# Waste Collection Route Optimisation in Municipal Solid Waste Management

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***Abstract*—Collection and transport account for the largest share of municipal solid waste (MSW) management costs, yet route planning in many Indian cities is still done manually. This report examines how Operations Research (OR) has been applied to this problem by analysing two journal articles in depth: Kim, Kim and Sahoo (2006), who model commercial waste collection as a vehicle routing problem with time windows (VRPTW) and deploy a solution at Waste Management, Inc.; and Bonomo, Durán, Larumbe and Marenco (2012), who reduce skip-container collection in Buenos Aires to a travelling salesman problem (TSP) and solve it exactly. For each article the report sets out the real-life context, the objective, constraints and problem type, the mathematical model, the solution method and tools, the validation, and a critical assessment. To show the modelling in full, a Capacitated Vehicle Routing Problem (CVRP) is then formulated for K/West ward of the Brihanmumbai Municipal Corporation (BMC), which lifted about 311 tonnes of waste per day in 2025. Thirteen collection points are routed to the Versova Lagoon Refuse Transfer Station and solved to proven optimality with the HiGHS solver. The optimal plan covers 54.5 km in five trips, against 55.8 km for a nearest-neighbour rule and 59.2 km in six trips for the Clarke–Wright savings heuristic. Raising vehicle payload from 8 to 12 tonnes cuts optimal distance by 29%.**

***Index Terms*—operations research, vehicle routing problem, waste collection, travelling salesman problem, mixed-integer programming, Mumbai**

## I. INTRODUCTION TO OPERATIONS RESEARCH AND THE PROBLEM TYPE

### 1.1 Operations Research

Operations Research is the discipline of using mathematical models, optimisation and analytics to support decisions about the allocation of scarce resources. A typical OR study follows a fixed sequence: define the real-life problem, formulate a mathematical model with an objective function, decision variables and constraints, solve the model with an exact or heuristic method, and validate the result against reality before implementation. The standard OR toolkit includes linear programming, transportation and assignment models, network models, project scheduling (PERT/CPM), integer programming and metaheuristics. This report draws on integer programming, network models and metaheuristics, applied to a public-services problem.

### 1.2 The routing problem family

Waste collection belongs to the family of routing problems on networks:

- Travelling Salesman Problem (TSP): one vehicle visits every location exactly once at minimum distance.
- Vehicle Routing Problem (VRP): a fleet of vehicles based at a depot serves a set of customers at minimum total cost.
- Capacitated VRP (CVRP): each vehicle has a load limit. This is the natural model for compactor trucks that must unload at a transfer station.
- VRP with Time Windows (VRPTW): each stop must be served within a given time interval.
- Arc routing: the streets themselves, not points, must be traversed, as in door-to-door residential collection.

All of these are NP-hard, so large instances need heuristics, while small and medium instances can often be solved exactly with modern solvers.

### 1.3 Why waste collection is a suitable OR problem

Mumbai lifted an average of 6,955 tonnes of municipal waste per day in 2025, according to ward-level Right to Information (RTI) data compiled by Praja Foundation (2026). The BMC Solid Waste Management department has a 2026–27 budget

estimate of ₹3,830 crore, about 12% of the corporation's revenue budget (Praja Foundation, 2026). Tavares et al. (2009) note that collection may account for more than 70% of the total waste management budget, much of it for fuel. Praja Foundation (2026) also notes that BMC publishes no database of collection routes and that "garbage not lifted" was the most common solid waste complaint in 2025, with 13,718 cases. A cost-heavy, route-driven activity with measurable inputs and a clear objective, namely distance, time or fuel, is exactly where OR is suitable.

1.4 Objectives and structure of this report

The objectives are to: (1) select and analyse two journal articles that apply OR to waste collection; (2) extract and explain their problem formulations, models and solution methods; (3) demonstrate the modelling approach on a Mumbai instance; and (4) reflect critically on strengths, limitations and possible extensions. Section 2 explains the selection, Sections 3 and 4 analyse the two articles, Section 5 compares them with each other and with the wider literature, Section 6 presents the Mumbai application, Section 7 gives the critical reflection, and Section 8 concludes.

