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A COMPUTATIONAL ENGINEERING FRAMEWORK FOR CARBON FOOTPRINT ASSESSMENT AND SUSTAINABILITY OPTIMIZATION IN LARGE-SCALE ACADEMIC EVENT

Gouthami Eragamreddy^{1*}, Indrajit Pal², Dr. Sriramakavacham Ramacharan³,
Prasun Chakrabarti⁴

^{1*}Assistant Professor, Department of Electrical and Electronics Engineering,
G. Narayanamma Institute of Technology and Science, Hyderabad, India.

e-mail: gouthami.erp@gnits.ac.in, orcid: <https://orcid.org/0000-0002-9961-9238>

²Associate Professor, Disaster Preparedness, Mitigation and Management, Asian Institute
of Technology, Bangkok, Thailand. e-mail: indrajit-pal@ait.ac.th,

orcid: <https://orcid.org/0000-0002-8743-8122>

³Professor, Department of Information Technology, G. Narayanamma Institute of
Technology and Science, Hyderabad, India. e-mail: s.ramacharan@gnits.ac.in,

orcid: <https://orcid.org/0000-0003-1058-2211>

⁴Professor, Department of Computer Science and Engineering, Sir Padampat Singhania
University, Udaipur, India. e-mail: drprasun.cse@gmail.com,

orcid: <https://orcid.org/0000-0001-8062-4144>

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SUMMARY

Problem: Academic events, which require considerable amounts of energy, transportation, catering, water, material usage, and waste generation, lack integrated computational methodologies for assessment and optimization of their ecological footprint. **Approach:** The paper suggests a framework for computational engineering analysis and sustainability optimization of academic events, which involves activity-based modeling of carbon emissions, circular economy principles, IoT-Edge-Cloud sensing and monitoring architecture, and multi-objective optimization. A constrained four-objective problem (minimization of carbon emissions, energy, and waste, maximization of Circularity Index) is solved by MGWO and SPEA2 algorithms, and a Java-based Green Event Planner tool calculates initial, minimized and residual emissions based on activity information and emission factors. 1,000 people scenario is used to compare a conventional setup (Scenario A) with a green event setup (Scenario B). **Results:** In terms of resource performance, the optimized configuration lowered energy use by 4,200 to 2,750 kWh (34.5%), carbon footprinting by 3,250 to 1,780 kg CO₂e (45.2%; from 3.25 to 1.78 kg CO₂e per participant), water use by 30% and solid waste by 37.1%. There was an increase in the share of renewable energy sources from 15% to 40%, the share of materials with recyclable/reusable potential from 22% to 65%, the Circularity Index from 0.35 to 0.68 (+94.3%) and the Sustainability Index Score from 0.47 to 0.82 (+74.5%). Travel interventions can be credited for 48.97% of reductions estimated by the source-wise planner and 81.6% according to the ablation study; this result is consistent with the maximum elasticity coefficient (+0.82) for the transportation category. **Conclusion:** The proposed framework offers a data-based approach for supporting resource-efficient, sustainable and low-carbon oriented decisions about organizing academic events.

Key words: *carbon footprint assessment, academic events, circular economy, multi-objective optimization, modified grey wolf optimizer, spea2, net-zero events.*

INTRODUCTION

Climate change needs immediate attention from all sectors; at the same time, HEIs should act because they develop sustainability through research, educational processes, and management of campus activities [1] [2]. Large-scale events like conferences, symposiums, workshops and academic meetings require a large amount of energy use, travel, catering and material use, thus, emitting greenhouse gases (GHG) [3] [4]. While universities are involved in knowledge generation related to climate change mitigation and circular economy (CE) transition, they also continue using inefficient event management approaches that emit GHG [5] [6][7]. The gap between sustainability leadership of academia and inefficient event organization indicates the importance of rethinking the concept of event management in the context of the SDGs 7, 12 and 13 that are focused on affordable and clean energy, responsible consumption and production, and climate action [8] [9]. CO₂ analysis and action planning on campuses are becoming a common practice in HEIs [10]. Digital technology plays a significant role in making the process of environmental performance transparent and efficient.

Level of evidence from events has proven the potential for reductions. Recent evidence from an event study in Thailand proves that through quantification of the Scope 1, Scope 2 and Scope 3 emissions from travel, energy consumption and waste, and then through offsetting through the Thailand Voluntary Emission Reduction (T-VER) scheme, it was possible to attain carbon neutrality from an academic event at the cost of very little money [11]. Evidence from life-cycle analysis of physical, virtual and hybrid academic conferences proves that participant travel accounts for most emissions, followed by accommodation, food, and venue electricity [3] [4] [12]. On the other hand, CE regulations, data-driven approach, and sustainable technology have increasingly been adopted in low-carbon transition [13] [14].

Monitoring through digital systems and computational optimization are two key enablers in such processes. The integration of sustainability-monitoring systems enables the continuous analysis of carbon footprints in higher education buildings, and machine learning methods enable the easy computation of carbon footprints [15] [16][26]. Mathematical models with carbon constraints and the joint optimization of energy, water and emissions have resulted in positive effects on the environment in construction, power generation and low-carbon energy systems [14] [17] [18]. Optimization techniques such as swarm intelligence, like the Grey Wolf Optimizer (GWO), together with modified versions and evolutionary algorithms like SPEA2, are suitable for such non-linear multi-objective problems [19] [20] [21] [22]. However, these approaches have not been jointly used in temporary multi-domain systems like academic conferences.

In order to fill the above research gap, a computational approach has been designed in this paper and validated based on the information related to a large-scale academic event. The comparison is done between the traditional conference management approaches and the sustainable event arrangement scheme that can be generated using the Modified Grey Wolf Optimizer (MGWO) and the Strength Pareto Evolutionary Algorithm 2 (SPEA2), where changes in energy consumption, carbon emission, water usage, waste generation and material circularity have been quantified [24].

The contributions of the current research include: (i) Design of carbon footprint and sustainability assessment framework; (ii) Incorporation of circular economy with energy, waste, mobility and resource metrics; (iii) Design of constrained multi-objective optimization problem with decision variables, objective function and constraints; (iv) Design of MGWO and SPEA2 for resource optimization for sustainability along with the help of Internet-of-Things, Edge and Cloud enabled monitoring system and the Green Event Planner software, and (v) Performance comparison of traditional and green events using ten metrics with the help of ablation and sensitivity analysis.

The rest of the paper is structured as follows. The review of the literature and research gap identification are covered in Section 2. The proposed methodology with Problem Statement, System Architecture and Mathematical Model, MGWO–SPEA2 algorithm, and Green Event Planner are discussed in Section 3.

Section 4 covers the results, which include software used, dataset, initial parameter values, metric equations, performance evaluation, ablation studies, and sensitivity analysis. Conclusions are provided in Section 5.

LITERATURE SURVEY

Carbon Assessment in Higher Education Institutions

The issue of sustainability assessment and carbon footprint management of HEIs is currently shifting its attention toward issues of energy usage, transportations, waste, water usage and operations of institutions. Kiehle et al. [11] have assessed the carbon footprint of the University of Oulu, while Paredes-Canencio et al. [25] have assessed the carbon footprint of HEIs, whereas Farkas et al. [10] carried out an integrated assessment of campus CO₂ with the development of the action plan. Deda et al. [26] have incorporated both GHG Protocol and ISO 14064 in their assessment together with the hybrid economic approach aimed at estimating Scope 3 emissions, which are frequently overlooked. Moreover, Maulidevi et al. [17] have developed an integrated system for monitoring the carbon footprint of higher education buildings. Basheer et al. [4] identified priorities of stakeholders regarding the issues of energy efficiency and sustainable procurement as the HEIs' sustainability indicators.

