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

The Genesis: From Biodiversity to Urban Chaos

The Inspiration

Sanskruti, 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

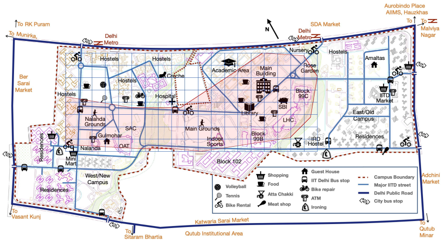

Figure: ROI with 137 Grid Cells overlaid on IITD Campus Map

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 ($\beta_S \approx 0$):

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

Numerical Result ($N = 40{,}000$/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:

- 3 Bin Types: **Recyclable**, **Compostable**, **General**.
- Each bin has a **cost**, a **service radius** R_t, and a **capacity** K_t.
- **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
$y_{j,t}$	Install bin type t at location j?	$\{0, 1\}$	**Binary Decision**
$a_{i,j,t}$	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_t	Service radius	30–50 m	Constant
K_t	Bin capacity (dual FRP)	20–30 kg	Constant
C_t	Bin procurement cost	Rs. 10–15K	Constant
B	Total budget	Rs.	Constraint

Ref: Disney 30-ft rule; Glasdon bin-spacing norms (30–50 m); CPCB waste norms.

3.2 Mathematical Formulation (MILP)

Minimize Total User Inconvenience

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

Subject to:

1. **Coverage**: Every zone must be fully served. $\sum_{j,t} a_{i,j,t} = 1 \quad \forall\, i$
2. **Logical Link**: No assignment without installation. $a_{i,j,t} \leq y_{j,t} \quad \forall\, i, j, t$
3. **Capacity**: Bins must not overflow. $\sum_{i} F_i \cdot w \cdot a_{i,j,t} \leq K_t \cdot y_{j,t} \quad \forall\, j, t$
4. **Accessibility**: $a_{i,j,t} = 0$ if $D_{ij} > R_t$
5. **Budget**: $\sum_{j,t} C_t \cdot y_{j,t} \leq B$

3.2 Optimization Analysis & Insights

Complexity

- **NP-hard** Facility Location.
- Discretize ROI into 20m $\times$ 20m grid.
- 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_t constraint).
- Relaxing binary $\rightarrow$ LP gives lower bound.

Data Summary:

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

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

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?	$\{0, 1\}$	**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 $i \to j$	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 × 0.25 L/hr = **10,000 LPH**. At 250 LPH/station ⇒ 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.

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 bins within 30–50 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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