## II. SELECTION OF RESEARCH ARTICLES

Two peer-reviewed journal articles were chosen to cover different problem types, solution philosophies and settings, so that the comparison is informative.

| | Article 1 | Article 2 |
|---|---|---|
| Reference | Kim, Kim and Sahoo (2006), Computers & Operations Research, 33(12), 3624–3642 | Bonomo, Durán, Larumbe and Marenco (2012), Waste Management & Research, 30(3), 311–324 |
| Setting | Commercial waste collection, Waste Management, Inc., North America | Skip-container collection, southern zone of Buenos Aires, Argentina |
| Problem type | VRPTW with multiple disposal trips and driver lunch breaks | Reduced to a TSP |
| Method | Extended Solomon insertion heuristic | Exact solution with the Concorde solver |
| Why selected | Large-scale industrial deployment; defines benchmark instances | Exact method with measured real-world savings; includes a vehicle-wear objective |

## III. ARTICLE 1: KIM, KIM AND SAHOO (2006), WASTE COLLECTION VEHICLE ROUTING PROBLEM WITH TIME WINDOWS

3.1 Real-life context

- Problem: The authors address a real-life waste collection VRPTW that must account for multiple disposal trips and drivers' lunch breaks. They note that waste collection is often treated as an arc routing problem without time windows, but that view applies only to residential collection. The industry has three major areas, namely commercial, residential and roll-on–roll-off collection, and the article focuses on commercial collection, where stops may have time windows.
- Domain: Logistics and public-utility services (the waste management industry).
- Why OR is suitable: Vehicles must unload at disposal facilities as they fill, stops have service windows, and drivers must take breaks. Together these make manual planning slow and inconsistent, whereas an optimisation model can search a vast number of combinations of assignments and sequences. The proposed algorithms were deployed for real collection problems at Waste Management, Inc., which operates nearly 26,000 collection and transfer vehicles.

3.2 Modelling and problem formulation

Type of problem: A VRPTW variant with intermediate facilities, in which a vehicle may visit a disposal site several times during one route.

Objective: Efficient routes that serve all stops while using few vehicles and little travel. Later studies that compare their results against this article measure it by distance travelled and number of vehicles used (Benjamin & Beasley, 2010).

Constraints (as described in the article): Each stop is served once within its time window; vehicle capacity is respected, with load reset to zero at each disposal visit; every route starts and ends at the depot; each driver receives a lunch break.

Mathematical model: The article's contribution is the problem definition, benchmark data and algorithm. The standard mixed-integer form of this problem class is given below for explanation; the notation is the

author's own representation and not a reproduction of the article's equations.

- Sets: depot 0; customer stops C; disposal facilities D; all nodes N = {0} ∪ C ∪ D
- Parameters: travel time and distance $t_{ij}$, $d_{ij}$; demand $q_i$; service time $s_i$; time window $[e_i, l_i]$; vehicle capacity Q; lunch-break window and duration
- Variables: $x_{ij} = 1$ if a vehicle drives directly from i to j; $a_i$ = start time of service at i; $u_i$ = load on board after serving i

Objective: minimise $\Sigma\, d_{ij} \cdot x_{ij}$ (and, in a hierarchical form, the number of vehicles used)

(1) Every customer stop is entered and left exactly once.
(2) Flow conservation: arrivals at each node equal departures from it.
(3) Time feasibility: if $x_{ij} = 1$ then $a_j \geq a_i + s_i + t_{ij}$, and $e_i \leq a_i \leq l_i$.
(4) Load: if $x_{ij} = 1$ and $j \in C$ then $u_j = u_i + q_j \leq Q$; if $j \in D$ then the load resets to 0.
(5) A lunch break of the required length is scheduled within its permitted window on each route.

Assumptions. Demand at each stop is known in advance and served in one visit; the fleet is homogeneous; travel times are deterministic.

3.3 Solution methodology

Because real instances are too large for exact methods, the authors extend Solomon's well-known insertion algorithm so that it handles disposal trips and lunch breaks. They also release a set of waste collection VRPTW benchmark problems, which became the standard test bed for later work. Validation therefore had two forms: performance on the benchmark instances and successful deployment in the live operations of Waste Management, Inc. Later metaheuristic studies reported better solutions on the same benchmarks in distance and number of vehicles, which shows both the value of the benchmark set and the room left by the original heuristic (Benjamin & Beasley, 2010).