Event-Level Sustainability and Circular Economy

Less attention has been paid to the topic of event-level sustainability. Petchchedchoo et al. [13] proved the applicability of carbon-neutral event management through systematic accounting of travel, energy, waste and offset needs. Cavallin Toscani et al. [6] made a comparison between in-person, virtual and hybrid academic conferences, and Aronson et al. [7] revealed 428 kg CO₂e per attendee for a three-day conference in environmental engineering with two-thirds of global warming potential coming from intercity travel. Food consumption is another environmental concern [12]. Resource efficiency, waste reduction, reuse, recycling and inter-organizational cooperation are key aspects of CE research in higher education institutions [5] [6] [7]; Specific indicators have been designed for measuring the CE transformation of universities [25]. Several reviews have shown that the incorporation of CE practices with climate-mitigation actions contributes to achieving carbon neutrality [13]. However, existing studies on events and CE use predefined sustainability criteria and not an optimization approach to event management.

Digital Monitoring and Optimization Approaches

Various digital technologies, such as IoT, smart sensors, edge processing, cloud computing and data analytics, allow constant monitoring of energy, water, mobility and other environmental metrics, supporting sustainable development goals [10][27]. Models for monitoring university buildings and simplified machine learning carbon footprint tools increase the availability of data; however, digital monitoring alone does not provide an optimal allocation of energy, transport, materials or waste management resources, which implies that computational optimization should be incorporated into the process [15] [16]. Optimization methods for carbon and resource management have become increasingly popular, with examples including carbon constraint scheduling, co-optimization of carbon reduction and sequestration in the electricity sector and CE-based co-optimization of energy, water and emissions [14] [17] [18]. Various versions of MGWO have been applied to solving problems with improved exploration and exploitation, while improved versions of SPEA2 have been created for multi-objective optimization [20] [22]. While the research shows the benefits of optimization in environmental decision making, it applies to energy, industrial, construction or infrastructure systems, not to large-scale academic conferences.

Inference and Research Gap

Table 1 presents the capabilities of the examined techniques. It is clear from the literature that there have been advancements in carbon evaluation, circular economy, digital tracking and optimization of the environment; nevertheless, these capabilities are studied separately. There is very little work done in

combining carbon assessment at the event level, CE indicators, IoT-Edge-Cloud based monitoring, and multi-objective optimization in one decision support system for academic events. This work tries to fill this gap.

Table 1. Comparison of existing approaches and the proposed framework

Approach	Carbon Assessment	Circular Economy	Digital Monitoring	Multi-objective Optimization	Event-specific
Campus carbon assessment [8] [9]	Yes	Limited	Limited	No	No
HEI monitoring model [15]	Yes	Moderate	Yes	No	No
Carbon-neutral event study [11]	Yes	Moderate	Limited	No	Yes
CE-based HEI approaches [5] [7]	Moderate	Yes	Limited	Limited	Limited
Energy–water–emission optimization [14]	Yes	Yes	Limited	Yes	No
Carbon-constrained optimization [17]	Yes	Limited	No	Yes	No
Proposed framework	Yes	Yes	IoT–Edge–Cloud enabled	MGWO + SPEA2	Yes

PROPOSED METHODOLOGY

The suggested methodology involves five successive stages: (i) problem statement, event boundaries and sustainability indicators definition; (ii) collection and pre-processing of event activity data via the IoT–Edge–Cloud system (See figures 1–3); (iii) carbon emission modeling on the basis of the activity model and problem statement; (iv) exploration of sustainability-oriented configurations by means of MGWO and SPEA2 (Algorithm 1); and (v) baseline, reduction and residual emission assessment using the Green Event Planner.

Problem Statement

Large academic events organized by higher education institutions entail interlinked requirements related to electricity use, participant transportation, catering, water use, material use, and waste production. Earlier studies on carbon assessment in higher education institutions have established that electricity use, transportation, and institutional processes play a significant role in the emission of greenhouse gases, while event studies have found that the effective management of travel, energy, and waste is key in achieving optimal carbon performance. Yet, traditional event management methodologies typically focus on the assessment of each of these aspects in isolation without adequate support for determining the best combination of sustainable practices.

The engineering problem explored in this paper is thus the quantification of the environmental footprint of an academic event and finding the most feasible combination of resource management practices that can achieve reductions in energy usage, carbon emissions, and waste production along with increased renewable energy use and material recycling. This will require the incorporation of event activity information alongside emission factors, circular economy metrics, resource constraints, and multi-objective optimization. Optimization-related studies have shown that joint consideration of energy, water, emissions, and operational constraints has great potential; yet, their direct application to academic events is scarce.

Consequently, the suggested model considers carbon footprint evaluation, circular economy, digital tracking systems, and optimization using the MGWO/SPEA2 approach to facilitate sustainable event planning. The architecture of the proposed system is illustrated in figure 3, while the decision variables, objectives, and constraints are described.

Overall Flow and System Architecture

The suggested sustainability framework incorporates Open Sustainable Technology (OST), the concepts of the circular economy (CE), digital monitoring, assessment of the carbon footprint and multi-objective optimization to facilitate the planning of large-scale academic events with sustainability in mind. The framework broadens the scope of traditional sustainability evaluation of events by expanding it from the carbon footprint to a data-based decision-making approach for the entire duration of the event.

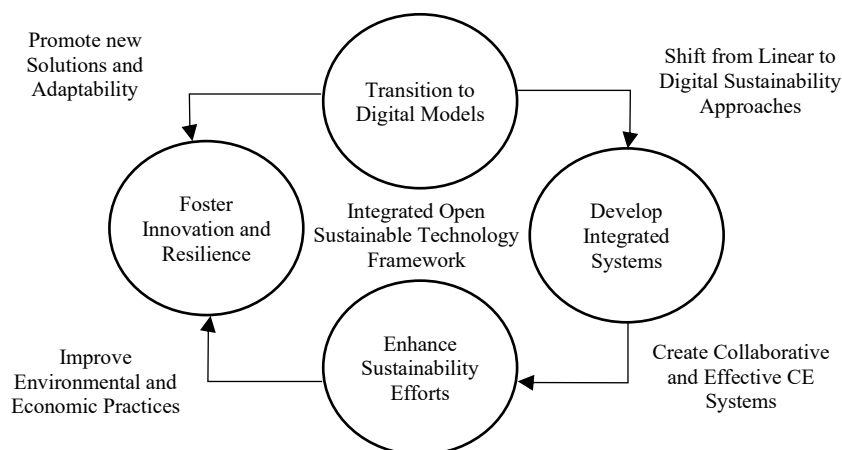


Figure 1. Integrated open sustainable technology (OST) framework

This overall structure is shown in figure 1. It comprises four interrelated steps: (i) digitization of models, (ii) system integration, (iii) sustainable practices improvement, and (iv) innovation and resilience promotion. By linking the event-resource information with digital tracking and sustainability assessment, the structure makes it possible for the framework to assess activities related to energy, transport, water, materials, catering, and waste. The OST approach thus serves as a technological basis for combining the event-related data with the carbon assessment and optimization modules.

