

Sustainable “Rendezvous”: A Festival Systems Challenge

Comprehensive Process Optimization (Modules 3.1–3.4)

Sustainability Task Force

Department of Chemical Engineering

Course: CLL782 – Process Optimization
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The Genesis: From Biodiversity to Urban Chaos

The Inspiration

Sanskriti, General Secretary (Cultural Affairs), hails from the biodiverse landscapes of **West Champaran, Bihar**.

- **Observation:** Urban life offers convenience but at a massive, silent environmental cost.
- **The Trigger:** “Rendezvous” (Asia’s Largest Fest) generates **tons of waste**, acting as a microcosm of urban un-sustainability.

The Vision

“Sustainability is not about restriction, but about acting responsibly and optimizing resources.”

Transform Rendezvous from a logistical challenge into a **Model of Sustainability**.

The Objective

Use **Systems Engineering & Optimization** to:

- 1 Quantify Impact.
- 2 Optimize Infrastructure.
- 3 Minimize Waste.

Scope: The High-Intensity Zone

To ensure impact, we focus on the festival's core activity hub.

Parameter	Value
Total Campus	320 Acres
Target ROI	82 Acres (26%)
Key Venues	OAT, Nalanda, SAC, LHC
Peak Footfall	~40,000/day
Grid System	137 Cells (≈ 0.6 ac)
Total (4 Days)	~160,000 attendees

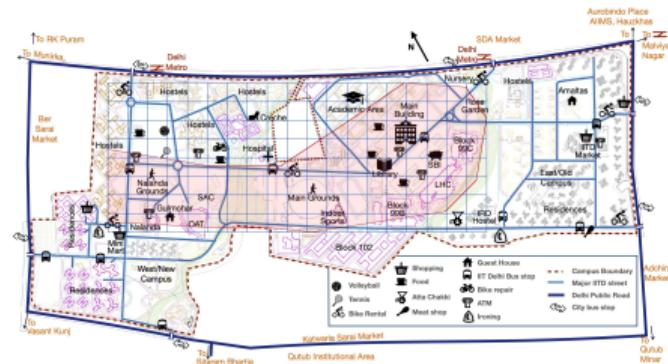


Figure: ROI with 137 Grid Cells overlaid on IITD Campus Map

3.1 Problem Statement

Objective

Define an environmental impact function $E = f(N, S, A)$ that quantifies the **total ecological footprint** of the festival — incorporating energy use, waste generation, and emissions — and find the conditions that **minimize** E .

Key Questions Addressed:

- Can we capture non-linear phenomena like **crowding effects** and **diminishing returns**?
- What is the **ideal event scale** (stalls, hours) that minimizes footprint?
- Does the objective function need modification to better capture the sustainable festival design?

3.1 Variables & Assumed Constants

Table: Module 3.1 — Variables and Parameters

Symbol	Description	Unit	Type
N	Number of attendees	Persons	Decision Var
S	Number of food stalls	Stalls	Decision Var
A	Activity duration (concerts, events)	Activity-hrs	Decision Var
E	Total environmental load	kg CO ₂ -eq	Objective
α_1	Per-capita base impact	2.5 kg/p	Constant
α_2	Per-stall embodied energy impact	18 kg/stall	Constant
α_3	Per-activity base impact	12 kg/act-hr	Constant
β_N	Crowding nonlinearity coeff. (exp. 1.3)	0.002	Constant
β_S	Stall scaling nonlinearity coeff. (exp. 1.2)	0.5	Constant
β_A	Activity scaling coeff. (exp. 0.8)	5.0	Constant
γ_{NS}	Congestion penalty coefficient	0.0005	Constant

Ref: Bettencourt et al. (2007) for $N^{1.3}$ scaling; CPCB (2021) for waste norms; CEA (2024) for grid emission.