3.4 Findings and implications

The article's main results are a precise formal definition of the waste collection VRPTW, the benchmark instances, and a practical algorithm that was put into production at a major operator. Its impact is methodological as much as practical: it established the problem as a research topic and gave researchers a common test bed.

3.5 Critical reflection

- Strengths: realistic features (disposal trips, lunch breaks, time windows), industrial deployment, and public benchmarks that allow fair comparison.
- Limitations: an insertion heuristic gives no guarantee of optimality and no bound on the gap; the focus on commercial collection excludes residential door-to-door routing; demand and travel times are treated as deterministic.
- Extensions: stronger metaheuristics such as tabu search and variable neighbourhood search (Benjamin & Beasley, 2010), adaptive large neighbourhood search, stochastic demand and travel times, and fuel or emissions objectives.

## IV. ARTICLE 2: BONOMO, DURÁN, LARUMBE AND MARENCO (2012), A METHOD FOR OPTIMIZING WASTE COLLECTION USING MATHEMATICAL PROGRAMMING: A BUENOS AIRES CASE STUDY

4.1 Real-life context

- Problem: A new residential waste collection system being implemented in Buenos Aires required residents to deposit their garbage in dumpster or skip-type containers located throughout the city. The authors optimise the routes of the vehicles that service these containers in the southern zone of the city. Each collection vehicle can hold 15,000 kg of waste, and the purpose of the study was to improve the routes then followed by the vehicles.
- Domain: Urban public services and logistics.
- Why OR is suitable: The street network can be represented as a graph, so that graph theory and mathematical programming can be applied. Reducing the problem to a classic, well-studied TSP allows the use of a highly efficient, proven exact solver.

4.2 Modelling and problem formulation

Type of problem: The waste collection problem is reduced to the classic TSP.

Objective: Minimise the distance travelled by each collection vehicle. In addition to this typical criterion, the study adds the objective of reducing vehicle wear and tear, measured by the physical concept of mechanical work.

Constraints: Every container on a vehicle's route is visited exactly once and the route forms a single closed tour. Vehicle capacity is not part of the TSP: the containers assigned to each vehicle are taken as given, and only the visiting order is optimised. Street directions matter, because many streets are one-way, so a data correction process described in the article is applied to the street network before solving.

Mathematical model: The standard integer programming form of the TSP is shown below to explain the problem class; it is the textbook formulation and not a copy of the article's notation. It is written in symmetric form for simplicity. Because the Buenos Aires network has one-way streets, the cost of travelling from i to j can differ from j to i, so the real instance is an asymmetric TSP, in which each node has exactly one incoming and one outgoing arc instead of degree 2.

- Variables: $x_e = 1$ if edge $e = \{i, j\}$ is used in the tour, 0 otherwise
- Parameters: $c_e$, the cost of edge e (distance, or mechanical work in the wear-based version)

Objective: minimise $\Sigma\, c_e \cdot x_e$

(1) Degree constraints: $\Sigma\, x_e$ over the edge's incident to node i equals 2 for every node i

(2) Subtour elimination: for every proper subset S of nodes, $\Sigma\, x_e$ over the edges with both ends in S is at most $|S| - 1$

Assumptions. Costs are fixed and direction-dependent (one-way streets); the collection process can be represented as a graph after data correction; the set of containers served by each vehicle is fixed before routing.

4.3 Solution methodology

The reduced problem is solved with the Concorde solver, a specialised exact TSP code, combining graph theory with mathematical programming. Validation had two parts. First, the input data were checked: the traffic directions of many streets in the four collection zones, particularly those used in the optimal routes, were verified against other digital maps and aerial photographs. Second, the optimised routes were compared with the routes actually followed in the areas studied.