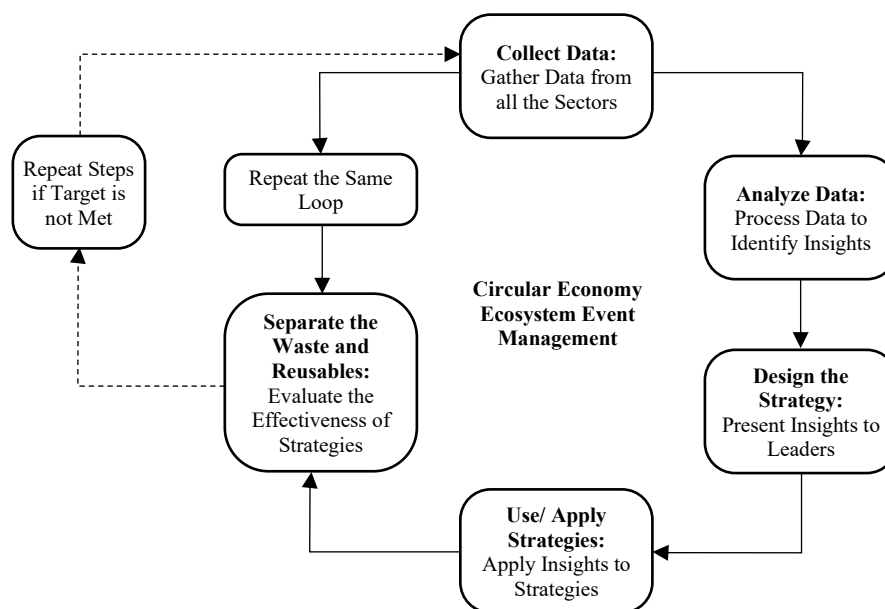


Figure 2. Circular economy ecosystem for event management

The Circular Economy guidelines align with the OST model by limiting material usage and waste generated through the lifecycle of events. The use of the 7R method, which stands for Rethink, Refuse, Reduce, Reuse, Repair, Regift, and Recycle, is utilized during the pre-event planning, event planning, and post-event evaluation phases, as shown in figure 2. The data concerning events are analyzed for ways to limit the use of disposable materials, reuse, and recycle.

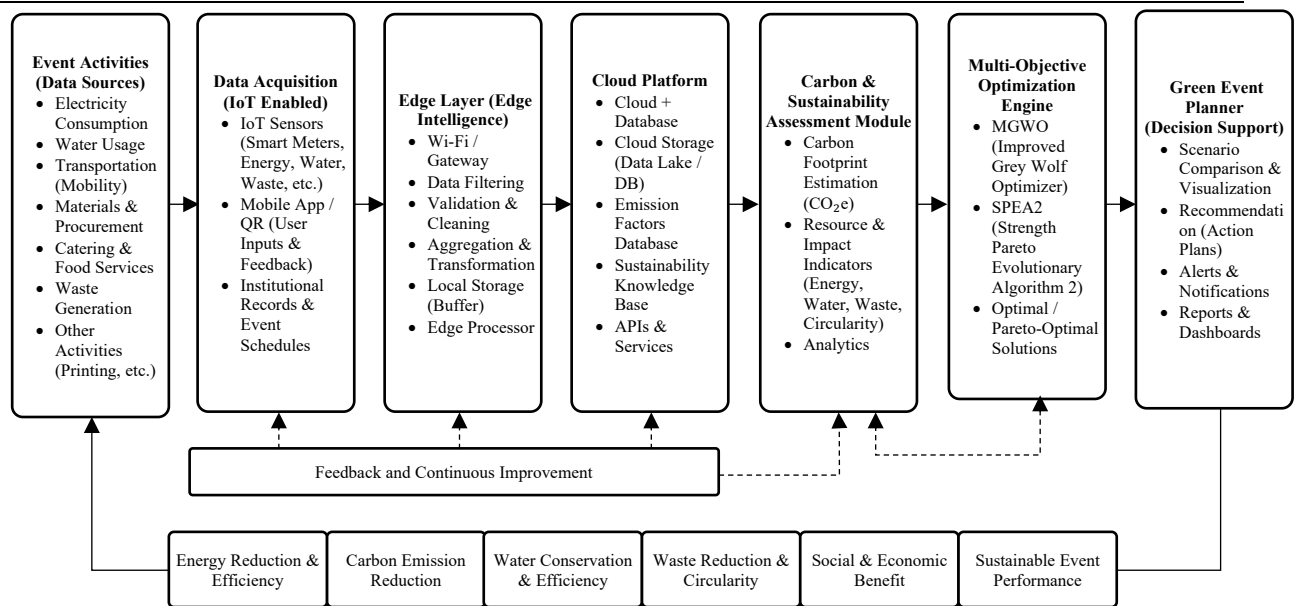


Figure 3. Integrated optimization architecture for sustainable academic event management

To define the engineering data flow, the framework consists of four key functional blocks: data acquisition, edge/pre-processing of data, computational evaluation and optimization, and decision-making. Event activity data concerning electricity, water, transportation, materials, catering, and waste make up the input layer. When implemented in real-time, IoT-driven sensing technology could be used for resource monitoring purposes, while edge computing will filter and aggregate collected data before sending it to the computational platform. The preprocessed event activity data will be then combined with the corresponding emission factors to estimate carbon emissions and sustainability metrics. The generated data will be then fed into the MGWO and SPEA2 optimization frameworks for sustainability-based resource configuration evaluation. Figure 3 illustrates that event activity data concerning electricity, water, transportation, materials, catering, and waste are gathered via institutional databases and IoT sensors. Such data are filtered and aggregated at the edge level and sent to the cloud platform. The resultant indicators are then passed into the MGWO and SPEA2 optimization engines, whose results are conveyed via the Green Event Planner for decision support on sustainability issues. The full description of the carbon emission model along with the optimization goals is given in Section 3.3.

Mathematical Description of the Methodology

Carbon-Emission Model

The suggested framework for calculating the carbon footprint is based on activity data with its specific emission factors. The main activities that have to be taken into account are electricity use, transport of participants, catering, material use, and waste production. The activities are measured in their physical units and then transformed into (CO₂e) equivalents for summing up. It allows one to avoid summation of different kinds of data like energy, material, and transport data.

For an activity i , the associated carbon emission is calculated using equation (1):

$$C_i = A_i * EF_i \quad (1)$$

Where A_i represents the activity data for source i , EF_i is the corresponding emission factor, and C_i is the resulting emission in kg CO₂e. The total carbon footprint of the event is therefore obtained from equation (2):

$$C_{total} = \sum_{i=1}^n A_i EF_i \quad (2)$$

where n denotes the number of emission-generating activities within the defined event boundary. The computational implementation considers electricity consumption, waste generation, catering, and participant transportation as the principal carbon-emission sources. The existing computational model similarly converts electricity, waste, meals, and travel activity into baseline CO_{2e} using activity-specific emission factors.

Resource and Circular-Economy Constraints

These Circular Economy (CE) techniques as discussed in Section 3.2 are reflected in the optimization process by means of material reuse, recycling, renewable energy, and resource use constraints. The 7Rs framework is not explicitly used but is embedded in the mathematical formulation through specific decision variables.

The material reuse and recycling requirements are expressed by equation (3) and (4):

$$\begin{aligned} R_{\text{reuse}} &\geq r_{\text{reuse}} M_{\text{total}} & (3) \\ R_{\text{recycle}} &\geq r_{\text{recycle}} M_{\text{total}} & (4) \end{aligned}$$

where M_{total} is the total material requirement and r_{reuse} and r_{recycle} are the target reuse and recycling fractions. The renewable-energy requirement is similarly represented by equation (5):

$$E_{\text{ren}} \geq r_{\text{ren}} E_{\text{demand}} \quad (5)$$

Where E_{ren} represents renewable-energy contribution and E_{demand} is the total event-energy requirement.

