles (mi)                         | Controls the average trip length needed to get to the Super Bowl, and therefore the travel emissions produced.         |
| (c) Flight share by distance band                 | Quantitative | Proportion of trips by air         | BTS mode-share curves show air share rising steeply beyond ~300 miles, strongly affecting total CO <sub>2</sub> e.     |
| (d) Car occupancy ( $\rho$ )                      | Quantitative | Persons per vehicle                | Higher occupancy means lower road emissions.                                                                           |
| (e) Transport infrastructure score**              | Qualitative  | 1–5 (categorical)                  | Airport capacity, transit access, and intercity links dictate the most realist mode split of transport methods.        |
| Criterion #2: Energy Use (Hotels & Stadium)       |              |                                    |                                                                                                                        |
| (a) Hotel electricity per room-night              | Quantitative | kWh/room-night                     | This is the most significant energy component during the event, after travel.                                          |
| (b) Hotel water per room-night                    | Quantitative | gal/room-night                     | Considers the water used in lodging for heating, pumping, etc.                                                         |
| (c) Grid carbon intensity (hotel/stadium)         | Quantitative | kg CO <sub>2</sub> /kWh            | Converts electricity use in hotels and stadium to into CO <sub>2</sub> e to allow for measurement of carbon footprint. |

|    |                                               |              |                                        |                                                                                                                          |
|----|-----------------------------------------------|--------------|----------------------------------------|--------------------------------------------------------------------------------------------------------------------------|
| 1  | (d) Local efficiency factor                   | Quantitative | Dimensionless index                    | Tweaks hotel energy usage up or down based on local energy regulations.                                                  |
| 2  |                                               |              |                                        | Accounts for HVAC, lighting, broadcasting, and other operational loads for the duration of the event.                    |
| 3  | (e) Stadium electricity load                  | Quantitative | MWh per event                          | Longer events and any energy use beforehand would increase the electricity consumption of the stadium.                   |
| 4  |                                               |              |                                        | Local temperature and humidity drive HVAC intensity for both hotels and stadiums.                                        |
| 5  |                                               |              |                                        |                                                                                                                          |
| 6  | (f) Event duration                            | Quantitative | Hours (h)                              |                                                                                                                          |
| 7  |                                               |              |                                        |                                                                                                                          |
| 8  |                                               |              |                                        |                                                                                                                          |
| 9  |                                               |              |                                        |                                                                                                                          |
| 10 | (g) Energy & climate**                        | Qualitative  | 1–5 (climate burden)                   |                                                                                                                          |
| 11 |                                               |              |                                        |                                                                                                                          |
| 12 |                                               |              |                                        |                                                                                                                          |
| 13 | Criterion #3: Water Use                       |              |                                        |                                                                                                                          |
| 14 |                                               |              |                                        |                                                                                                                          |
| 15 | (a) Event water load (stadium)                | Quantitative | gal/event                              | Water demand of restrooms and various concessions stands at the stadium.                                                 |
| 16 |                                               |              |                                        | Water used in meals on the day of the game                                                                               |
| 17 | (b) Meal water footprint                      | Quantitative | L/meal                                 |                                                                                                                          |
| 18 |                                               |              |                                        |                                                                                                                          |
| 19 |                                               |              |                                        | Criterion #4: Waste & Materials (Food & Packaging)                                                                       |
| 20 |                                               |              |                                        |                                                                                                                          |
| 21 | (a) Embedded CO <sub>2</sub> e of meals       | Quantitative | kg CO <sub>2</sub> e/meal              | Cradle-to-grate emissions for typical game-day food offerings.                                                           |
| 22 |                                               |              |                                        | Fraction of prepared food that remains unconsumed. Drives additional disposal and upstream wasted impacts.               |
| 23 | (b) Food waste rate                           | Quantitative | Fraction of food mass                  | Total CO <sub>2</sub> e from production to consumption.                                                                  |
| 24 |                                               |              |                                        | Fraction of total solid waste sent to recycling or compost instead of landfill or incineration facilities.               |
| 25 | (c) Packaging GHG intensity                   | Quantitative | kg CO <sub>2</sub> e/kg packaging      | Land filled waste tonnage is converted into CO <sub>2</sub> e based on methane capture and oxidation.                    |
| 26 |                                               |              |                                        | Total mass of solid waste generated by affiliated people on the day of the game, calculated using waste per capita.      |
| 27 | (d) Diversion rate                            | Quantitative | Fraction diverted                      | City and state mandates for recycling, composting, and reduction of single-use packaging.                                |
| 28 |                                               |              |                                        |                                                                                                                          |
| 29 |                                               |              |                                        |                                                                                                                          |
| 30 |                                               |              |                                        |                                                                                                                          |
| 31 | (e) Landfill GHG factor                       | Quantitative | kg CO <sub>2</sub> e per kg landfilled |                                                                                                                          |
| 32 |                                               |              |                                        |                                                                                                                          |
| 33 | (f) Total waste tonnage                       | Quantitative | tons/event                             |                                                                                                                          |
| 34 |                                               |              |                                        |                                                                                                                          |
| 35 | (g) Local waste regulation score**            | Qualitative  | 1–5 (policy strength)                  |                                                                                                                          |
| 36 |                                               |              |                                        |                                                                                                                          |
| 37 |                                               |              |                                        |                                                                                                                          |
| 38 |                                               |              |                                        |                                                                                                                          |
| 39 |                                               |              |                                        |                                                                                                                          |
| 40 |                                               |              |                                        |                                                                                                                          |
| 41 |                                               |              |                                        |                                                                                                                          |
| 42 |                                               |              |                                        |                                                                                                                          |
| 43 | Criterion #5: Grid Carbon Intensity & Climate |              |                                        |                                                                                                                          |
| 44 |                                               |              |                                        |                                                                                                                          |
| 45 | (a) Grid CO <sub>2</sub> intensity            | Quantitative | kg CO <sub>2</sub> /kWh                | Base emission factor for regional electricity that supplies both stadium and lodging.                                    |
| 46 |                                               |              |                                        | Represents how local climate can increase or decrease heating and cooling demands relative to a temperature baseline.    |
| 47 |                                               |              |                                        |                                                                                                                          |
| 48 | (b) Climate / HVAC burden score**             | Qualitative  | 1–5 (climate burden)                   | Summarizes renewable portfolio standards, efficiency codes, and clean-power mandates that affects the long-run grid mix. |
| 49 |                                               |              |                                        |                                                                                                                          |
| 50 |                                               |              |                                        |                                                                                                                          |
| 51 | (c) Local energy regulations score**          | Qualitative  | 1–5 (policy strength)                  |                                                                                                                          |
| 52 |                                               |              |                                        |                                                                                                                          |
| 53 |                                               |              |                                        |                                                                                                                          |
| 54 |                                               |              |                                        |                                                                                                                          |
| 55 |                                               |              |                                        |                                                                                                                          |
| 56 |                                               |              |                                        |                                                                                                                          |
| 57 |                                               |              |                                        |                                                                                                                          |
| 58 | ** Geography-dependent factors                |              |                                        |                                                                                                                          |

### 3.4 Data Collection and Metric Formulation

## Criterion #1: Travel Emissions

### (a) Total Travel CO<sub>2</sub>e:

Computed using DESNZ aviation emission factors [21] and EPA road CO<sub>2</sub>/mile values [22], applied after distance and mode-share estimation. For each host city  $j$ , the per-spectator travel footprint is

$$CO2_j^{\text{travel}} = \frac{1}{N_j} (N_j^{\text{air}} d_j^{\text{air}} EF^{\text{air}} + N_j^{\text{road}} d_j^{\text{road}} EF^{\text{road}}),$$

Where  $d_j^{\text{air}}$  and  $d_j^{\text{road}}$  are average trip distances by mode and  $EF^{\text{air}}, EF^{\text{road}}$  are mode-specific emission factors.

### (b) Distance to Population Centroid:

Computed using the Haversine formula between each host city and the 2020 U.S. population centroid, using Census

Bureau coordinates [23] and Veness' calculator [24]:

$$d_j = 2R \arcsin \sqrt{\sin^2 \left( \frac{\varphi_j - \varphi_c}{2} \right) + \cos \varphi_j \cos \varphi_c \sin^2 \left( \frac{\lambda_j - \lambda_c}{2} \right)},$$

With  $(\varphi_j, \lambda_j)$  the city coordinates,  $(\varphi_c, \lambda_c)$  the centroid, and  $R$  the Earth radius.

### (c) Flight Share by Distance Band:

Taken from BTS long-distance mode-share datasets, which specify air/road probabilities as a function of trip length [25]. For each city  $j$ , the air share  $p_j^{\text{air}} = f(d_j)$  is read from the BTS curve.

### (d) Car Occupancy:

Uses national average vehicle occupancy rates reported in BTS datasets [25]; this scales road emissions via

$$d_j^{\text{road}} = \frac{VMT_j}{\rho_{\text{car}}},$$

Where  $\rho_{\text{car}}$  is average persons per vehicle.