4.4 Findings and implications

The optimised routes reduced the distance travelled by each vehicle by 10% to 40% compared with existing routes. The shorter distances led in turn to substantial decreases in work done and therefore in vehicle wear and tear. Extrapolating to the entire southern zone of Buenos Aires indicates potential savings of more than US$200,000 per year for the civic authorities, in addition to less traffic disruption, less driver fatigue and less pollution.

4.5 Critical reflection

- Strengths: an exact method with proven optimal tours, a real case with measured savings, transparent treatment of data quality, and a second objective (wear) that matters to the operator.
- Limitations: the TSP reduction suits skip-container collection and does not carry over directly to door-to-door residential collection; capacity and the split of containers between vehicles are fixed outside the model; time windows and traffic are not modelled; the savings estimate is an extrapolation from sampled areas.
- Extensions: a capacitated model that also decides which vehicle serves which container, time windows and driver shifts, dynamic re-optimisation as container fill levels change, and integration with fleet sizing.

## V. COMPARATIVE ANALYSIS

| Dimension | Kim et al. (2006) | Bonomo et al. (2012) |
|---|---|---|
| Problem type | VRPTW with disposal trips | TSP (skip containers) |
| Solution philosophy | Constructive heuristic | Exact solver |
| Optimality guarantee | No | Yes, for the reduced problem |
| Capacity handling | Inside the model (disposal trips) | Outside the model (containers pre-assigned) |

| | | |
|---|---|---|
| Scale | Large commercial fleets | Zone-level collection |
| Evidence of impact | Deployment and benchmarks | 10–40% shorter routes; savings above US$200,000 per year |
| Cost driver | Distance and vehicles | Distance and mechanical work |

The two articles show a central trade-off in OR practice. Rich, realistic constraints push towards heuristics, while a simplified structure allows exact optimisation. Both are legitimate; the choice depends on problem size, data quality and the cost of a suboptimal plan.

Wider literature: Other studies fill in the picture. Benjamin and Beasley (2010) apply tabu search and variable neighbourhood search to the Kim et al. benchmarks, with up to 2,092 customers and 19 disposal facilities, and improve on earlier results. Wy, Kim and Kim (2013) extend the problem to roll-on–roll-off containers using large neighbourhood search. Tavares et al. (2009) use 3D GIS modelling in Cape Verde and show that minimising fuel rather than distance saved 8% in Praia, even though the fuel-optimal route was 1.8% longer. Yalçınkaya and Kaleli (2025) configure a GIS vehicle routing solver to mimic capacitated arc routing in İzmir, cutting distance by 21.47% and fuel by 24.57%. In India, Ghose, Dikshit and Sharma (2006) built a GIS minimum-cost routing model for Asansol, and Joshi, Sharma and Kumar (2021) proposed a routing model for Jaipur using ArcGIS. The Indian studies rely mainly on GIS shortest-path tools and rarely state a full mathematical model or compare against heuristic baselines, and none of the studies found models a Mumbai ward. Section 6 addresses this gap.

## VI. ILLUSTRATIVE APPLICATION: A CVRP MODEL FOR K/WEST WARD, MUMBAI

To demonstrate the mathematical modelling in full, this section formulates and solves a CVRP on public data for Mumbai. It is an original illustration, not one of the two analysed articles.

### 6.1 Study area and data

K/West ward covers Andheri West, Juhu, Vile Parle West and Jogeshwari West. RTI data for 2025 put its population at 788,691 and waste lifted at 113,515 tonnes, about 311 tonnes per day (0.39 kg per person). It has the most bulk-waste-generator societies in Mumbai, 392, of which 95% hand their waste to BMC (Praja Foundation, 2026). The ward lies next to the Versova Lagoon Refuse Transfer Station (VLRTS), one of the transfer points for Mumbai's ward waste (Municipal Corporation of Greater Mumbai, n.d.).

The instance models one collection shift: compactors start empty at VLRTS, collect from 13 secondary collection points and return to VLRTS to unload. VLRTS therefore acts as both depot and disposal site, which is standard for transfer-station systems.