The renewable energy usage in the case of green-event configuration studied here rose from 15% in the baseline event to 40% in the optimized event, whereas the reusable / recyclable material usage rose from 22% to 65%. The figures have been considered as sustainability configurations for the particular event only.

The event-energy balance is constrained by equation (6):

$$E_{\text{grid}} + E_{\text{ren}} \geq E_{\text{demand}} \quad (6)$$

with the operating limits given in equations (7) and (8):

$$0 \leq E_{\text{ren}} \leq E_{\text{ren,max}} \quad (7)$$

$$0 \leq E_{\text{grid}} \leq E_{\text{grid,max}} \quad (8)$$

where E_{grid} is the electricity supplied from the grid and $E_{\text{ren,max}}$ and $E_{\text{grid,max}}$ denote the corresponding available limits.

Multi-Objective Optimization Formulation

The management of event problem contains several environmental goals that can't be taken into account separately. Grid-energy usage reduction influences CO₂ emissions; recycling and waste separation influence waste residuals and circular economy. Thus, the optimization problem is stated as a multi-objective problem.

Decision vector is defined as equation (9):

$$x = [x_E, x_{\text{ren}}, x_{\text{reuse}}, x_{\text{recycle}}, x_w] \quad (9)$$

where x_E represents the energy-use decision, x_{ren} the renewable-energy contribution, x_{reuse} and x_{recycle} the

material reuse and recycling decisions, and x_w the waste-management decision.

The principal objective functions are defined in equations (10)–(13):

$$\min F_1(x) = C_{total}(x) \quad (10)$$

$$\min F_2(x) = E_{total}(x) \quad (11)$$

$$\min F_3(x) = W_{residual}(x) \quad (12)$$

and

$$\max F_4 = CI(x) \quad (13)$$

where C_{total} is the total event carbon footprint, E_{total} is the total energy consumption, $W_{residual}$ is the residual solid waste, and CI is the Circularity Index. The Circularity Index is an index that is used to denote the level at which materials are reused and recycled, thus avoiding the end-of-life process.

The decision variables are subject to the physical and CE constraints defined in equations (3)–(8), together with the normalization bounds in equation (14):

$$0 \leq x_i \leq 1, j = 1, \dots, m \quad (14)$$

where m represents the number of normalized decision variables.

Water use is kept as an extra performance measure for sustainability, not as a separate optimization criterion because the constructed model compares water minimization in both traditional and green event formats.

Algorithm: MGWO–SPEA2-Based Optimization

The Modified Grey Wolf Optimizer (MGWO) and Strength Pareto Evolutionary Algorithm 2 (SPEA2) are applied for exploring the decision space and assessing sustainability configurations. The MGWO is used for providing population-based exploration and exploitation for searching low-impact resource configurations while SPEA2 is suitable for Pareto-based assessment due to the fact that the enhancement of one objective impacts another environmental objective. The use of these two algorithms complements the multi-objective approach and allows comparing alternative solutions by such parameters as carbon emissions, energy consumption, and waste generation.

MGWO search operator. In the grey-wolf hierarchy, the three best solutions (α, β and δ) guide the remaining search agents. For a leader $p \in \{\alpha, \beta, \delta\}$, the encircling behaviour of a candidate solution $X(t)$ at iteration t is modelled by equations (15) and (16), with the coefficient vectors A and C given by equation (17), where r_1 and r_2 are uniformly distributed random vectors in $[0, 1]$. The updated position is the average of the three leader-guided positions, as expressed in equation (18).

$$D_p = |C \cdot X_p(t) - X(t)|, p \in \{\alpha, \beta, \delta\} \quad (15)$$

$$X_k = X_p(t) - A \cdot D_p, k = 1, 2, 3 \quad (16)$$

$$A = 2a \cdot r_1 - a, C = 2 \cdot r_2 \quad (17)$$

$$X(t+1) = \frac{X_1 + X_2 + X_3}{3} \quad (18)$$

In the modified variant adopted here, the control parameter a decreases non-linearly from 2 to 0 according to equation (19), where T_{max} is the maximum number of iterations, so that exploration is maintained for longer in the early iterations and exploitation is intensified towards the end of the search.

$$a(t) = 2 \left[1 - \left(\frac{t}{T_{\max}} \right)^2 \right] \quad (19)$$

SPEA2 fitness assignment. SPEA2 [21] maintains an external archive Q_t of non-dominated solutions. For every individual i in the union of the population P_t and the archive Q_t , the strength $S(i)$ is the number of solutions that i dominates (Equation (20)), and the raw fitness $R(i)$ is the sum of the strengths of its dominators (Equation (21)). A density term based on the distance σ_i^k to the k -th nearest neighbour in objective space, with $k = \sqrt{N + N}$, is added to obtain the final fitness $F(i)$ in equation (22); non-dominated solutions have $F(i) < 1$.

$$S(i) = |\{j \mid j \in P_t \cup Q_t \wedge i \succ j\}| \quad (20)$$

$$R(i) = \sum_{j \in P_t \cup Q_t, j \succ i} S(j) \quad (21)$$

$$F(i) = R(i) + \frac{1}{\sigma_i^k + 2} \quad (22)$$

In the hybrid procedure summarized in Algorithm 1, SPEA2 fitness assignment and environmental selection maintain the Pareto archive, and the three archive members with the lowest $F(i)$ act as the α , β and δ leaders for the MGWO position update. The compromise solution closest to the ideal point of the normalized objectives is finally passed to the Green Event Planner.

Firstly, the activity-based carbon footprint for each candidate solution is computed using equation (1) and (2). Solutions not meeting the constraints of energy usage and CE are eliminated or penalized; otherwise, solutions will be assessed based on the objective functions in equations (10) - (13). The sustainability configuration thus generated will be passed on to the Green Event Planner as detailed in Section 3.5.

Algorithm 1. Hybrid MGWO–SPEA2 procedure for sustainability-oriented event configuration

Algorithm 1: MGWO–SPEA2 event-configuration optimization

Input: activity data A_i , emission factors EF_i , CE targets and bounds (Equations (3)–(8)), population size N , archive size $\bar{N}$, iterations $T_{\max}$

Output: Pareto archive Q and selected green-event configuration x^*

- 1: Initialize N normalized decision vectors x (Equation (9)) within the bounds of equation (14); set $Q_0 \leftarrow \emptyset$, $t \leftarrow 0$
- 2: while $t < T_{\max}$ do
- 3: for each $x \in P_t$: evaluate C_{total} (Equations (1)–(2)) and objectives F_1 – F_4 (Equations (10)–(13)); penalize violations of Equations (3)–(8)
- 4: Assign SPEA2 fitness $F(i)$ to all members of $P_t \cup Q_t$ (Equations (20)–(22))
- 5: $Q_{t+1} \leftarrow$ non-dominated members of $P_t \cup Q_t$; truncate or fill to $\bar{N}$ using the density term
- 6: Select α , β , δ as the three members of Q_{t+1} with the lowest $F(i)$
- 7: Update $a(t)$ (Equation (19)) and the coefficient vectors A , C (Equation (17))
- 8: for each search agent: compute X_1 , X_2 , X_3 (Equations (15)–(16)), update the position (Equation (18)) and clip to $[0, 1]$
- 9: $t \leftarrow t + 1$

10: end while

11: Select the compromise solution x^* from Q and pass it to the Green Event Planner (Section 3.5)

Computational Tool: Green Event Planner

Towards the development of the suggested framework, a computational model known as “Green Event Planner” was created in Java SE 17. This system aims at calculating the carbon footprint of academic events, assessing the emissions that can be reduced due to sustainability practices, and estimating the residual emissions which should be mitigated or offset. The computational model utilizes the pre-obtained data about event activities, inputted via the user interface. The main input variables include the use of electricity, waste production, number of meals served, local transportation and outstation transportation. The output variables comprise carbon emissions, emissions reductions, residual emissions, and the offset requirement.