### (e) Transport Infrastructure\*\*:

Scored qualitatively using airport capacity, transit availability, and intercity connectivity from municipal

transportation reports, on a 1-5 scale.

## Criterion #2: Energy Use

### (a) Hotel Electricity Use:

Per-room-night electricity values sourced from AHLA Responsible Stay and U.S. Green Lodging Trends benchmarks [26]. For city  $j$ , the per-spectator hotel electricity is approximated by

$$E_j^{\text{hotel}} = \frac{N_j^{\text{room}} \cdot CPOR_j^{\text{elec}} \cdot \eta_j^{\text{eff}}}{N_j},$$

where  $CPOR_j^{\text{elec}}$  is the electricity CPOR and  $\eta_j^{\text{eff}}$  a local efficiency factor.

(b) *Hotel Water Use:*

Lodging-sector water-intensity statistics taken from AHLA Responsible Stay datasets [26], treated analogously as  $W_j^{hotel}$  per spectator.

(c) *Grid Carbon Intensity (Hotel/Stadium):*

Regional kg CO<sub>2</sub>/kWh values extracted from EPA eGRID subregional datasets [27]. Electricity-related emissions are

$$CO2_j^{elec} = EF_j^{grid} (E_j^{hotel} + E_j^{stad}),$$

where  $EF_j^{grid}$  is the local grid factor.

(d) *Local Efficiency Factor:*

Regional hotel efficiency indices derived from Responsible Stay benchmarking studies [26], used as the multiplicative modifier  $\eta_j^{eff}$ .

(e) *Stadium Electricity Load:*

Event power demand taken from utility reports such as Entergy data for the Superdome [28] and historical Super Bowl infrastructure analyses [29]. For city  $j$ ,

$$E_j^{stad} = P_j^{stad} \cdot t_j^{event},$$

with  $P_j^{stad}$  the average stadium demand and  $t_j^{event}$  the event duration.

(f) *Event Duration:*

Established from official Super Bowl scheduling and published operational timelines.

(g) *Energy & Climate\*\*:*

HVAC burden estimated using NOAA/ASHRAE climate-zone classifications and international sports-event sustainability guidelines [30–32], and scored from 1-5.

### Criterion #3: Water Use

(a) *Event Water Load:*

Estimated using the standard 3~gal/attendee stadium planning baseline, consistent with municipal water reports (e.g., San Diego [33]):

$$W_j^{event} = \alpha_{water} \cdot N_j,$$

with  $\alpha_{water} \approx 3$  gal/person.

(b) *Meal Water Footprint:*

Embodied blue water for meals based on food LCA studies from international event sustainability plans (Birmingham 2022, Paris 2024) [30–32] Per-spectator meal water is

$$W_j^{meal} = WF_j^{meal} \cdot n_j^{meals},$$

where  $WF_j^{meal}$  is the liters/meal factor and  $n_j^{meals}$  the average number of meals.

### Criterion #4: Waste & Materials

(a) *Embedded CO<sub>2</sub>e of Meals:*

Cradle-to-gate food GHG values taken from international food-LCA databases and event food-procurement guidelines [34]. Total meal emissions per spectator are

$$CO2_j^{meal} = EF_j^{meal} \cdot n_j^{meals}.$$

(b) *Food Waste Rate:*

Based on historical Super Bowl waste audits, including Rush2Recycle documentation reported by WasteDive [29], and treated as a fraction  $f_j^{waste} \in [0,1]$  of prepared food mass.

(c) *Packaging GHG Intensity:*

Packaging CO<sub>2</sub>e factors derived from EPA WARM life-cycle inventory datasets [35]. For a packaging mass  $m_j^{pack}$  per spectator,

$$CO2_j^{pack} = EF^{pack} \cdot m_j^{pack}.$$

(d) *Diversion Rate:*

Obtained from municipal recycling and composting statistics, referenced in Super Bowl waste-management summaries [29], and used as  $r_j^{div}$ .

(e) *Total Tonnage Generated:*

Mass-flow estimates taken from historical Super Bowl waste audits and economic impact reports [36,37]. If  $w^{pp}$  is per-person waste,

$$T_j = \frac{w^{pp} \cdot N_j}{1000},$$

converting to tons.

(f) *Landfill Emissions Factor:*

CO<sub>2</sub>e per kg landfilled sourced from the EPA WARM landfill module [35]; landfill emissions for city  $j$  are

$$CO2_j^{landfill} = (1 - r_j^{div}) \cdot T_j \cdot EF^{landfill}.$$

(g) *Local Waste Regulations\*\*:*

Scored using city recycling mandates, composting requirements, and local packaging rules on a 1--5 scale.

Criterion #5: Grid Carbon Intensity & Climate

(a) *Grid CO<sub>2</sub> /kWh:*

Electricity emission intensities taken directly from EPA eGRID subregional datasets [27]. These govern the conversion from kWh to CO<sub>2</sub>e in the electricity term  $CO2_j^{elec}$  above.

(b) *Climate/HVAC Burden\*\*:*

Scored using NOAA/ASHRAE climate zone data and temperature/humidity profiles influencing building HVAC loads [30-32], on a 1--5 scale.

(c) *Local Energy Regulations\*\**:

Scored using state renewable portfolio standards, utility clean-energy disclosures, and international event-sustainability frameworks [30-32]; higher scores reflect stronger long-run decarbonization policies.

### 3.5 Weighting Method

#### Analytical Hierarchy Process

The AHP method was used to deduce judgement-based weights for the five top-level environmental criteria in our model: Travel Emissions, Grid Carbon Intensity, Energy Use, Water Use, and Waste and Materials. This process is suitable as it allows for the quantification of pre-established judgements regarding the relative importance of each factor. The pairwise comparison matrix utilized was Saaty's 1--9 scale. Refer to table 2.

**Table 2.** Saaty's Fundamental Scale for Pairwise

| Value | Interpretation         |
|-------|------------------------|
| 1     | Equivalent importance  |
| 3     | Slight importance      |
| 5     | Strong importance      |
| 7     | Very strong importance |
| 9     | Extreme importance     |

Based on a preliminary literature review, travel emissions were deemed the most influential factor, then grid carbon intensity, energy, water, and waste. This leads to the following pairwise comparison matrix in which rows and columns followed the ordering in A shown below. The composite model process is shown in Figure 2.

(Travel, Grid CI, Energy, Water, Waste).

$$A = \begin{bmatrix} 1 & 3 & 5 & 6 & 7 \\ \frac{1}{3} & 1 & 3 & 4 & 5 \\ \frac{1}{5} & \frac{1}{3} & 1 & 2 & 3 \\ \frac{1}{6} & \frac{1}{4} & \frac{1}{2} & 1 & 2 \\ \frac{1}{7} & \frac{1}{5} & \frac{1}{3} & \frac{1}{2} & 1 \end{bmatrix}.$$

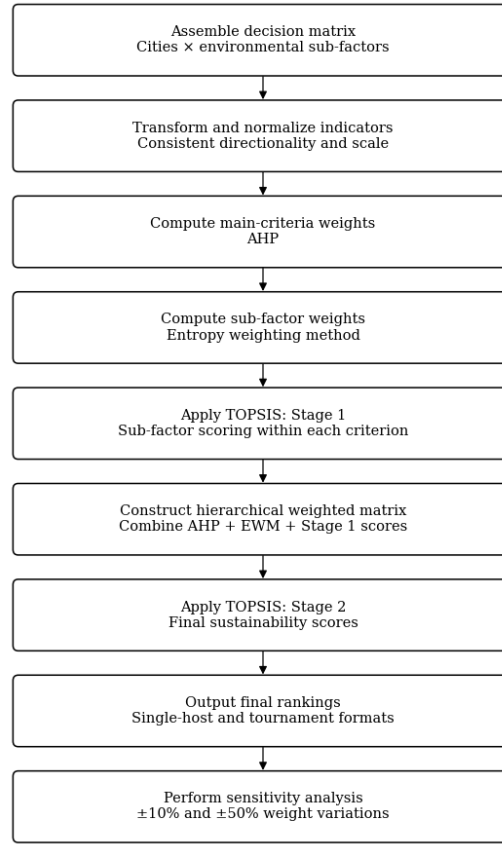


**Figure 1.** Model Creation Workflow

### Deriving the Priority Vector

The principal eigenvector of  $(A)$  gives the normalized criterion weights. A consistency index  $(CI = (\lambda_{max} - n)/(n - 1))$  and consistency ratio  $(CR = CI/RI)$  confirms their reliability. Using  $\lambda_{max} \approx 5.27, n = 5$ , and  $RI = 1.12$ ,  $CR \approx 0.06 < 0.10$ , which is acceptable

$$w^{pHp} = \begin{bmatrix} 0.40 \\ 0.27 \\ 0.16 \\ 0.11 \\ 0.06 \end{bmatrix}$$

### Entropy Weighting

As the AHP is subjective measure when regarded alone, a more objective, data-driven Shannon entropy weighting method was also used. This process compares the amount of useful information in each criterion to its variability among host cities. At the end, criteria which exhibit more variation are assigned greater entropy weights as they contribute more to the larger model. Proportions were computed as  $p_{ij} = r_{ij} / \sum_{i=1}^m r_{ij}$ . Using Shannon's entropy, the entropy value for criterion  $j$  is

$$e_j = -k \sum_{i=1}^m p_{ij} \ln(p_{ij}), \quad k = 1/\ln(m),$$

with the convention  $p_{ij} \ln(p_{ij}) = 0$  when  $p_{ij} = 0$ . The diversification degree is  $d_j = 1 - e_j$ , and the final entropy weights follow by normalization:

$$w_j^{ENT} = d_j / \sum_{j=1}^n d_j.$$

#### Performance Matrix for Entropy Calculation

To compute entropy weights, this performance matrix  $X$  was constructed for all candidate cities against the five top-level criteria:

$$X = \begin{bmatrix} x_{11} & x_{12} & x_{13} & x_{14} & x_{15} \\ x_{21} & x_{22} & x_{23} & x_{24} & x_{25} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ x_{m1} & x_{m2} & x_{m3} & x_{m4} & x_{m5} \end{bmatrix}$$

where the columns correspond to the same metrics as shown previously:

(Travel, Grid CI, Energy, Water, Waste).