Table 1. Collection points, approximate coordinates, road distance to VLRTS and waste per shift.

| Node | Collection point | Lat, long (approx.) | Road km to VLRTS | Waste (t) |
|---|---|---|---|---|
| 0 | Versova Lagoon RTS (depot) | 19.1385, 72.8135 | 0.00 | – |
| 1 | Juhu Beach / Juhu Tara Road | 19.0988, 72.8265 | 6.47 | 4.5 |
| 2 | JVPD Scheme | 19.1075, 72.8360 | 5.85 | 3.0 |
| 3 | Vile Parle West (Irla) | 19.1030, 72.8395 | 6.72 | 4.0 |
| 4 | Gulmohar Road | 19.1135, 72.8385 | 5.35 | 2.5 |
| 5 | D.N. Nagar | 19.1260, 72.8320 | 3.35 | 3.5 |
| 6 | Four Bungalows | 19.1300, 72.8250 | 2.15 | 3.0 |
| 7 | Seven Bungalows | 19.1300, 72.8180 | 1.48 | 3.5 |
| 8 | Lokhandwala Complex | 19.1405, 72.8270 | 2.01 | 4.5 |
| 9 | Oshiwara | 19.1500, 72.8340 | 3.51 | 4.0 |
| 10 | Jogeshwari West | 19.1390, 72.8450 | 4.63 | 3.5 |
| 11 | Amboli | 19.1290, 72.8440 | 4.72 | 3.0 |
| 12 | Azad Nagar | 19.1275, 72.8375 | 3.92 | 2.5 |
| 13 | Andheri Market (S.V. Road) | 19.1185, 72.8460 | 5.70 | 4.0 |
| | Total | | | 45.5 |

Data construction: The ward total and facilities are published data. Collection-point locations are well-known localities placed at approximate coordinates, because BMC does not publish bin-level locations or routes. Distances are straight-line (haversine) distances multiplied by a road circuity factor of 1.4, a common approximation for dense urban grids; 1.3 is tested as a sensitivity case. The 45.5 tonnes for the shift (about 15% of the ward's daily 311 tonnes) is allocated across points in proportion to local density and commercial activity, so these are estimates, not measured weights. The compactor payload is 10 tonnes per trip, in line with BMC's shift towards high-capacity enclosed vehicles (Free Press Journal, 2026); 8 and 12 tonnes are tested. The method is built so that GPS-measured distances and weighbridge data can replace the modelled inputs directly.

6.2 Mathematical model

The problem is a symmetric CVRP written as a two-index mixed-integer linear programme with Miller–Tucker–Zemlin (MTZ) load constraints.

Sets and parameters: $N = \{0, 1, \ldots, 13\}$ is the set of nodes, where 0 is VLRTS, and $C = N \setminus \{0\}$ is the set of collection points. $d_{ij}$ is the road distance from i to j (km); $q_i$ is the waste at point i (tonnes); $Q = 10$ tonnes is the vehicle payload; $K_{min} = \lceil \Sigma\, q_i / Q \rceil = \lceil 45.5 / 10 \rceil = 5$ is the minimum number of trips.

Decision variables: $x_{ij} \in \{0, 1\}$ equals 1 if a vehicle travels directly from i to j; $u_i$ is the cumulative load of the vehicle after leaving point i, with $q_i \le u_i \le Q$.

Objective: Minimise total distance: $Z = \Sigma_{i \in N} \Sigma_{j \in N,\, j \ne i} d_{ij} \cdot x_{ij}$

Constraints:

(1) $\Sigma_{i \in N,\, i \ne j} x_{ij} = 1$ for all $j \in C$

(2) $\Sigma_{j \in N,\, j \ne i} x_{ij} = 1$ for all $i \in C$

(3) $\Sigma_{j \in C} x_{0j} = \Sigma_{i \in C} x_{i0} \ge K_{min}$

(4) $u_i - u_j + Q \cdot x_{ij} \le Q - q_j$ for all $i, j \in C$, $i \ne j$

(5) $q_i \le u_i \le Q$ for all $i \in C$; $x_{ij} \in \{0, 1\}$

Constraints (1) and (2) ensure every collection point is entered and left exactly once. Constraint (3) balances trips leaving and returning to VLRTS and sets a lower bound on their number. Constraint (4) carries load forward along each route: if a vehicle goes from i to j, its load at j must be at least its load at i plus $q_j$. This both enforces capacity and removes subtours that do not pass through the depot. The model has 182 binary variables, 13 continuous variables and 184 constraints.