3.1 Mathematical Formulation

Environmental Load Function

$$E = \underbrace{(\alpha_1 N + \alpha_2 S + \alpha_3 A)}_{\text{Base Load}} + \underbrace{(\beta_N N^{1.3} + \beta_S S^{1.2} + \beta_A A^{0.8})}_{\text{Non-linear Scaling}} + \underbrace{\left(\gamma_{NS} \frac{N^2}{S} \right)}_{\text{Congestion Penalty}}$$

Component Interpretation:

- **Base Load** ($\alpha_1 N + \alpha_2 S + \alpha_3 A$): Direct consumption proportional to attendees, infrastructure, and activities.
- **Non-linear Scaling:**
 - $\beta_N N^{1.3}$: Super-linear crowding — more people \Rightarrow disproportionately more littering (Urban Scaling Law).
 - $\beta_S S^{1.2}$: Supply-chain fragmentation with increasing stalls.
 - $\beta_A A^{0.8}$: Economies of scale in activities (Six-Tenths Rule).
- **Congestion Penalty** (N^2/S): The critical “queue” term.
 - Too few stalls ($S \downarrow$) \Rightarrow Long queues \Rightarrow Frustration & Littering ($E \uparrow\uparrow$).
 - Too many stalls ($S \uparrow$) \Rightarrow Wasted embodied energy ($\alpha_2 S \uparrow$).

3.1 Optimization & Insights

Optimal Stall Count (Fixed N)

Differentiating E w.r.t. S and setting to zero:

$$\frac{\partial E}{\partial S} = \alpha_2 + 1.2 \beta_S S^{0.2} - \gamma_{NS} \frac{N^2}{S^2} = 0$$

Approximating for small β_S ($\beta_S \approx 0$):

$$\alpha_2 \approx \gamma_{NS} \frac{N^2}{S^2} \implies S^* \approx N \sqrt{\frac{\gamma_{NS}}{\alpha_2}}$$

Numerical Result ($N = 40,000/\text{day}$):

$$S^* \approx 40000 \sqrt{\frac{0.0005}{18}} \approx 210$$

Key Insights:

- Current practice (~100 stalls) is **under-provisioned**.
- Congestion penalty **dominates** at low S .
- Increasing to ~ 210 stalls paradoxically

3.2 Problem Statement

Objective

Formulate a **Facility Location Problem (FLP)** to optimally place dustbins across the 82-acre festival zone, minimizing average walking distance weighted by footfall density.

Key Considerations:

- **Dual-compartment bins** (Wet + Dry) per SWM Rules 2016.
 - **Green**: Compostable / Organic (food waste).
 - **Blue**: Recyclable (paper, plastic, bottles).
- Each unit has a **cost C** , **service radius R** , and **capacity K** .
- **Greener Protection**: Bins on hardscape edges only (no trampling of lawns).
- Designed for **peak surge** demand (Star Night: 40,000 in the zone).

3.2 Variables, Constants & Data

Table: Module 3.2 — Nomenclature

Sym	Description	Unit	Type
y_j	Install dual-bin at location j ?	{0, 1}	Binary Decision
$a_{i,j}$	Fraction of zone i demand \rightarrow bin j	[0, 1]	Continuous Decision
F_i	Peak footfall at zone i	Ppl/hr	Parameter
D_{ij}	Walking distance $i \rightarrow j$	m	Parameter
w	Waste generation rate	0.15 kg/p	Constant
R	Service radius	40 m	Constant
K	Bin capacity (dual FRP unit)	30 kg	Constant
C	Bin procurement cost (per unit)	Rs. 12K	Constant
B	Total budget	Rs.	Constraint

Ref: SWM Rules 2016 (Wet+Dry segregation); Disney 30-ft rule; Glasdon norms (30–50 m).

3.2 Mathematical Formulation (MILP)

Minimize Total User Inconvenience

$$\text{Min } Z = \sum_{i=1}^m \sum_{j=1}^p F_i \cdot a_{i,j} \cdot D_{ij}$$

Subject to:

- 1 **Coverage:** Every zone must be fully served. $\sum_j a_{i,j} = 1 \quad \forall i$
- 2 **Logical Link:** No assignment without installation. $a_{i,j} \leq y_j \quad \forall i, j$
- 3 **Capacity:** Bins must not overflow. $\sum_i F_i \cdot w \cdot a_{i,j} \leq K \cdot y_j \quad \forall j$
- 4 **Accessibility:** $a_{i,j} = 0$ if $D_{ij} > R$
- 5 **Budget:** $\sum_j C \cdot y_j \leq B$

3.2 Optimization Analysis & Insights

Complexity

- **NP-hard** Facility Location.
- Discretize ROI into 137 cells ($50m \times 50m$).
- Solvable via Branch-and-Bound (Gurobi / CBC).