Each entry  $x_{ij}$  is obtained from the modelling framework for city  $i$ .

Entropy weighting makes sure that more variable metrics like those with geographic dependency, receive higher weights, while criteria which rarely vary receive lower weights. These objective weights are combined with the AHP weights to form the hybrid weighting process.

#### Hybrid Weighting: Combining AHP and Entropy

As explained previously, this hybrid weighting process leverages the judgement-based importance scores as well as the objectivity of entropy weighting to create a weighting process that is both conceptually significant and quantitatively sound.

Forming a convex combination of the two weights:  $w^{AHP} = (w_1^{AHP}, \dots, w_n^{AHP})$  and  $w^{ENT} = (w_1^{ENT}, \dots, w_n^{ENT})$ .

$$w_j = \alpha w_j^{AHP} + (1 - \alpha) w_j^{ENT}, \quad j = 1, \dots, n,$$

$\alpha \in [0,1]$  controls the balance between judgement and data. Setting  $\alpha = 0.5$  means equivalent importance to both AHP and entropy.

Ergo, the resulting hybrid weight vector is

$$w = \alpha w^{AHP} + (1 - \alpha) w^{ENT},$$

$$w = \begin{bmatrix} 0.5(0.40 + w_1^{ENT}) \\ 0.5(0.27 + w_2^{ENT}) \\ 0.5(0.16 + w_3^{ENT}) \\ 0.5(0.11 + w_4^{ENT}) \\ 0.5(0.06 + w_5^{ENT}) \end{bmatrix}.$$

These weights are normalized since both  $w^{AHP}$  and  $w^{ENT}$  have been normalized beforehand. These final hybrid weights are used in the subsequent TOPSIS procedure to rank sustainability.

## Ranking Method (TOPSIS)

After the hybrid weights  $w$  have been determined, the TOPSIS method is used to rank the candidate host cities. The goal is to select the city that is simultaneously closest to the ideal (best) solution and farthest from the negative (worst) solution in a weighted multi-dimensional space. Let  $X = [x_{ij}]$  be the performance matrix, where  $x_{ij}$  is the value of criterion  $j$  for city  $i$ , with  $i = 1, \dots, m$  and  $j = 1, \dots, n$ .

### Step 1: Vector Normalization

Each column of  $X$  is vector-normalized to obtain  $Y = [y_{ij}]$ , which is dimensionless:

$$y_{ij} = x_{ij} / \sqrt{\sum_{i=1}^m x_{ij}^2}, \quad i = 1, \dots, m, j = 1, \dots, n.$$

### Step 2: Weighted Normalized Matrix

The hybrid weights from before,  $w = (w_1, \dots, w_n)$ , are applied to create the weighted normalized matrix

$$V = [v_{ij}], \text{ where } v_{ij} = w_j y_{ij}.$$

### Step 3: Ideal Best and Ideal Worst Solutions

Since, all criteria are cost-type, the ideal best value for  $j$  is the column minimum and the ideal worst is the column maximum:

$$v_j^+ = \min_i v_{ij} \text{ and } v_j^- = \max_i v_{ij}, \text{ for } j = 1, \dots, n.$$

### Step 4: Separation Measures

For each city  $i$ , the Euclidean distances from the best and worst ideal solutions are

$$S_i^+ = \sqrt{\sum_{j=1}^n (v_{ij} - v_j^+)^2}, \quad S_i^- = \sqrt{\sum_{j=1}^n (v_{ij} - v_j^-)^2}, \quad i = 1, \dots, m.$$

### Step 5: Closeness Coefficient and Ranking

The TOPSIS closeness coefficient for city  $i$  is then

$$C_i = S_i^- / (S_i^+ + S_i^-), \quad i = 1, \dots, m.$$

$C_i \in [0,1]$ ; larger values mean cities closer to the ideal solution.

## Hierarchical Application of TOPSIS

In this model, TOPSIS was not only used at the top level to aggregate main criteria, but also used within each large criteria to aggregate sub-factors into one singular score.

For each main criterion, a local performance matrix  $X^{(g)} = [x_{ij}^{(g)}]$  was created, where  $x_{ij}^{(g)}$  is the value of one of the 25 sub-factors  $j$  within pathway  $g$  for an arbitrary city  $i$ . Using either entropy-based weights or simple judgement-based weights for the sub-factors of  $g$ , the output of the first TOPSIS procedure is a single normalized score  $S_i^{(g)}$  for each city.

In the matrix below, each column represents a major pathway and each row corresponds to a candidate host city.

$$Z = \begin{bmatrix} S_1^{(Travel)} & S_1^{(Grid)} & S_1^{(Energy)} & S_1^{(Water)} & S_1^{(Waste)} \\ S_2^{(Travel)} & S_2^{(Grid)} & S_2^{(Energy)} & S_2^{(Water)} & S_2^{(Waste)} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ S_m^{(Travel)} & S_m^{(Grid)} & S_m^{(Energy)} & S_m^{(Water)} & S_m^{(Waste)} \end{bmatrix},$$

In the second application of TOPSIS, the hybrid weights  $w$  obtained are inputted to produce final closeness coefficients  $C_i$  and therefore, the composite sustainability ranking.

### 3.6 Extension to a Single-Sport Championship Tournament

To extend the HMCDM model from a single Super Bowl host city to a single-sport championship tournament (e.g., a World Cup or continental championship) by treating each match as an individual event and aggregating its impacts across the full tournament. Essentially, the HMCDM model is being applied once to each match and then summed to produce a composite sustainability score for the entire event. This is because single-sport championship tournaments last multiple days (whereas the Super Bowl lasts for several hours) and multiple stadiums are being used simultaneously (whereas the Super Bowl only uses 1).

Notation:

Let:

$j \in \{1, \dots, J\}$  index candidate hosting plans,

$m \in \mathcal{M}_j$  index matches in plan  $j$ ,

$c(j, m)$  denote the host city of match  $m$ ,

$N_{jm}$  be attendance at match  $m$ ,

$N_j = \sum_{m \in \mathcal{M}_j} N_{jm}$  be total attendance in plan  $j$ ,

$w_{jm} = N_{jm}/N_j$  be the attendance share of match  $m$ .

For each match we compute leaf-level factor values

$$f_i(j, m), \quad i = 1, \dots, I,$$

where  $i$  indexes detailed factors (e.g., travel  $CO_2e$ , diversion rate, grid  $CO_2/kWh$ ).

#### Tournament-Level Aggregation

Each hosting plan  $j$  produces a tournament-level factor value  $x_{ij}$  from its match-level quantities.

#### 1. Extensive (additive) factors

For totals such as  $CO_2e$ , energy, water, or waste, we first compute the tournament total

$$F_i(j) = \sum_{m \in \mathcal{M}_j} f_i(j, m),$$

and then normalize per spectator via

$$x_{ij} = F_i(j)/N_j.$$

Thus  $x_{ij}$  represents the per-attendee tournament footprint for factor  $i$ .

## 2. Intensive (average) factors

For factors naturally expressed as averages (e.g., diversion rate, average distance traveled, flight share, grid intensity), we use the attendance-weighted mean:

$$x_{ij} = \sum_{m \in \mathcal{M}_j} w_{jm} f_i(j, m).$$

Here each match contributes according to its share of total attendance,  $w_{jm} = N_{jm}/N_j$ .

## Additional Data Requirements for Multi-Match Tournament Modelling

As this E-HCMDM involves many more days, matches, and ranked events, the model also inherently requires mode data. The new or modified metrics are shown below, grouped according to the five major criteria from before.

### Criterion #1: Travel Emissions

#### (a) Total Travel CO<sub>2</sub>e:

Total travel CO<sub>2</sub>e is taken from international transport and mobility benchmarking sources, specifically the International Energy Agency and the International Civil Aviation Organization [38,39].

$$\text{CO2}_j^{\text{travel}} = \frac{1}{N_j} (N_j^{\text{air}} d_j^{\text{air}} \text{EF}^{\text{air}} + N_j^{\text{road}} d_j^{\text{road}} \text{EF}^{\text{road}}),$$

Where  $d_j^{\text{air}}$  and  $d_j^{\text{road}}$  are average trip distances by mode and  $\text{EF}^{\text{air}}, \text{EF}^{\text{road}}$  are mode-specific emission factors.