Input Parameters and Emission Factors

The data on activities are translated to CO₂e using the emission factors that are shown in table 2. The emission factors used for calculations in the model coincide with the ones used in the evaluation of the selected event scenario.

Table 2. Input parameters and emission factors used in the green event planner

Activity	Input Variable	Unit	Emission Factor
Electricity consumption	E_{kWh}	kWh	0.75 kg CO ₂ e/kWh
Waste generation	W_{kg}	kg	0.50 kg CO ₂ e/kg
Catering	M_{meals}	meals	1.50 kg CO ₂ e/meal
Local travel	T_{local}	person-km	0.15 kg CO ₂ e/person-km
Outstation travel	T_{out}	person-km	0.10 kg CO ₂ e/person-km

The baseline carbon footprint is calculated using the activity-based formulation defined in Section V. For the computational implementation, the baseline emission is expressed by equation (23):

$$C_B = (E_{kWh}EF_E) + (W_{kg}EF_W) + (M_{meals}EF_M) + (T_{local}EF_L) + (T_{out}EF_O) \quad (23)$$

where C_B is the baseline carbon emission and EF_E , EF_W , EF_M , EF_L , and EF_O are the corresponding emission factors for electricity, waste, meals, local travel, and outstation travel, respectively.

Emission Reduction Estimation

The reduction potential for the sustainability-oriented event planning process is estimated through the Green Event Planner by taking into account energy savings, waste management, sustainable catering, and transport interventions. The reduction factors are computed using equations (24)–(27):

$$R_E = 0.30(E_{kWh}EF_E) \quad (24)$$

$$R_W = 0.70(W_{kg}EF_W) \quad (25)$$

$$R_M = 0.20(M_{meals}EF_M) \quad (26)$$

$$R_T = 0.20(T_{local}EF_L) + 0.50(T_{out}EF_O) \quad (27)$$

where R_E , R_W , R_M , and R_T represent the estimated reduction in emissions due to energy, waste, catering, and transportation interventions, respectively. The adopted scenario therefore considers a 30% reduction potential for electricity-related emissions, 70% for waste-related emissions, 20% for catering-related emissions, 20% for local travel emissions, and 50% for outstation travel emissions.

The residual carbon emission after implementing the sustainability interventions is obtained from equation (28):

$$C_R = C_B - (R_E + R_W + R_M + R_T) \quad (28)$$

where C_R is the residual carbon footprint. If $C_R > 0$, the remaining quantity represents the carbon emission requiring additional mitigation or offsetting. When the residual value reaches zero, the evaluated configuration satisfies the modelled net-zero target.

Computational Workflow

This process can be divided into four steps performed sequentially. First, event activities involving such items as electricity, waste, catering and transportation of participants are added to the Green Event Planner. Next, the activity data are converted using emission factors in order to compute the baseline carbon footprint. In the third step, the sustainability-oriented reduction factors are employed to compute the potential for reductions as well as residual emissions. The last step involves the evaluation of the carbon footprint relative to the baseline configuration and the carbon offset requirement estimation.

The computation sequence is as follows: event activity data → emission factor conversion → baseline carbon footprint estimation (Equation (23)) → reduction potential estimation (Equations (24) – (27)) → residual emissions and offset requirement (Equation. (28)). This decision-making tool thus enables us to compare conventional approaches to events organization with sustainability-oriented event management practices.

RESULTS AND DISCUSSION

Software Details

The Green Event Planner has been developed using Java SE 17 as an interactive software that inputs the event activity information and outputs the baseline emissions, estimated reductions, residual emissions and offsets required (Section 3.5). The MGWO–SPEA2 optimization technique (Section 3.4) has been developed using the same Java SE 17 platform. The interface for event participants and consumption of resources has been developed using Lovable, the event database has been consolidated using Microsoft Excel and the result graphs have been created (Figures 4–8), while Microsoft Visio has been used for creating architecture diagrams (Figures 1–3).

Dataset Details

The dataset is associated with a major academic event carried out at G. Narayanamma Institute of Technology and Science (GNITS), Hyderabad, India, involving around 1,000 participants. Activity information was collected from institutional event records and pre-existing resource consumption data (Section 3.2) and is structured as two scenario records: Scenario A, based on traditional event methods, and Scenario B, based on the sustainable setting achieved using the framework developed in this study. Each scenario includes eight event level attributes: total energy consumption (kWh), share of renewable energy (%), carbon emissions (kg CO₂e), water consumption (L), solid waste generation (kg), recycled / reusable material share (%), Circularity Index (CI) and Sustainability Index Score (SIS), along with Sustainability Efficiency Index (SEI). The Green Event Planner considers five activity level attributes: electricity consumption, waste generation, meals provided, local travel and outstation travel (Table 2).

Parameter Initialization

Experiment parameter settings are provided in table 3. Emission factors were based on table 2; the reduction factors of the interventions were based on equations (24) - (27). Sensitivity analysis was performed with perturbations of ±10% for the selected parameters. Parameter settings for the MGWO and SPEA2 algorithms were chosen to optimize results vs. computational costs in the 5-parameter scenario.

Table 3. Parameters initialized for the experiments

Parameter	Symbol	Value
Number of participants	N_p	1,000
Emission factors (electricity, waste, meals, local and outstation travel)	$EF_E, EF_W, EF_M, EF_L, EF_O$	As in table 2
Reduction factors: energy / waste / catering	–	0.30 / 0.70 / 0.20
Reduction factors: local / outstation travel	–	0.20 / 0.50
Renewable-energy share, Scenario A / B	r_{ren}	0.15 / 0.40
Reused and recycled material share, Scenario A / B	$r_{reuse} + r_{recycle}$	0.22 / 0.65
Decision variables	m	5, normalized to [0, 1]
Population size (MGWO) / archive size (SPEA2)	$N / \tilde{N}$	30 / 30
Maximum number of iterations	T_{max}	100
Control parameter	a	$2 \rightarrow 0$, equation (19)
Sensitivity perturbation	$\Delta p/p$	$\pm 10\%$

Metrics Formulae

Energy savings, carbon savings, water savings, solid wastes and per participant intensity calculations are done using equation (29) where X_A and X_B represent values for Scenario A and Scenario B respectively. The relative improvement of index type indicators (CI, SIS, and SEI) can be found using equation (30), while relative changes of share type indicators (RE share and RR share) are calculated in percentage points using equation (31). The per participant energy and carbon intensities are calculated using equation (32), where N_p represents the number of participants. Circularity Index is calculated as the portion of the total material requirements that are retained through reuse, recycling, and recovery using equation (33), and the elasticity coefficient is calculated using equation (34), where p represents the perturbed parameter.

$$Reduction (\%) = \frac{X_A - X_B}{X_A} \times 100 \quad (29)$$

$$Improvement (\%) = \frac{Y_B - Y_A}{Y_A} \times 100 \quad (30)$$

$$\Delta_{pp} = S_B - S_A \quad (31)$$

$$I_E = \frac{E_{total}}{N_p}, \quad I_C = \frac{C_{total}}{N_p} \quad (32)$$

$$CI = \frac{M_{reuse} + M_{recycle} + M_{recover}}{M_{total}} \quad (33)$$

$$\varepsilon_p = \frac{\Delta C_{total}/C_{total}}{\Delta p/p} \quad (34)$$

Performance Comparison

The suggested model has been tested through an analysis of the data related to a major academic conference having around 1000 participants. In this analysis, two cases of event management are considered: case A, which symbolizes traditional methods of organizing events, and Case B, which is the sustainable event management case achieved through the suggested framework. Energy usage, renewable energy use, CO2 emission, water consumption, generation of waste, recycling/reusing efficiency, CI, and SIS have been taken into account in the evaluation.