Assumptions: (1) Each point is fully served by one vehicle visit and waste is not split across trips. (2) Vehicles are identical and each trip starts and ends empty at VLRTS. (3) Distances are symmetric and fixed, so traffic, one-way streets and time of day are ignored. (4) There are no time windows or shift-length limits; five trips of 7–15 km fit within one shift. (5) Distance is the cost driver, so fuel and wear scale with kilometres travelled.

6.3 Solution methodology and validation

The model was coded in Python 3 with the PuLP modelling library and solved with HiGHS, an open-source branch-and-cut solver for mixed-integer programmes. HiGHS proved optimality in about 10 seconds on a standard cloud machine, so no heuristic is needed at this scale. For comparison, two heuristics that reflect how routes are often built by hand were also run:

- Nearest neighbour (NN): from VLRTS, the vehicle repeatedly drives to the closest unvisited point that still fits in its remaining capacity, then returns to unload.
- Clarke–Wright savings (CW): every point starts on its own out-and-back trip, and trips are merged in order of the distance saved, $s_{ij} = d_{0i} + d_{0j} - d_{ij}$, as long as the merged load stays within Q.

Three validation checks were applied:

First, every route in every solution was re-checked to confirm that each point is served once and no trip exceeds 10 tonnes. Second, the exact optimum must be no longer than either heuristic, which it is. Third, the optimal number of trips (five) equals the theoretical minimum $K_{min}$, so the solution is fleet-efficient as well as distance-efficient. Sensitivity runs then varied vehicle capacity (8, 10 and 12 tonnes) and the circuity factor (1.3 and 1.4).

6.4 Results

The exact model serves all 13 points in five trips totalling 54.5 km, with vehicles loaded to 91% of capacity on average. Each trip covers a compact cluster, and the two longest trips are the ones that reach the southern end of the ward near Juhu and Vile Parle (Figure 1).

Table 2. Optimal trips from the exact model.

| Trip | Route (from and back to VLRTS) | Load (t) | Distance (km) |
|---|---|---|---|
| 1 | Juhu Beach → Vile Parle West (Irla) | 8.5 | 15.21 |
| 2 | JVPD Scheme → Gulmohar Road → Andheri Market | 9.5 | 13.90 |
| 3 | Seven Bungalows → D.N. Nagar → Four Bungalows | 10.0 | 6.98 |
| 4 | Oshiwara → Lokhandwala Complex | 8.5 | 7.32 |
| 5 | Jogeshwari West → Amboli → Azad Nagar | 9.0 | 11.09 |
| | Total | 45.5 | 54.50 |

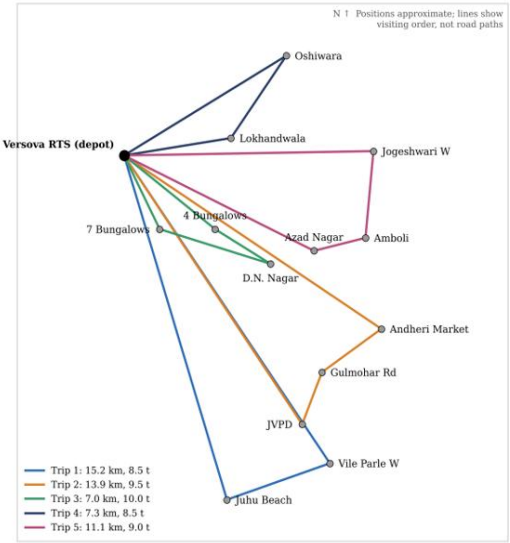


Figure 1. Optimal collection trips in K/West ward (exact CVRP solution, payload 10 t).

Comparison with heuristics: Nearest neighbour reaches 55.8 km in five trips, only 2.3% above the optimum, because the network is small and clustered. Clarke–Wright performs worse here, at 59.2 km and six trips (8.6% above optimum), because its early merges fill some trips unevenly and leave Lokhandwala on a trip of its own. A single heuristic can look reasonable yet be noticeably off, and only an exact solution shows how far off it is.