#### (b) Distance to Population Centroid:

Distance to the population centroid is informed by FIFA reporting on host-city geography and travel patterns from the 2014 Brazil World Cup [40].

$$d_j = 2R \arcsin \sqrt{\sin^2 \left( \frac{\varphi_j - \varphi_c}{2} \right) + \cos \varphi_j \cos \varphi_c \sin^2 \left( \frac{\lambda_j - \lambda_c}{2} \right)},$$

With  $(\varphi_j, \lambda_j)$  the city coordinates,  $(\varphi_c, \lambda_c)$  the centroid, and  $R$  the Earth radius.

#### (c) Flight Share by Distance Band:

Flight share as a function of trip distance is based on official FIFA host-city documentation for World Cup tournaments [41]. For each city  $j$ , the air share  $p_j^{\text{air}} = f(d_j)$  is read from the BTS curve.

#### (d) Car Occupancy:

Car occupancy is estimated using the Bureau of Transportation datasets [42]. This scales road emissions via

$$d_j^{\text{road}} = \frac{\text{VMT}_j}{\rho_{\text{car}}},$$

Where  $\rho_{\text{car}}$  is average persons per vehicle.

(e) *Transport Infrastructure\*\**:

Taken from the World Economic Forum's transport infrastructure and mobility reporting [43].

(f) *Average matches attended per fan (NEW)*:

Spectators are assumed to attend multiple matches within a tournament. A constant value of 3 matches per spectator is used to scale travel emissions, consistent with tournament attendance patterns reported by Data Appeal [44].

(g) *Number of host cities/stadiums (NEW)*:

The number of host cities and stadiums is taken from FIFA stadium technical documentation [45].

## Criterion #2: Energy Use

(a) *Hotel Electricity Use*:

Local efficiency factors are on Sustainable Hospitality Alliance Hotel Energy Benchmarks [46]. For city  $j$ , the per-spectator hotel electricity is approximated by

$$E_j^{\text{hotel}} = \frac{N_j^{\text{room}} \cdot \text{CPOR}_j^{\text{elec}} \cdot \eta_j^{\text{eff}}}{N_j},$$

where  $\text{CPOR}_j^{\text{elec}}$  is the electricity CPOR and  $\eta_j^{\text{eff}}$  a local efficiency factor.

(b) *Hotel Water Use*:

Hotel water consumption is based on Sustainable Hospitality Alliance Hotel Water Benchmarks [47], treated analogously as  $W_j^{\text{hotel}}$  per spectator.

(c) *Grid Carbon Intensity (Hotel/Stadium)*:

Grid carbon intensity values are based UEFA and ITP benchmarks [46,48]. Electricity-related emissions are

$$\text{CO}_2^{\text{elec}} = \text{EF}_j^{\text{grid}} (E_j^{\text{hotel}} + E_j^{\text{stad}}),$$

where  $\text{EF}_j^{\text{grid}}$  is the local grid factor.

(d) *Local Efficiency Factor*:

Local efficiency factors are based on UEFA stadium energy-use reporting and related venue efficiency benchmarks [49].

(e) *Average stadium capacity (NEW)*:

Average stadium capacity is taken FIFA technical sheets [45].

(f) *Match-level stadium electricity  $E^{\text{stad}}(j, m)$  (MWh)*:

Stadium electricity use is based on UEFA stadium electricity use data [49]. Total energy use is computed as:

$$E_{\text{tot}}(j) = \sum_m E^{\text{stad}}(j, m) + E^{\text{hotel}}(j)$$

and per attendee energy given by

$$x_{\text{energy}}(j) = E_{\text{tot}}(j)/N_j.$$

(g) *Event Duration:*

Event duration is based on the FIFA venue documentation [45].

### Criterion #3: Water Use

(a) *Match-level stadium water use  $W^{\text{stad}}(j, m)$  (gal):*

Event water load is based on Food and Agriculture Organization (FAO) water-footprint datasets [34]. Total water consumption is:

$$W_{\text{tot}}(j) = \sum_m W^{\text{stad}}(j, m) + W^{\text{hotel}}(j)$$

with per-spectator water footprint:

$$x_{\text{water}}(j) = W_{\text{tot}}(j)/N_j.$$

Values scaled by capacity and country-level baselines.

(b) *Meal Water Footprint:*

Meal water footprint is based on FAO water-footprint guidelines and the Poore and Nemecek study [34,50]. Per-spectator meal water is

$$W_j^{\text{meal}} = WF_j^{\text{meal}} \cdot n_j^{\text{meals}},$$

where  $WF_j^{\text{meal}}$  is the liters/meal factor and  $n_j^{\text{meals}}$  the average number of meals.

(c) *National per-capita water use (NEW):*

National per-capita water use is sourced from World Bank Water Data [51].

### Criterion #4: Waste & Materials

(a) *Embedded CO<sub>2</sub>e of Meals:*

Embedded CO<sub>2</sub>e of meals is based on the Poore and Nemecek study [50]. Total meal emissions per spectator are

$$\text{CO}_2_j^{\text{meal}} = \text{EF}_j^{\text{meal}} \cdot n_j^{\text{meals}}.$$

(b) *Food Waste Rate:*

Food waste rate is based on EPA WARM packaging and waste datasets [35], and treated as a fraction  $f_j^{\text{waste}} \in [0,1]$  of prepared food mass.

(c) *Packaging GHG Intensity:*

Packaging GHG intensity is based on EPA WARM lifecycle inventory data [35]:

$$\text{CO}_2_j^{\text{pack}} = \text{EF}^{\text{pack}} \cdot m_j^{\text{pack}}.$$

(d) *Diversion rate  $r_{\text{div}}(j, m)$  (0–1):*

Diversion rate is based on FIFA sustainability reporting and waste management benchmarks [29]:

$$x_{diversion}(j) = (\sum_m r_{div}(j, m) T(j, m)) / (\sum_m T(j, m)).$$

$$x_{diversion}(j) = (\sum_m r_{div}(j, m) T(j, m)) / (\sum_m T(j, m)).$$

(e) *Total Tonnage Generated:*

Total solid waste is based on a study by Zafari and Golzary [52].

$$T_j = \frac{w^{\text{pp}} \cdot N_j}{1000},$$

converting to tons.

(f) *Landfill Emissions Factor:*

CO<sub>2</sub>e per kg landfilled sourced from the EPA WARM landfill module [35]; landfill emissions for city  $j$  are

$$\text{CO2}_j^{\text{landfill}} = (1 - r_j^{\text{div}}) \cdot T_j \cdot \text{EF}^{\text{landfill}}.$$

(g) *Local Waste Regulations:*

Local waste regulation score is based on OECD waste policy datasets [53].

(h) *Landfill methane-capture quality* (NEW, 1–5):

Landfill methane capture quality is based on Intergovernmental Panel on Climate Change (IPCC) environmental and infrastructure classification guidelines [54].

### Criterion #5: Grid Carbon Intensity

(a) City-specific grid factor  $EF^{grid}(c(j,m))$  (kg  $CO_2$  /kWh):

Grid CO<sub>2</sub> intensity is based on EPA eGrid data [27]. A weighted average is computed as:

$$x_{grid}(j) = \left( \sum_m E^{stad}(j, m) EF^{grid}(c(j, m)) \right) / \left( \sum_m E^{stad}(j, m) \right).$$

(b) *Climate/HVAC Burden (1–5):*

Climate/HVAC burden is based on ASHRAE climate zone classifications [55].

(c) *Local energy regulations score (1-5):*

Local energy regulations score is based on IRENA renewable energy policy datasets [56].

## 4. Model Application and Results

#### 4.1 Historical Host-City Rankings

Data was collected for all 6 cities, both those who have hosted in the past as well as those scheduled to host soon. The input values used for analysis are seen in Table 3 below.