Expected Outcomes

- **High density** near OAT/Amul (food zones, high F_i).
- **Sparse** along Main Road (low F_i , R constraint).
- Relaxing binary \rightarrow LP gives lower bound.

Data Summary:

- Total peak waste: $40,000 \times 0.15 = \mathbf{6,000}$ kg/day.
- At $K = 30$ kg/bin \Rightarrow minimum ~ 200 dual-bins needed.
- Budget feasibility: $200 \text{ bins} \times \text{Rs. } 12\text{K} \approx \text{Rs. } 24 \text{ Lakhs.}$

3.3 Problem Statement

Objective

Design an efficient **waste collection and processing logistics** system that transports 6,000 kg/day of segregated waste from generation zones to processing facilities, minimizing total cost.

System Architecture:

- **Sources (i):** Demand zones within the 82-acre ROI.
- **Sinks (j):** 3 Processing Facilities:
 - 1 On-Campus Biogas/Compost (~1 km, Cap: 500 kg/day).
 - 2 Okhla Landfill/WTE (~12 km, Unconstrained capacity).
 - 3 Okhla Recycling Aggregator (~11 km, Net revenue).
- **Fleet:** Electric Tippers (Tata Ace EV).

3.3 Variables, Constants & Data

Table: Module 3.3 — Nomenclature

Sym	Description	Unit	Type
$x_{i,j}$	Waste flow from zone i to facility j	kg	Continuous Decision
v_k	Deploy vehicle k ?	{0, 1}	Binary Decision
W_i	Total waste at zone i	kg	Parameter
D_{ij}	Distance zone i to facility j	km	Parameter
V_{cap}	Vehicle payload (Tata Ace EV)	600–750 kg	Constant
C_{dist}	Transport cost per km	Rs. 15–20/km	Constant
$C_{handling}$	Handling cost per kg	Rs./kg	Constant
C_{fixed}	Fixed cost per vehicle per day	Rs. 500–800	Constant
$C_{proc,j}$	Processing cost at facility j	Rs./kg	Constant

Assumptions: Direct transport (Star network); Homogeneous fleet; Linear costs.

3.3 Formulation (Minimum Cost Flow)

Minimize Total Logistics Cost

$$Z = \underbrace{\sum_{i,j} x_{i,j} (C_{dist} D_{ij} + C_{handling} + C_{proc,j})}_{\text{Variable Cost (Transport + Processing)}} + \underbrace{C_{fixed} \cdot \sum_k v_k}_{\text{Fixed Fleet Cost}}$$

Subject to:

- 1 **Waste Clearance** (all waste removed): $\sum_j x_{i,j} = W_i \quad \forall i$
- 2 **Facility Throughput**: $\sum_i x_{i,j} \leq Cap_j \quad \forall j$
- 3 **Fleet Capacity**: $\sum_{i,j} x_{i,j} \leq V_{cap} \cdot \sum_k v_k$
- 4 **Non-negativity**: $x_{i,j} \geq 0, v_k \in \{0, 1\}$

3.3 Sensitivity Analysis & Insights

Complexity

- Core: LP Transportation Problem
(Totally Unimodular \Rightarrow Polynomial).
- Integer constraint on $v_k \Rightarrow$ MILP, but single scalar \Rightarrow very low complexity.

Sensitivity (+20% Waste)

If $W'_i = 1.2 W_i$:

- Check: $\sum W'_i \leq \sum Cap_j$?
- Variable costs scale **linearly**.
- But vehicle fixed cost has a **step-function** jump if fleet is saturated.

Key Insights:

- **Waste Composition:** 40% Organic, 40% Recyclable, 20% Inert (CPCB norms).
- **Bottleneck:** On-campus biogas (500 kg) saturates first \Rightarrow overflow to landfill.
- **Revenue Opportunity:** Recycling aggregator provides net *revenue* (Rs. 5–10/kg) for segregated waste.