Comparison of ten performance indicators, calculated through equations (29) to (32), are presented in table 4.

Table 4. Comparative performance of the conventional (Scenario A) and green-event (Scenario B) configurations

Parameter	Scenario A: Conventional Event	Scenario B: Green Event	Improvement
Energy Consumption (kWh)	4,200	2,750	-34.5%
Renewable Energy Share (%)	15	40	+25 percentage points
CO ₂ Emissions (kg CO ₂ e)	3,250	1,780	-45.2%
Water Consumption (L)	15,000	10,500	-30.0%
Solid Waste Generation (kg)	620	390	-37.1%
Recycled/Reusable Material (%)	22	65	+43 percentage points
Circularity Index (CI)	0.35	0.68	+94.3%
Sustainability Index Score (SIS)	0.47	0.82	+74.5%
Energy intensity (kWh/participant)	4.20	2.75	-34.5%
Carbon intensity (kg CO ₂ e/participant)	3.25	1.78	-45.2%

In the case of green event configuration, energy usage is reduced from 4,200 kWh to 2,750 kWh, which is a decrease of around 34.5%. On the other hand, renewable energy share rises from 15% to 40%, resulting in an increase of 25 percent. The findings show that the integration of energy efficiency and increased renewable energy usage will help to significantly decrease reliance on grid-based energy sources.

The carbon footprint for the event reduces from 3,250 kg CO₂e to 1,780 kg CO₂e, which is an overall decrease of 45.2%. This is, therefore, clear that the resource management framework yields a great deal of improvement over traditional event configuration.

Water use fell from 15,000 L to 10,500 L, amounting to a reduction of 30%. The generation of solid waste was cut down from 620 kg to 390 kg, or about 37.1%. At the same time, the share of recycled or reusable waste grew from 22% to 65%, implying better recovery of event-related resources.

The Circularity Index grew from 0.35 to 0.68, which amounts to an improvement of about 94.3% with respect to the base level. Likewise, the Sustainability Index Score increased from 0.47 to 0.82, or 74.5% relative increase. This demonstrates that not only resource efficiency is enhanced but the event circularity as well.

Normalization of these parameters with respect to the number of participants using equation (32) leads to energy intensity of 4.20 and 2.75 kWh/participant and carbon intensity of 3.25 and 1.78 kg CO₂e/participant.

Performance Evaluation

Energy and Carbon Performance

Energy consumption can be considered one of the most important controllable factors in organizing academic events as all such elements as lighting, cooling, presentations, computers, catering services, etc., consume energy. The comparison of energy consumption in the traditional and suggested event settings is given in figure 4.

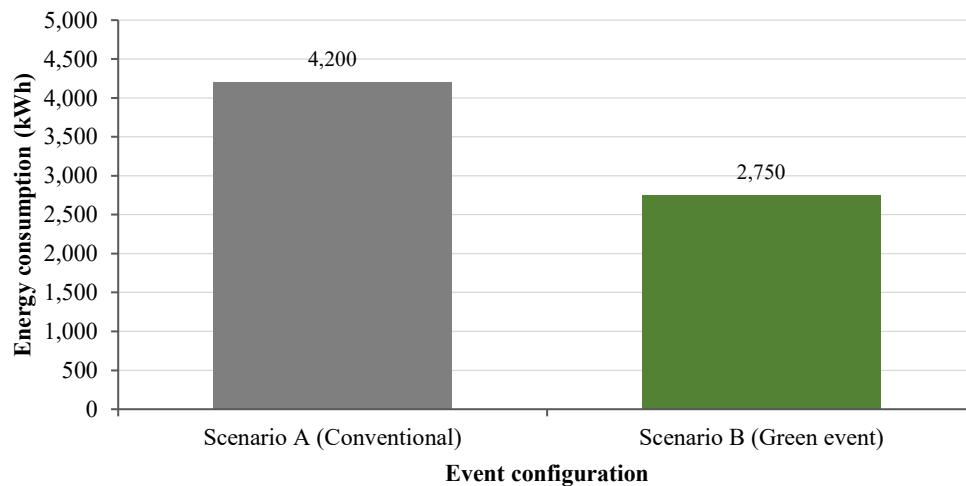


Figure 4. Energy consumption under the conventional (Scenario A) and green-event (Scenario B) configurations

The drop from 4200 kWh to 2750 kWh represents an energy saving of about 1450 kWh, which translates into savings of 34.5%. On top of that, the rise in the percentage of renewable energy to 40% increases the carbon efficiency of the event even more. In such a way, the total amount of carbon emissions for the event drops from 3250 kg CO_{2e} to 1780 kg CO_{2e}, representing a saving of 1470 kg CO_{2e}, which is equal to 45.2%.

The higher relative decrease of carbon emissions compared to energy consumption suggests that the improvement is due to both the decrease in electricity use and a change in the energy portfolio. This is supported by sensitivity analysis carried out in section 4.8, where renewable energy fraction was found to have elasticity coefficient of -0.74 , and transportation was identified as the most sensitive variable with coefficient of $+0.82$.

Water Consumption and Sustainability Efficiency

Water conservation is yet another crucial element in sustainable event management. Figure 5 shows the variation in the use of water along with the Sustainability Efficiency Index (SEI).

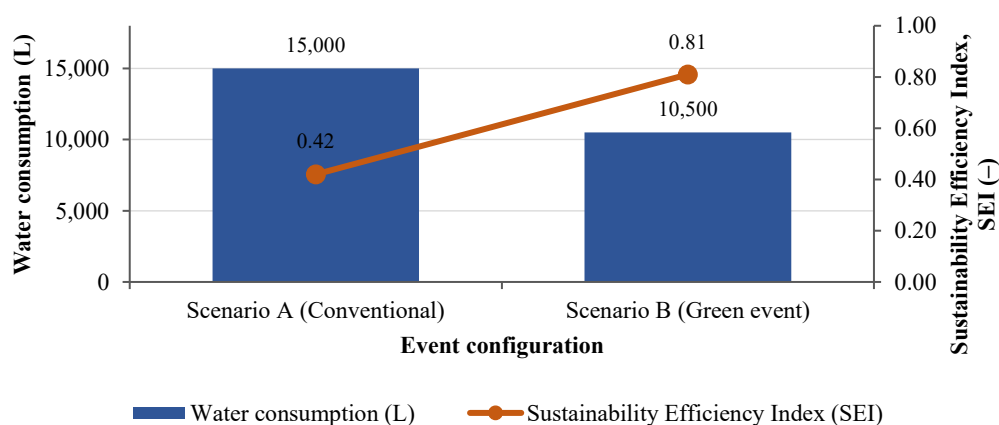


Figure 5. Water consumption and sustainability efficiency index (SEI) under scenarios A and B

Water usage was reduced from 15,000 liters in the conventional system to 10,500 liters in the green event system, thus a reduction by 30%. On the other hand, the SEI increased from 0.42 to 0.81. This implies that there has been an increase in sustainability performance due to reduced resource use.