**Table 3.** Multi-city factor values for HCMDM

| Factor                         | New Orleans | Inglewood | Glendale | Las Vegas | Santa Clara | Atlanta |
|--------------------------------|-------------|-----------|----------|-----------|-------------|---------|
| Criterion #1: Travel Emissions |             |           |          |           |             |         |

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|                                                    |        |        |        |        |        |        |
|----------------------------------------------------|--------|--------|--------|--------|--------|--------|
| Total travel CO <sub>2</sub> e (kg/spectator)      | 107    | 297    | 231    | 254    | 326    | 103    |
| Distance to population centroid (mi)               | 532    | 1474   | 1146   | 1261   | 1619   | 514    |
| Flight share (BTS-based)                           | 0.80   | 0.96   | 0.93   | 0.95   | 0.97   | 0.80   |
| Car occupancy                                      | 1.67   | 1.67   | 1.67   | 1.67   | 1.67   | 1.67   |
| Transport infrastructure score (1–5)               | 3      | 5      | 4      | 5      | 5      | 4      |
| Criterion #2: Energy Use (Hotels & Stadium)        |        |        |        |        |        |        |
| Hotel electricity (kWh/room-night)                 | 20     | 20     | 20     | 20     | 20     | 20     |
| Hotel water (gal/night)                            | 85     | 75     | 80     | 90     | 70     | 82     |
| Grid carbon intensity (kg CO <sub>2</sub> /kWh)    | 0.3659 | 0.2056 | 0.4320 | 0.4320 | 0.2056 | 0.4396 |
| Local efficiency factor                            | 1.10   | 0.92   | 1.08   | 1.05   | 0.90   | 0.98   |
| Stadium electricity load (MWh/event)               | 96     | 96     | 96     | 96     | 96     | 96     |
| Event duration (h)                                 | 8      | 8      | 8      | 8      | 8      | 8      |
| Criterion #3: Water Use                            |        |        |        |        |        |        |
| Event water load (gal/event)                       | 220000 | 195000 | 205000 | 230000 | 190000 | 215000 |
| Meal water footprint (L/meal)                      | 1450   | 1350   | 1500   | 1550   | 1300   | 1450   |
| Criterion #4: Waste & Materials (Food & Packaging) |        |        |        |        |        |        |
| Embedded CO <sub>2</sub> e of meals (kg/meal)      | 3.5    | 3.5    | 3.5    | 3.5    | 3.5    | 3.5    |
| Food waste rate                                    | 0.5    | 0.5    | 0.5    | 0.5    | 0.5    | 0.5    |
| Packaging GHG intensity (kg CO <sub>2</sub> e/kg)  | 2.0    | 2.0    | 2.0    | 2.0    | 2.0    | 2.0    |
| Diversion rate                                     | 0.12   | 0.55   | 0.30   | 0.50   | 0.60   | 0.35   |
| Landfill GHG factor (kg CO <sub>2</sub> e/kg)      | 1.1    | 1.1    | 1.1    | 1.1    | 1.1    | 1.1    |
| Total tonnage generated                            | 40     | 40     | 40     | 40     | 40     | 40     |
| Local waste regulation score (1–5)                 | 1      | 5      | 3      | 4      | 5      | 3      |
| Grid Carbon Intensity & Climate                    |        |        |        |        |        |        |
| Grid CO <sub>2</sub> intensity (kg/kWh)            | 0.3659 | 0.2056 | 0.4320 | 0.4320 | 0.2056 | 0.4396 |

|                                              |   |   |   |   |   |   |
|----------------------------------------------|---|---|---|---|---|---|
| Climate/HVAC<br>burden score (1–<br>5)       | 4 | 2 | 3 | 2 | 2 | 3 |
| Local energy re-<br>gulations score<br>(1–5) | 1 | 5 | 3 | 2 | 5 | 2 |

The values listed in Table 3 represent variation in relation to the five major criteria regarding the environment used in the proposed framework, namely, travel emissions, energy consumption, water consumption, waste/materials, and carbon intensity of the electricity grid. These criteria were standardized and then analyzed using the proposed methodology of hybrid AHP-Entropy and hierarchical TOPSIS method discussed earlier. This analysis was done using computer programming code written in Python which is detailed in **Appendix A**.

The composite sustainability rankings generated after utilizing the HMCDM methodology are depicted in Figure 3 below.

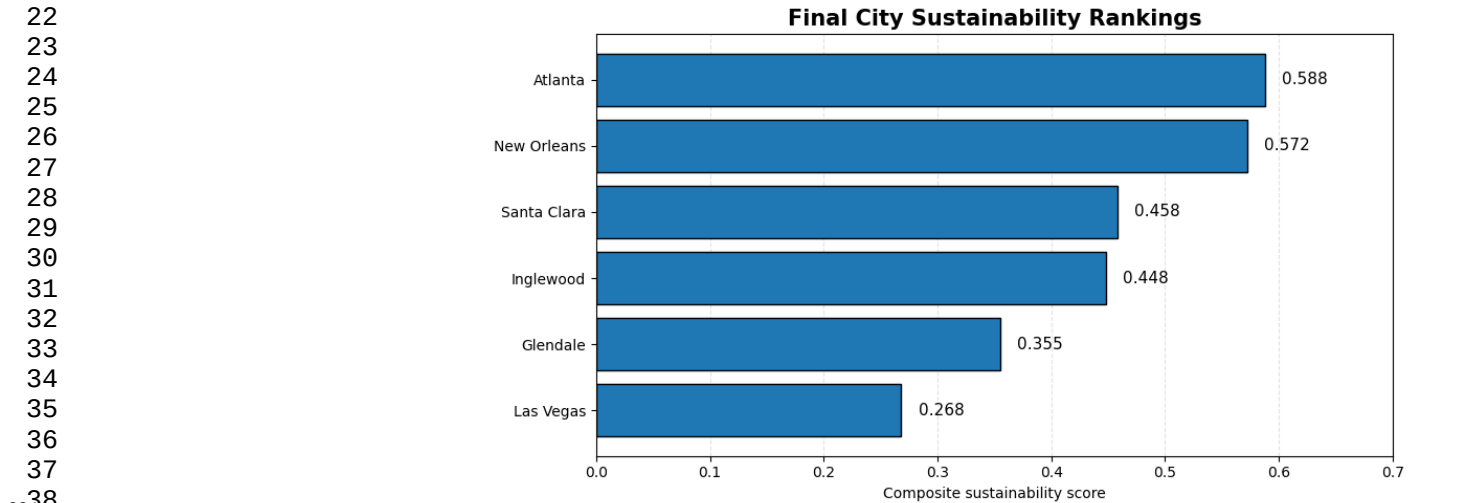


**Figure 2.** Final City Sustainability Rankings

According to Figure 3 above, Atlanta scored highest in terms of composite sustainability (0.588), followed closely by New Orleans (0.572); meanwhile, Las Vegas (0.268) scored lowest among all cities considered. There were significant differences between cities, especially in relation to measures for transportation and regional electricity carbon intensity.

#### 4.2 First-Time Host City Analysis

The HMCDM technique was then used on three potential first-time hosts of the Super Bowl: Seattle, Kansas City, and Nashville. These cities were chosen because of their different geographical locations and different regional energy/environmental policies.

Table 4 presents the values used as inputs for the candidate cities.

**Table 4.** Additional host city factor values: Seattle, Kansas City, Nashville

| Factor                         | Seattle | Kansas City | Nashville |
|--------------------------------|---------|-------------|-----------|
| Criterion #1: Travel Emissions |         |             |           |

|                                                    |        |        |        |
|----------------------------------------------------|--------|--------|--------|
| Total travel CO <sub>2</sub> e (kg/spectator)      | 327    | 45     | 79     |
| Distance to population centroid (mi)               | 1625   | 225    | 395    |
| Flight share (BTS-based)                           | 0.97   | 0.45   | 0.70   |
| Car occupancy                                      | 1.67   | 1.67   | 1.67   |
| Transport infrastructure score (1–5)               | 4      | 3      | 4      |
| Criterion #2: Energy Use (Hotels & Stadium)        |        |        |        |
| Hotel electricity (kWh/room-night)                 | 18     | 20     | 21     |
| Hotel water (gal/night)                            | 75     | 80     | 85     |
| Grid carbon intensity (kg CO <sub>2</sub> /kWh)    | 0.0910 | 0.7090 | 0.6170 |
| Local efficiency factor                            | 0.90   | 1.00   | 1.05   |
| Stadium electricity load (MWh/event)               | 96     | 96     | 96     |
| Event duration (h)                                 | 8      | 8      | 8      |
| Criterion #3: Water Use                            |        |        |        |
| Event water load (gal/event)                       | 195000 | 210000 | 225000 |
| Meal water footprint (L/meal)                      | 1300   | 1450   | 1550   |
| Criterion #4: Waste & Materials (Food & Packaging) |        |        |        |
| Embedded CO <sub>2</sub> e of meals (kg/meal)      | 3.5    | 3.5    | 3.5    |
| Food waste rate                                    | 0.5    | 0.5    | 0.5    |
| Packaging GHG intensity (kg/kg)                    | 2.0    | 2.0    | 2.0    |
| Diversion rate                                     | 0.58   | 0.34   | 0.28   |
| Landfill GHG factor (kg/kg)                        | 1.1    | 1.1    | 1.1    |
| Total tonnage generated                            | 40     | 40     | 40     |
| Local waste regulation score (1–5)                 | 4      | 3      | 2      |
| Criterion #5: Grid Carbon Intensity & Climate      |        |        |        |
| Grid CO <sub>2</sub> intensity (kg/kWh)            | 0.0910 | 0.7090 | 0.6170 |
| Climate/HVAC burden score (1–5)                    | 2      | 3      | 3      |
| Local energy regulations score (1–5)               | 5      | 1      | 2      |

Using the same normalization, weighting, and hierarchical TOPSIS procedures described previously, composite sustainability rankings were generated for each candidate city.