3.4 Problem Statement

Objective

Plan **water refill station** locations using a **Capacitated P-Median** formulation. Minimize total cost (installation + user walking inconvenience) to support a reusable water bottle policy and **eliminate single-use plastic**.

Key Considerations:

- Each participant receives a metallic bottle (cost recovered via festival pass).
- Stations can only be installed at **pre-designated feasible locations** (near existing plumbing).
- Demand is **splittable**: aggregate probability of users visiting nearby stations.
- Delhi climate \Rightarrow high hydration need (~ 250 ml/hr/person).

3.4 Variables, Constants & Data

Table: Module 3.4 — Nomenclature

Sym	Description	Unit	Type
y_j	Install station at location j ?	{0, 1}	Binary Decision
$x_{i,j}$	Fraction of zone i served by j	[0, 1]	Continuous Decision
d_i	Water demand at zone i	Ppl/hr	Parameter
D_{ij}	Walking distance $i \rightarrow j$	m	Parameter
f_j	Installation + operation cost	Rs. 1 Lakh	Constant
cap_j	Station dispensing capacity	250 LPH	Constant
C_{walk}	Monetary value of walking	Rs. 0.02/m	Constant

Ref: Blue Star/Voltas 150–300 LPH specs; WHO hydration norms; Market pricing (Indiamart).

Peak Water Demand: $40,000 \times 0.25 \text{ L/hr} = 10,000 \text{ LPH}$. At 250 LPH/station \Rightarrow Min. ~ 40 stations.

3.4 Formulation (Capacitated P-Median)

Minimize Generalized Cost

$$Z = \underbrace{\sum_{j=1}^p f_j y_j}_{\text{Installation (CAPEX)}} + \underbrace{\sum_{i=1}^m \sum_{j=1}^p \alpha_{ij} x_{i,j}}_{\text{User Inconvenience}}$$

where $\alpha_{ij} = d_i \cdot D_{ij} \cdot C_{walk}$ is the weighted walking cost coefficient.

Subject to:

1 Demand Satisfaction: $\sum_j x_{i,j} = 1 \quad \forall i$

2 Station Capacity: $\sum_i d_i x_{i,j} \leq cap_j \cdot y_j \quad \forall j$

(Also acts as logical link: if $y_j = 0$, capacity is 0.)

3 Integrality: $y_j \in \{0, 1\}, \quad 0 \leq x_{i,j} \leq 1$

3.4 Solution Strategy & Insights

Algorithmic Approach

- 1 **Greedy:** Iteratively add the station yielding max cost reduction.
- 2 **Lagrangian Relaxation:** Relax demand constraints; decompose into knapsack sub-problems.
- 3 **Exact:** Branch-and-Bound (Gurobi/CBC). With $m \approx 50$, $p \approx 20$: converges in seconds.

Fairness Note: Current objective minimizes *average* distance. A **Minimax** secondary constraint could ensure no zone walks more than a threshold.

Key Trade-offs

- High $f_j \Rightarrow$ Fewer, centralized stations (long walks).
- Low $f_j \Rightarrow$ Distributed topology (short walks).
- **Shadow Price** of capacity constraint reveals bottleneck stations to upgrade.

Integrated Blueprint & Next Steps

System-Level Summary

- 1 **Mod 3.1:** Right-size infrastructure ($S^* \approx 210$ stalls) to cut congestion-led waste.
- 2 **Mod 3.2:** Place ~ 200 dual-bins (Wet+Dry) within 40 m radius to capture waste at source.
- 3 **Mod 3.3:** Route 6,000 kg/day via optimized fleet (minimize cost, maximize recycling revenue).
- 4 **Mod 3.4:** Deploy ~ 40 refill stations to eliminate single-use plastic.

Module 3.5 (Next): System Integration

Combine all modules into a **multi-objective optimization**: minimize total cost *and* environmental impact *and* user inconvenience, subject to combined constraints from Modules 3.1–3.4.

Thank You

*“Just like Mother Nature, we optimize continuously —
learning, adapting, and improving.”*

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