Waste Reduction and Circularity

Material Recovery and Waste Generation are directly related to the Circular Economy pillar of the suggested framework. The comparison between the amount of solid waste generated and the Circularity Index is illustrated in figure 6.

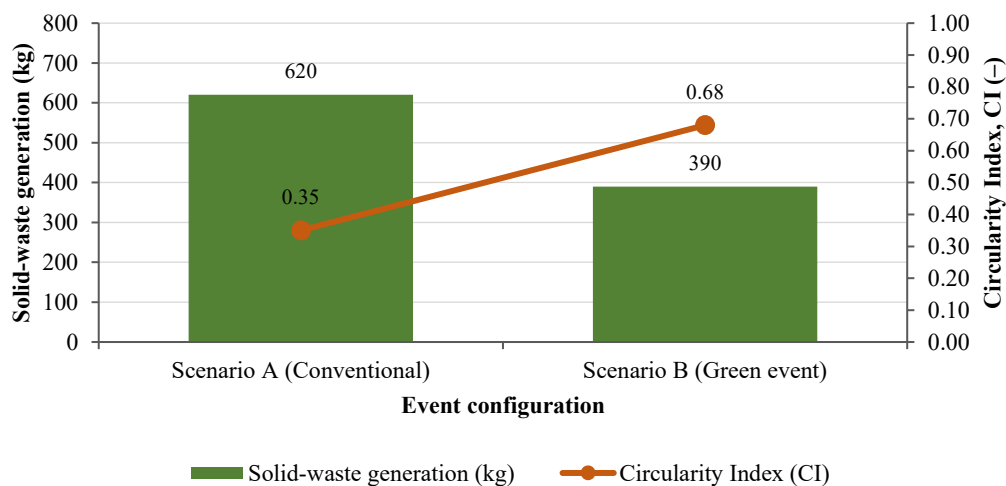


Figure 6. Solid-waste generation and circularity index (CI) under scenarios A and B

The generation of waste was reduced from 620 kg to 390 kg, which represents an approximate reduction of 37.1%. Along with this, there was an increase in the Circularity Index from 0.35 to 0.68. There was also an increase in the proportion of recycled/reused material from 22% to 65%.

These two simultaneous changes show that interventions related to circular economy not only led to waste minimization but also increase material efficiency. Thus, approaches like minimizing single-use materials, increasing reuse, improving segregation, and recycling of recyclable materials contribute to the environmental performance of the proposed approach to event management [23]. Relative increase in Circularity Index by 94.3% means an increase of 94.3% from 0.35 to 0.68 and not an increase of 94.3 percentage points.

Overall Sustainability Improvement

Figure 7 depicts the key performance indicators obtained using equations (29) and (30). From the results presented, there was a decrease of 45.2% in CO₂e emissions, a decrease of 37.1% in waste produced, a decrease of 30% in water usage, and an increase in SEI from 0.42 to 0.81, which is a 92.9% increase relative to the baseline value.

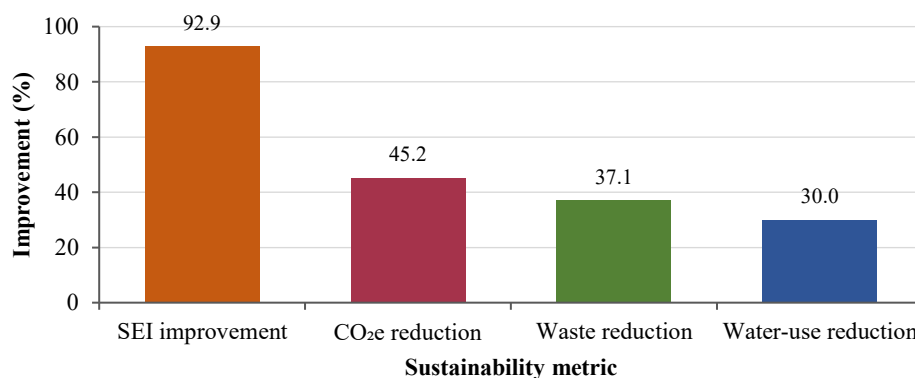


Figure 7. Relative improvement in key sustainability metrics achieved through the proposed framework

This study shows that carbon footprint reduction is associated with positive changes in other aspects of sustainability. This is a significant aspect of the suggested framework because traditional assessment of carbon footprint is usually done after the event while the suggested framework integrates the assessment with management of resources within the principles of the Circular Economy. Thus, the framework allows determining the area where sustainability measures will have the most impact on the environment.

Source-wise Carbon-Reduction Assessment and Ablation Study

The Green Event Planner (Section 3.5) was utilized to mitigate the emissions from the input events, and the results from the source-wise perspective are given in table 5. The reduction in the baseline emissions of 1,815.00 kg CO₂e is 888.75 kg CO₂e, resulting in 926.25 kg CO₂e emissions which will need further mitigation/offsetting, and based on equation (29), the percentage of source-wise emissions reduction is found to be 48.97%. The difference in the two percentages is due to the fact that one represents source-wise emissions and the other is for event level. The source-wise emissions planner reduces emissions in the five activities of table 2 based on fixed intervention factors, whereas the event level is from Scenario A and B comparison.

Table 5. Source-wise carbon-emission reduction estimated using the green event planner

Emission Source	Baseline Emission (kg CO ₂ e)	Reduction (kg CO ₂ e)	Residual Emission (kg CO ₂ e)
Energy	187.50	56.25	131.25
Waste	25.00	17.50	7.50
Catering	450.00	90.00	360.00
Travel	1152.50	725.00	427.50
Total	1815.00	888.75	926.25

Ablation tests were performed to determine the value of each of the intervention groups. Since the planner equation in equations (23)–(28) is additive, each experiment was done by dropping one of the intervention groups and keeping the rest as is; a travel-only scenario was tested as well. These results are presented in table 6 and figure 8.

Table 6. Ablation study of intervention groups in the green event planner

Configuration	Reduction (kg CO ₂ e)	Residual (kg CO ₂ e)	Reduction (%)	Loss vs. full model (pp)
Full model (all interventions)	888.75	926.25	48.97	–
Without energy intervention	832.50	982.50	45.87	3.10
Without waste intervention	871.25	943.75	48.00	0.96
Without catering intervention	798.75	1,016.25	44.01	4.96
Without travel intervention	163.75	1,651.25	9.02	39.94
Travel intervention only	725.00	1,090.00	39.94	9.02

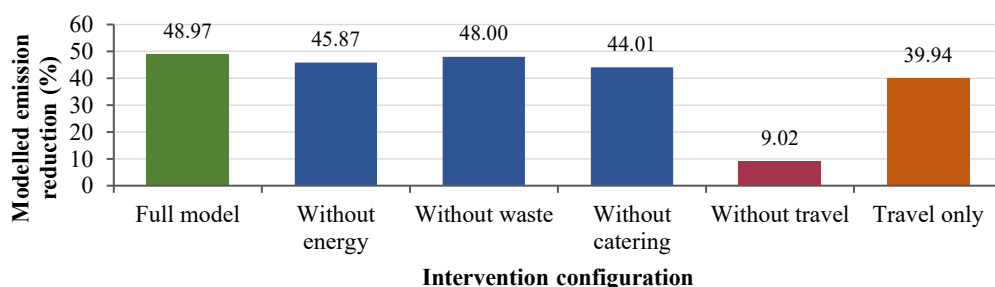


Figure 8. Ablation study: modelled carbon-emission reduction under alternative intervention configurations

Eliminating travel mitigation options decreases the reduction to 9.02% in the modeled reduction, showing that travel is responsible for 725.00 kg CO₂e or 81.6% of the overall modeled reduction while the catering, energy, and waste mitigations are responsible for 10.1%, 6.3%, and 2.0% respectively. This order is consistent with the sensitivity analysis done in Section 4.8 and with research on conference life-cycle assessment which shows that the participants' travel contributes the highest share to event carbon footprint. The low impact of the energy intervention option in the source-wise analysis can be attributed to the low electricity-related emissions (187.50 kg CO₂e) given by the planner in the input.