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**Regional Benchmark: Seattle, Kansas City, Nashville**

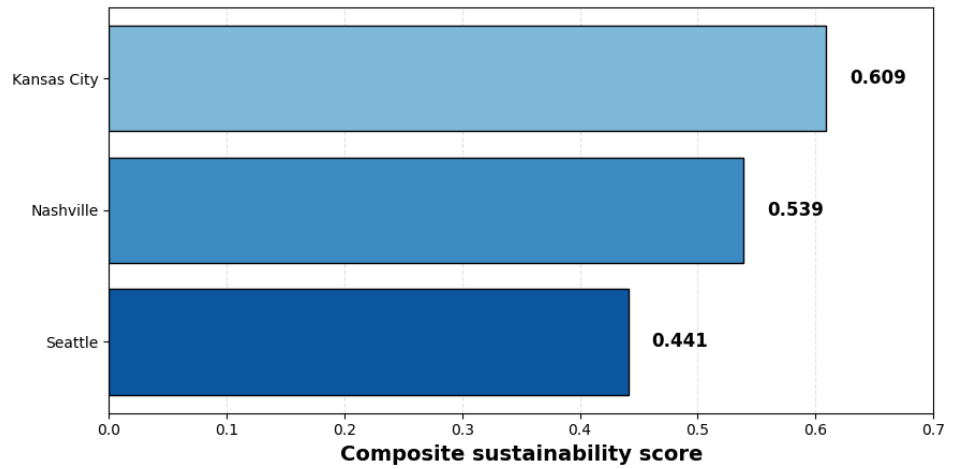


**Figure 3.** HMCDM Output for Seattle, Kansas City, and Nashville

Figure 4 shows that Kansas City achieved the highest sustainability score (0.609) among the evaluated first-time host cities, followed by Nashville (0.539) and Seattle (0.441). Despite Seattle exhibiting strong environmental performance in categories related to electricity carbon intensity and energy regulation, its geographic isolation substantially increased estimated transportation emissions, lowering its overall ranking.

#### 4.3 World Cup Extension Results

To test the scalability of the new approach, the HMCDM framework was further modified by incorporating the E-HMCDM model that was then applied to the selection of hosts for the FIFA World Cup.

The environmental parameters considered at the tournament level in this extended framework are provided in Table 5 below.

**Table 5.** Combined factor values for FIFA World Cup hosts (Germany, South Africa, Brazil, Russia, Qatar)

| Factor                                        | Germany | South Africa | Brazil | Russia | Qatar |
|-----------------------------------------------|---------|--------------|--------|--------|-------|
| Criterion #1: Travel Emissions                |         |              |        |        |       |
| Total travel CO <sub>2</sub> e (kg/spectator) | 150     | 450          | 380    | 320    | 400   |
| Distance to population centroid (mi)          | 900     | 4600         | 3500   | 3200   | 3900  |
| (c) Flight share (long-haul fraction)         | 0.60    | 0.90         | 0.80   | 0.75   | 0.95  |
| (d) Car occupancy (persons/vehicle)           | 2.0     | 2.2          | 2.0    | 2.0    | 2.2   |
| Transport infrastructure score (1–5)          | 5       | 3            | 3      | 3      | 4     |
| Average matches attended per fan (NEW)        | 3       | 3            | 3      | 3      | 3     |

| Number of host cities / stadiums<br>(NEW)            | 12/12  | 9/10   | 12/12  | 11/12  | 5/8    |
|------------------------------------------------------|--------|--------|--------|--------|--------|
| Criterion #2: Energy Use (Hotels & Stadium)          |        |        |        |        |        |
| Hotel electricity (kWh/room-night)                   | 18     | 16     | 18     | 22     | 26     |
| Hotel water (gal/night)                              | 70     | 60     | 65     | 75     | 90     |
| (c) Grid carbon intensity (kg CO <sub>2</sub> /kWh)  | 0.551  | 0.957  | 0.135  | 0.367  | 0.503  |
| (d) Local efficiency factor                          | 0.95   | 0.80   | 0.85   | 0.90   | 0.88   |
| Average stadium capacity (NEW)                       | 53592  | 49670  | 53592  | 47371  | 53191  |
| (f) Stadium electricity load (MWh/event)             | 16.1   | 14.9   | 16.1   | 14.2   | 16.0   |
| (g) Event duration (h)                               | 2      | 2      | 2      | 2      | 2      |
| Criterion #3: Water Use                              |        |        |        |        |        |
| (a) Event water load (gal/event)                     | 160776 | 149010 | 160776 | 142113 | 159573 |
| (b) Meal water footprint (L/meal)                    | 1200   | 1500   | 1400   | 1300   | 1600   |
| (c) National per-capita water use (L/day, NEW)       | 130    | 110    | 150    | 220    | 500    |
| Criterion #4: Waste & Materials (Food & Packaging)   |        |        |        |        |        |
| (a) Embedded CO <sub>2</sub> e of meals (kg/meal)    | 3.0    | 3.8    | 4.0    | 3.7    | 3.5    |
| (b) Food waste rate                                  | 0.40   | 0.50   | 0.50   | 0.45   | 0.50   |
| (c) Packaging GHG intensity (kg CO <sub>2</sub> /kg) | 2.0    | 2.0    | 2.0    | 2.0    | 2.0    |
| (d) Diversion rate                                   | 0.65   | 0.15   | 0.10   | 0.12   | 0.08   |
| (e) Landfill GHG factor (kg CO <sub>2</sub> /kg)     | 1.1    | 1.1    | 1.1    | 1.1    | 1.1    |
| (f) Total solid waste (tons/event)                   | 30.6   | 28.4   | 30.6   | 27.1   | 30.4   |
| (g) Local waste regulation score (1–5)               | 5      | 2      | 2      | 2      | 3      |
| (h) Landfill methane capture quality (NEW)           | 5      | 2      | 2      | 3      | 2      |
| Criterion #5: Grid Carbon Intensity & Climate        |        |        |        |        |        |
| (a) Grid CO <sub>2</sub> intensity (kg/kWh)          | 0.551  | 0.957  | 0.135  | 0.367  | 0.503  |
| (b) Climate/HVAC burden score (1–5)                  | 3      | 4      | 4      | 3      | 5      |

In contrast to the Super Bowl model, where single-host games were analyzed, the E-HMCDM model considers match-level aggregation and weighted tournament calculations based on the number of attendees at different venues and host locations. Other algorithms involved in the extended model are discussed in **Appendix A**.

The rankings generated using the extended model are presented in Figure 6 below.

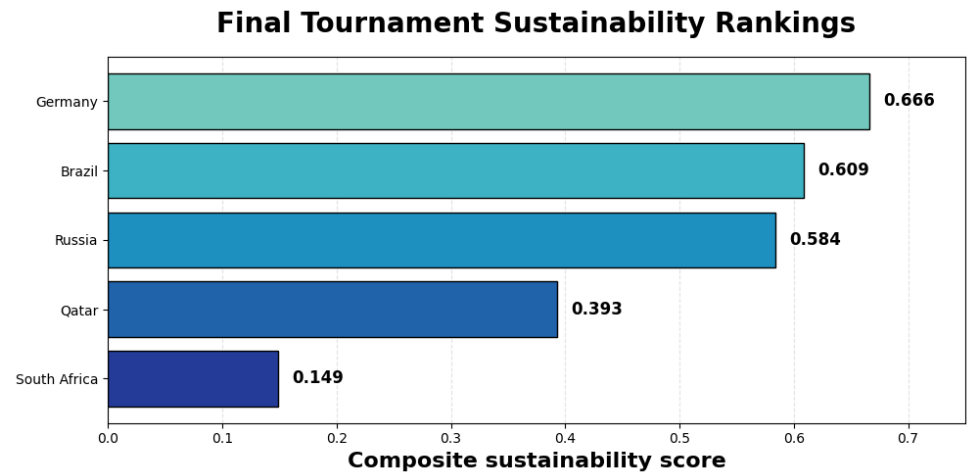


**Figure 4.** World Cup Sustainability Rankings

From the findings, there is clear diversity in terms of the level of environmental sustainability attained in the different host countries for the World Cup. Germany emerges as the country with the highest score (0.666), whereas South Africa (0.149) and Qatar (0.393) have lower scores.

## 5. Robustness Analysis

### 5.1 Sensitivity Analyses for HMCDM

To evaluate the robustness of the HMCDM framework, a sensitivity analysis was conducted by systematically varying the weights assigned to each of the five primary criteria. For each criterion, four perturbations were applied independently: +50%, -50%, +10%, and -10%. Following each adjustment, the remaining weights were proportionally rescaled to preserve their relative importance and ensure normalization (i.e., total weight equal to 1).

This process generated a total of twenty alternative weighting scenarios. For each scenario, the full model was recomputed and resulting rankings were compared against the baseline configuration.

As illustrated in Figure 5, the rankings of previously selected host cities remain highly stable across all perturbations. While minor variations in composite scores are observed, particularly among mid-ranked cities, no significant rank reversals occur. Notably, even under extreme weight adjustments ( $\pm 50\%$ ), the relative ordering of cities remains unchanged.

