

# 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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# Outline

1. The Genesis & Vision
2. Module 3.1: Environmental Load
3. Module 3.2: Dustbin Placement (FLP)
4. Module 3.3: Waste Collection Logistics
5. Module 3.4: Water Refill Stations
6. Conclusion

# 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
<b>Target ROI</b>	<b>82 Acres (26%)</b>
Key Venues	OAT, Nalanda, SAC, LHC
Peak Footfall	~40,000/day
Grid System	137 Cells ( $\approx 0.6$ ac)
Total (4 Days)	~160,000 attendees

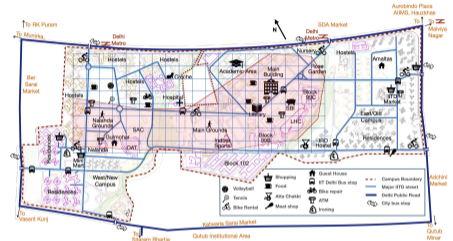


Figure: ROI with 137 Grid Cells overlaid on IITD Campus Map

## 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	<b>Decision Var</b>
$S$	Number of food stalls	Stalls	<b>Decision Var</b>
$A$	Activity duration (concerts, events)	Activity-hrs	<b>Decision Var</b>
$E$	Total environmental load	kg CO <sub>2</sub> -eq	Objective
$\alpha_1$	Per-capita base impact	2.5 kg/p	Constant
$\alpha_2$	Per-stall embodied energy impact	18 kg/stall	Constant
$\alpha_3$	Per-activity base impact	12 kg/act-hr	Constant
$\beta_N$	Crowding nonlinearity coeff. (exp. 1.3)	0.002	Constant
$\beta_S$	Stall scaling nonlinearity coeff. (exp. 1.2)	0.5	Constant
$\beta_A$	Activity scaling coeff. (exp. 0.8)	5.0	Constant
$\gamma_{NS}$	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  $\beta_S$  ( $\beta_S \approx 0$ ):

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

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

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

**Key Insights:**

- Current practice ( $\sim 100$  stalls) is **under-provisioned**.
- Congestion penalty **dominates** at low  $S$ .
- Increasing to  $\sim 210$  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**  $K$ .
- **Greenery 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 $j$ ?	$\{0, 1\}$	<b>Binary Decision</b>
$a_{i,j}$	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 ( $50\text{m} \times 50\text{m}$ ).
- 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  $\sim 200$  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 ( $\sim 1$  km, Cap: 500 kg/day).
  - 2 Okhla Landfill/WTE ( $\sim 12$  km, Unconstrained capacity).
  - 3 Okhla Recycling Aggregator ( $\sim 11$  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	<b>Continuous Decision</b>
$v_k$	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 ( $\sim 250$  ml/hr/person).

## 3.4 Variables, Constants & Data

Table: Module 3.4 — Nomenclature

Sym	Description	Unit	Type
$y_j$	Install station at location $j$ ?	$\{0, 1\}$	<b>Binary Decision</b>
$x_{i,j}$	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:**  $40,000 \times 0.25 \text{ L/hr} = \mathbf{10,000 \text{ LPH}}$ . At 250 LPH/station  $\Rightarrow$  Min.  $\sim 40$  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.

### 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.

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

# 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  $\sim 200$  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  $\sim 40$  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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