Sensitivity Analysis

Sensitivity analysis has been conducted using a $\pm 10\%$ change on three major sustainability parameters, namely the share of renewable energy, transportation effects, and waste segregation efficiency. The relevant elasticity coefficients are shown in table 7, according to equation (34).

Table 7. Sensitivity of carbon emissions to selected sustainability parameters

Parameter	Elasticity ($\Delta CO_2 / \Delta Parameter$)	Interpretation
Renewable Energy Fraction	-0.74	Increasing renewable-energy contribution reduces total emissions
Transportation	+0.82	Transportation has the strongest positive influence on event carbon emissions
Waste Segregation Efficiency	-0.58	Improved waste segregation contributes to reduction in total CO ₂ e

The value of the elasticity coefficient for transportation (+0.82) is higher than the other two variables, suggesting that transportation is the most sensitive variable affecting the carbon footprint of the event. The positive value means that more activities related to transportation contribute to the growth of the carbon footprint.

The value of the elasticity coefficient for renewable energy is -0.74, meaning that increasing the share of renewables decreases carbon emissions. The same applies to the coefficient for waste segregation -0.58; however, its impact on the carbon footprint is lower than those of the two other variables.

The sensitivity analysis suggests that organizing participants' transportation and renewable energy utilization must be prioritized while planning low-carbon events, followed by improving waste segregation and recovery.

Discussion, Validation and Limitations

Current research mostly analyzes carbon assessment, circular-economy approach, digital monitoring and optimization separately (Table 1). In contrast, the suggested framework brings all these elements together into one computational framework at the level of an event and, unlike after-the-fact carbon accounting and offsetting, connects emission assessment with energy management, material circularity, water savings and decision-making before and during the event. The reduction by 45.2% of CO₂e emissions at the event level, along with reductions by 34.5% of energy use, 37.1% of waste and 30% of water consumption, shows the benefit of combining multiple approaches in one framework. These numbers apply to the particular academic event under evaluation and cannot be extrapolated to universal levels of reductions, due to the influence of such factors as the event size, participants' travel habits, energy sources, venues specifics, catering services and materials demand.

From an institutional point of view, the findings demonstrate that the proposed framework can help to detect areas where high impact interventions could take place both before and during event planning. According to sensitivity analysis, transportation and renewable-energy utilization have a significant role in the formation of the event carbon footprint. Hence, institutional transport, shared mobility, public transport, hybrid participation, renewable-energy procurement, and energy efficiency of venues should be a priority for future green event planning.

The digital monitoring aspect should be viewed as an architectural feature of the framework under discussion. In the current experimental setup, Green Event Planner works based on the previously collected data regarding event activities, whereas the IoT–Edge architecture described in Section 3.2 opens up a way to collect such data automatically in the future.

The validation of the current model is limited to a large-scale educational event, and to the comparison of the conventional setup and the sustainability-focused setup; thus, it must be considered validation on a case study and computational assessment level and not on a continuous real-time IoT level. Also, the Green Event Planner works with pre-existing activity data. Validation of the framework with multiple events and continuous energy, water flow, waste measurement, and mobility meters would improve the generalizability of the framework.

CONCLUSION

The research offered a computation engineering approach to evaluate and minimize the impact of large-scale events organized by academia with regard to carbon-footprint evaluation based on activity levels, principles of the Circular Economy, monitoring using IoT-Edge-Cloud technology, and multi-objective optimization using MGWO-SPEA2 combined with the Green Event Planner developed on Java SE 17. The analysis of an academic event which gathered around 1,000 people showed that the green event configuration decreased energy use from 4,200 to 2,750 kWh (34.5%), carbon emissions from 3,250 to 1,780 kg CO₂e (45.2% or 3.25 to 1.78 kg CO₂e per person), water use from 15,000 to 10,500 L (30%) and solid waste generation from 620 to 390 kg (37.1%). The proportion of renewable energy increased from 15% to 40%, reusable/recyclable materials – from 22% to 65%, Circularity Index – from 0.35 to 0.68 (+94.3%), and Sustainability Index Score – from 0.47 to 0.82 (+74.5%). The source-wise planner suggested a reduction potential of 48.97% resulting in residual emissions of 926.25 kg CO₂e to be offset. Ablation test proved travel measures' contribution in the total modeled reduction as 81.6%, and the sensitivity test revealed the most influencing parameters of transportation (+0.82), renewable energy fraction (–0.74), and waste segregation efficiency (–0.58). It can be concluded that transportation control, use of renewable energy, energy conservation, and material reuse should be focused upon in the process of planning zero carbon emission events, and the framework provides institutions with a quantitative tool of net-zero event management. However, the current study involves only one single event with pre-collected activity data. Further research should involve validating of the framework on several events, integrating real-time IoT-measurements of energy, water, waste and mobility flows, benchmarking MGWO–SPEA2 against other multi-objective optimization algorithms, supporting decision-making on material consumption in event planning and development of the model towards net-zero events.

Author Contributions:

Conceptualization, Gouthami Eragamreddy, Indrajit Pal, Sriramakavacham Ramacharan, Prasun Chakrabarti; methodology, Gouthami Eragamreddy and Sriramakavacham Ramacharan; software, Gouthami Eragamreddy and Sriramakavacham Ramacharan; validation, Gouthami Eragamreddy, Indrajit Pal, Sriramakavacham Ramacharan, Prasun Chakrabarti ; formal analysis, Gouthami Eragamreddy, Indrajit Pal, Sriramakavacham Ramacharan, Prasun Chakrabarti ; investigation, Gouthami Eragamreddy; resources, Gouthami Eragamreddy; data curation, Gouthami Eragamreddy; writing—original draft preparation, Gouthami Eragamreddy; writing—review and editing, Gouthami Eragamreddy; visualization, Gouthami Eragamreddy, Indrajit Pal, ; supervision, Indrajit Pal, Sriramakavacham Ramacharan, Prasun Chakrabarti ; project administration, Gouthami Eragamreddy; funding acquisition, Gouthami Eragamreddy

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Data Availability Statement: The study is based on event-related activity and sustainability data associated with a large-scale academic event conducted at G. Narayanamma Institute of Technology and Science (GNITS). The data used for the computational assessment are available from the corresponding author upon reasonable request, subject to institutional and participant-data restrictions.

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Declaration of Generative AI and AI-Assisted Technologies

During the preparation of this manuscript, the authors used AI-assisted tools for language refinement, visualization support, and the preparation of illustrative graphical representations. AI-generated or AI-assisted outputs were subsequently reviewed, verified, and edited by the authors. The authors take full responsibility for the accuracy, interpretation, originality, and final content of the manuscript.

Software and Computational Tools

Mendeley was used for reference management, Microsoft Visio and Napkin AI were used to support the preparation of figures and graphical representations, and Lovable was used in developing the computational application/interface for event-participant and resource-consumption analysis. Claude AI was used as an assistive tool during comparative analysis and manuscript development. All computational results, interpretations, and conclusions presented in the manuscript were reviewed and validated by the authors.

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

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