These results indicate that the model is robust to subjective weighting choices and that overall rankings are primarily driven by underlying performance differences rather than parameter selection.

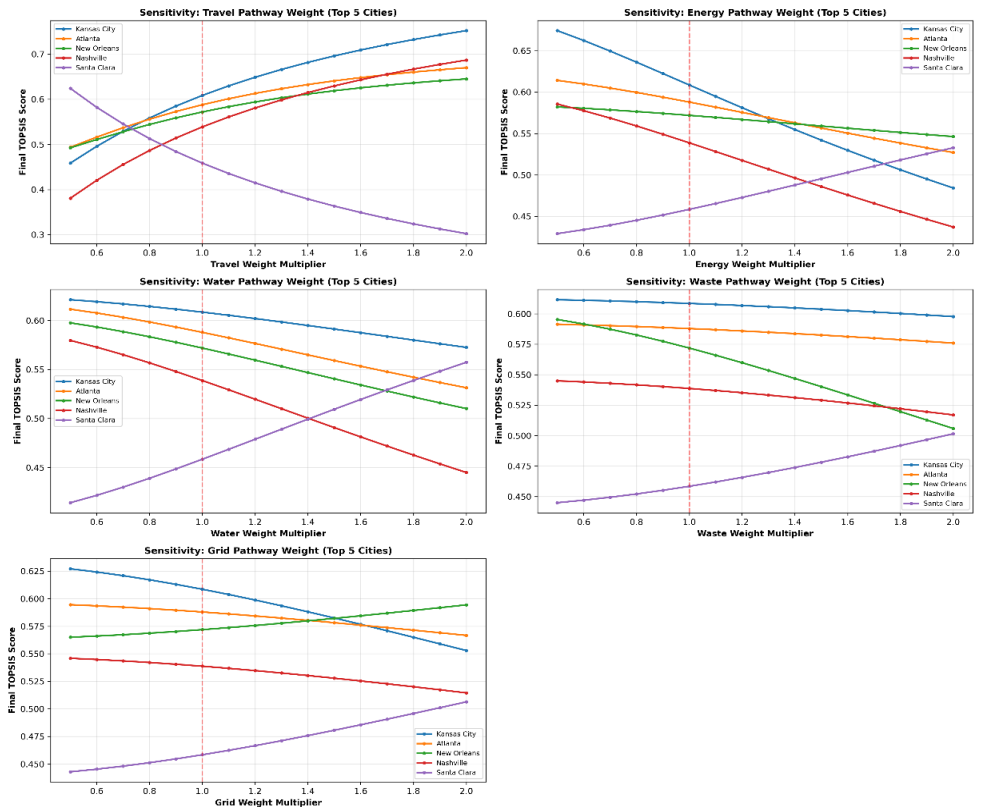


**Figure 1.** Sensitivity Analyses for Previous Host Cities

### Extended Model Sensitivity (E-HCMDM)

The same sensitivity testing procedure was applied to the extended model (E-HCMDM). Across all tested scenarios, the rankings remained invariant despite substantial perturbations in criterion weights. Similar to the HCMDM, as illustrated in Figure 6, the rankings of selected host countries remain largely stable across all manipulations.

This consistency further reinforces the robustness of the modeling framework and suggests that the extended model preserves structural stability under varying assumptions.

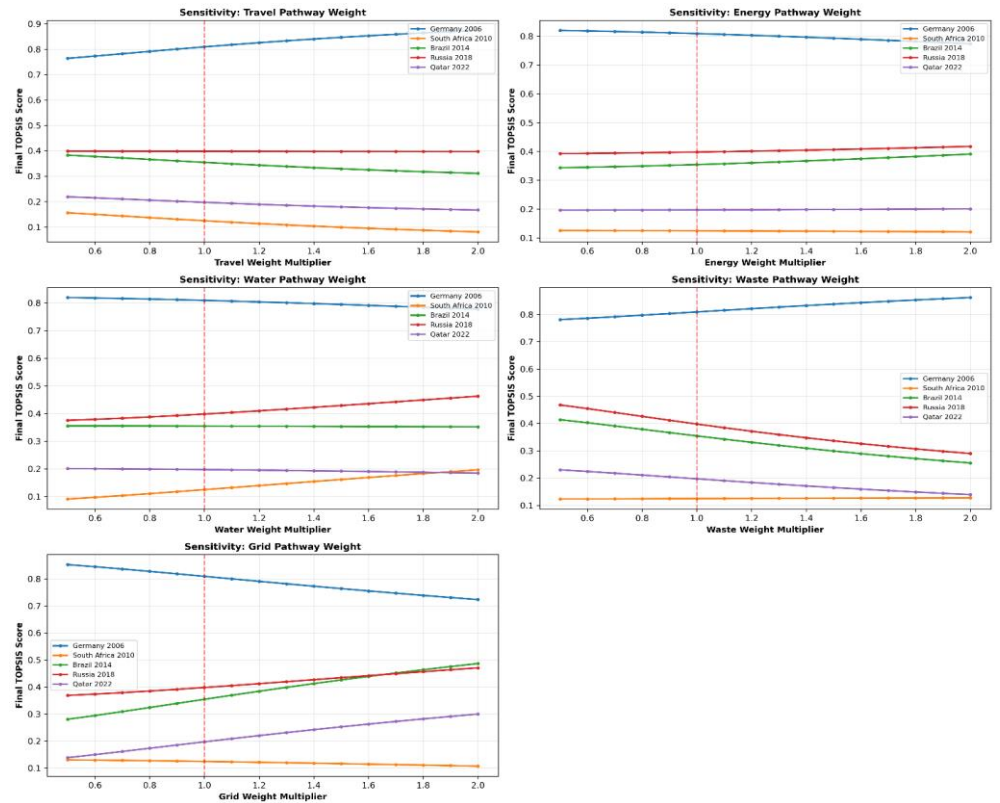


Figure 6. Sensitivity Analyses for E-HCMTM

## 6. Discussion

The present research develops a structured framework for the evaluation of the environmental sustainability of the cities of sports mega-events by integrating a detailed model of environmental footprint and a multi-criteria decision-making method. The results show that the sustainability of a city is not the outcome of a single factor, but the outcome of the interplay between transportation dynamics, regional energy systems, and infrastructure capacity.

### 6.1 Historical Host-City Rankings

The HCMTM analysis showed high variance among host cities of Super Bowl past years and projected host cities of future years for environmental sustainability indicators. The top two cities in terms of sustainability scores were Atlanta and New Orleans, respectively. Las Vegas was the bottom ranked city among the evaluated cities in the study.

The strong environmental sustainability performance shown by Atlanta and New Orleans can be attributed to low levels of emissions related to transportation activities. Both cities have geographical locations closer to the US population centroid and hence, lower transportation distances, thus limiting long-distance air travel. The heavy weight-age given to transportation emissions within the environmental indicator scoring system provided an advantage for the two cities.

Western host cities, including Santa Clara, Inglewood, and Las Vegas, had higher transportation footprints because of their distance from major population clusters. Despite some cities having a better system for waste management and cleaner power supply systems, the environmental cost imposed through spectator transportation could not be balanced out.

It can be inferred from the results that transportation accessibility may contribute significantly towards the sustainability of mega-sporting events compared to just improvements at an operational level alone. Hence, apart from efficiency in terms of environmental policies and venues, geographic accessibility of the event location should also be considered during the hosting process.

## 6.2 First-Time Host City Analysis

The use of the HMCDM model on cities for the first time as candidates revealed the flexibility of the approach even for such cases. Among all the evaluated cities, Kansas City had the highest level of sustainability, followed by Nashville and Seattle.

The high score obtained by Kansas City could be attributed to its geographical location in the middle of the United States, which helped to minimize the levels of spectator transportation emissions. Given that transportation accounted for most of the impact on the environment, it compensated for the relatively high carbon intensity of Kansas City's electricity network.

At the same time, despite being the city that showed the best results in terms of energy and environmental indicators because of a low level of carbon intensity in electricity production, Seattle did not place as high as other cities in transportation because of its relative isolation geographically.

Thus, the results have shown how important factors can influence sustainability in opposite directions and confirmed the applicability of the model for cities without previous experience of hosting mega-sports events.

## 6.3 World Cup Extension Results

The application of the HMCDM model to FIFA World Cup events highlights the scalability of the suggested method from sports competitions involving a single venue to larger-scale tournaments spanning numerous venues in different cities. Compared to the Super Bowl, FIFA World Cup involves longer tournament duration and greater transportation complexity.

Based on the findings from the analysis, Germany emerged as the country performing best regarding overall sustainability. South Africa and Qatar performed relatively poorly, with Germany demonstrating high scores related to transportation infrastructure, waste management and environmental governance. Qatar's poor performance results from higher energy requirements for cooling systems, water consumption and higher carbon intensity of energy sources used.

As shown by the tournament analysis, transportation-based emissions continue playing a key role in determining environmental sustainability of large sports events on a global level. Tournament formats implying significant long-distance travel between host cities caused much greater environmental impacts compared to regionally confined host formats.

More generally, this work shows that environmental sustainability in large sports events depends not only on stadium management practices, but also geographic layout of tournaments and their energy and transportation arrangements.

## 6.4 Robustness and Sensitivity

From the robustness test results, there were clear indications of great stability on the part of the framework across all weighting scenarios tested. The lack of any notable rank reversal even under perturbation of up to  $\pm 50\%$  in individual criterion weightings is an indication that the final ranking is based on performance of the various host cities and not on the choice of parameters used.

This indicates that the final ranking can be considered stable to changes made on the various weights assigned to different criteria. Though some moderate changes in total performance were noted for the middle-ranked cities, it was apparent that top- and bottom-ranking cities remained very stable throughout.

Because this method involves two kinds of weighting – AHP which is subjective in nature and entropy which is more objective – it was important that the framework remain stable to changes.

This same level of stability was witnessed within the extended tournament scale model (E-HMCDM).

### 6.5 Limitations

However, there are several shortcomings associated with the suggested methodological approach that need to be highlighted.

Firstly, the analysis is highly dependent upon secondary datasets and generalized assumptions due to difficulties in obtaining private event-specific data. In particular, spectator origin datasets and real-time transportation data were not available, forcing the researchers to resort to the use of population centroids and national-level transportation statistics.

Also, the model focuses solely on evaluating operational impacts that are relevant to the event's implementation itself. The long-term environmental impacts related to stadium construction, infrastructural growth, and further city development following the event were excluded due to the inconsistency of data availability across host cities.

Furthermore, the analysis made use of several categorical parameters, such as infrastructure quality and environmental policy effectiveness. While these values were calculated based on publicly available datasets, some level of subjectivity remains inevitable.

Finally, the study assumes an approximately linear dependence between event attendance and environmental impact category. While the assumption improves cross-comparisons of host cities, it might be too simplistic for describing some aspects of operational impacts.

Further research might improve the framework with the help of using real-time mobility data, lifecycle assessment, and dynamic modeling of behavioral patterns.

## 7. Conclusion

Hierarchical Multi-Criteria Decision Making framework was created in the current research as an approach to assessing the environmental sustainability of sports mega-event host cities. Through integration of environmental footprint modelling with AHP method, entropy weights estimation and TOPSIS technique, the proposed framework allows performing thorough comparisons of sustainability levels in different candidates in terms of environmental sustainability factors.

The results of research prove transportation emissions and regional electricity carbon intensity to be key factors in terms of sustainability during sports mega-event organization. Hosts located nearer to areas populated by people proved to be better in terms of their sustainability performance because less time is spent on traveling.

Finally, the presented framework was expanded to the case of FIFA World Cup competitions, which suggests its capacity for scaling up and analyzing the environmental sustainability of sports competitions involving numerous cities.

On a higher theoretical level, the use of the hierarchical multi-criteria decision making framework in evaluating environmental sustainability in relation to sports mega-event is consistent with the general trend of increased accountability of such events.

## 8. Future Research

Future research could build upon this study by including other metrics for research and environmental impact, such as infrastructure emissions or urban development and financial sustainability. Longitudinal studies could also be conducted to observe trends in sustainability over multiple events and time periods to better understand trends in mega event planning and sustainability.

Including policy analysis, especially in lower-income or developing nations, could also give insight into institutional barriers and their effects on sustainability. More precise behavioral data, such as actual spectator travel, could be included to further increase the accuracy and precision of this model and eliminate assumptions.

**Supplementary Materials:** Not applicable.

**Author Contributions:** Author Contributions: Conceptualization, C.Y.; methodology, C.Y.; software, C.Y.; validation, C.Y.; formal analysis, C.Y.; investigation, C.Y.; resources, C.Y.; data curation, C.Y.; writing—original draft preparation, C.Y.; writing—review and editing, A.Z.; visualization, C.Y. The author has read and agreed to the published version of the manuscript.

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**Conflicts of Interest:** The author declares no conflicts of interest.

## Abbreviations

The following abbreviations are used in this manuscript:

|                 |                                                     |
|-----------------|-----------------------------------------------------|
| AHP             | Analytic Hierarchy Process                          |
| APC             | Article Processing Charge                           |
| CO <sub>2</sub> | Carbon Dioxide                                      |
| E-HMCDM         | Extended Hierarchical Multi-Criteria Decision Model |
| EPA             | Environmental Protection Agency                     |
| ESG             | Environmental, Social, and Governance               |
| EWM             | Entropy Weighting Method                            |
| FIFA            | Fédération Internationale de Football Association   |
| GHG             | Greenhouse Gas                                      |
| HMCDM           | Hierarchical Multi-Criteria Decision Model          |
| ICAO            | International Civil Aviation Organization           |
| IEA             | International Energy Agency                         |
| IOC             | International Olympic Committee                     |
| ISO             | International Organization for Standardization      |
| MCDM            | Multi-Criteria Decision-Making                      |
| NFL             | National Football League                            |

|        |                                                                |
|--------|----------------------------------------------------------------|
| OECD   | Organisation for Economic Co-operation and Development         |
| TOPSIS | Technique for Order Preference by Similarity to Ideal Solution |
| UEFA   | Union of European Football Associations                        |
| WARM   | Waste Reduction Model                                          |
| WEF    | World Economic Forum                                           |

## Appendix A

### Appendix A.1

All calculations and data processing procedures were conducted in Python using the NumPy, pandas, and matplotlib libraries. Custom scripts were developed to automate AHP weighting calculations, entropy weighting procedures, hierarchical TOPSIS ranking, sensitivity analysis iterations, and sustainability visualization generation.

The computational workflow consisted of five primary stages:

1. sustainability indicator preprocessing
2. normalization and weighting of pathway indicators
3. local pathway evaluation using entropy-weighted TOPSIS
4. top-level hierarchical weighting through hybrid AHP–Entropy integration final city and tournament sustainability ranking generation

Representative excerpts of the computational framework are provided below.

#### AHP Weight Calculation

```
def ahp_weights(pairwise):
    pairwise = np.array(pairwise, dtype=float)
    eigvals, eigvecs = np.linalg.eig(pairwise)

    max_idx = np.argmax(eigvals.real)
    lambda_max = eigvals[max_idx].real

    weights = eigvecs[:, max_idx].real
    weights = weights / weights.sum()

    return weights
```

#### Entropy Weighting Method

```
def entropy_weights(X, is_benefit):
    X = np.array(X, dtype=float)
    m, n = X.shape
    X_norm = np.zeros_like(X)

    for j in range(n):
        col = X[:, j]
        col_min, col_max = col.min(), col.max()

        if is_benefit[j]:
            X_norm[:, j] = (col - col_min) / (col_max - col_min)
```

---

```

1105         else:
1106 1      X_norm[:, j] = (col_max - col) / (col_max - col_min)
1107 2
1108 3      P = X_norm / X_norm.sum(axis=0)
1109 4
1110 5      k = 1.0 / np.log(m)
1111 6      E = -k * np.sum(P * np.log(P + 1e-12), axis=0)
1112 7
1113 8      d = 1 - E
1114 9      weights = d / d.sum()
1115 10
1116 11      return weights
1117 12
1118 13
1119 14      TOPSIS Ranking
1120 15
1121 16      def topsis(X, weights, is_benefit):
1122 17
1123 18      X = np.array(X, dtype=float)
1124 19
1125 20      denom = np.sqrt((X ** 2).sum(axis=0))
1126 21      R = X / denom
1127 22
1128 23      V = R * weights
1129 24
1130 25      v_plus = np.max(V, axis=0)
1131 26      v_minus = np.min(V, axis=0)
1132 27
1133 28      S_plus = np.sqrt(((V - v_plus) ** 2).sum(axis=1))
1134 29      S_minus = np.sqrt(((V - v_minus) ** 2).sum(axis=1))
1135 30
1136 31      C = S_minus / (S_plus + S_minus)
1137 32
1138 33      return C
1139 34
1140 35
1141 36      Hybrid HMCDM Pipeline
1142 37
1143 38      w_ahp_top, CR_top, lambda_max_top = ahp_weights(A_top)
1144 39
1145 40      for name, info in pathways.items():
1146 41
1147 42      X_p = info["X"]
1148 43      is_benefit_p = info["is_benefit"]
1149 44
1150 45      w_ent_p = entropy_weights(X_p, is_benefit_p)
1151 46
1152 47      C_p = topsis(X_p, w_ent_p, is_benefit_p)
1153 48
1154 49      local_scores[name] = C_p
1155 50
1156 51      Z = np.column_stack([local_scores[name] for name in top_order])
1157 52
1158 53      w_ent_top = entropy_weights(Z, np.ones(Z.shape[1], dtype=bool))
1159 54
1160 55
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1162 57
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1164 59
1165 60
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1168 63
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1170 65

```

w\_top\_hybrid = alpha \* w\_ahp\_top + (1 - alpha) \* w\_ent\_top

C\_final = topsis(Z, w\_top\_hybrid, np.ones(Z.shape[1], dtype=bool))

Complete computational scripts, processed datasets, and visualization generation files are available from the corresponding author () upon reasonable request.

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