Table 3. Sensitivity to vehicle payload (circuity factor 1.4).

| Payload | Nearest neighbour | Clarke–Wright | Exact optimum |
|---|---|---|---|
| 8 t | 75.9 km, 7 trips | 71.0 km, 7 trips | 64.9 km, 6 trips |
| 10 t | 55.8 km, 5 trips | 59.2 km, 6 trips | 54.5 km, 5 trips |
| 12 t | 46.3 km, 4 trips | 46.6 km, 4 trips | 46.0 km, 4 trips |

Vehicle capacity matters far more than route order. At 8 tonnes the optimum needs six trips and 64.9 km; at 12 tonnes it needs four trips and 46.0 km, 29% less. The gap between heuristics and the optimum shrinks as capacity grows, from up to 17% at 8 tonnes to under 1.5% at 12 tonnes, because fewer, fuller trips leave less room for poor sequencing. Changing the circuity factor from 1.4 to 1.3 scales all distances down by about 7% but leaves the optimal trip structure unchanged, so the conclusions do not depend on that assumption.

6.5 Implications for BMC

K/West's 311 tonnes per day equal roughly 6.8 shifts of this size. Scaling the per-shift saving of the optimum over Clarke–Wright (4.7 km) gives about 11,700 km a year. At an assumed 3 km per litre and ₹90 per litre of diesel, that is about 3,900 litres and ₹3.5 lakh a year for one ward, before driver-hours and wear. Moving from 8-tonne to 10-tonne compactors saves about 10.4 km per shift on its own, or roughly 25,900 km a year. This supports BMC's 2026 decision to replace its fragmented fleet with fewer high-capacity vehicles under ward-wise contracts (Free Press Journal, 2026), and suggests that routing should be re-optimised whenever fleet capacity changes.

## VII. CRITICAL REFLECTION

7.1 Strengths of the modelling approaches

The literature and the Mumbai illustration show three strengths. Exact formulations give a transparent, testable benchmark and a proven optimum, as in Bonomo et al. (2012) and Section 6. Heuristic approaches such as Kim et al. (2006) scale to real fleets

and can include operational rules that are hard to formulate exactly. Open tools (Concorde, HiGHS, Python) mean that no expensive commercial solver is needed.

7.2 Limitations and assumptions

- Modelled inputs in the Mumbai case. Point-level waste quantities are allocated estimates and road distances use a circuity factor, because BMC does not publish bin-level weights or GPS routes.
- Static, deterministic models. All the models discussed treat demand and travel time as known. Traffic congestion, monsoon disruption and day-to-day variation in waste volume are not captured.
- Single depot. The Mumbai model omits the ward garage as a separate start point and the onward transfer to Kanjurmarg.
- Distance as the main cost. Tavares et al. (2009) show that fuel-optimal routes can differ from distance-optimal ones once vehicle load and gradient are included.
- Scale. Thirteen aggregated points stand in for hundreds of door-to-doors stops, so the full ward would need decomposition or metaheuristics.

7.3 Possibilities for extension and improvement

- Replace estimates with GPS traces and weighbridge records from BMC's integrated ward contracts.
- Add time windows for markets and commercial streets and driver shift limits, turning the model into a VRPTW as in Kim et al. (2006).
- Use a load-dependent fuel objective, or a multi-objective model that also counts CO2, following the wear-based objective of Bonomo et al. (2012) and the fuel-based approach of Tavares et al. (2009).
- Model separate wet and dry waste streams with their own vehicles and destinations, in line with the Solid Waste Management Rules, 2026.
- Scale to the full ward with a metaheuristic such as tabu search (Benjamin & Beasley, 2010), using the exact model to benchmark it.

## VIII. CONCLUSION

Operations Research gives municipalities a transparent, testable way to plan waste collection. The two articles analysed here show complementary approaches. Kim, Kim and Sahoo (2006) define the waste collection VRPTW and deliver a heuristic that runs in a large commercial operation, while Bonomo et al. (2012) reduce skip-container collection to a TSP, solve it exactly and document route reductions of 10–40% with potential savings above US$200,000 a year. Applied to K/West ward, an exact CVRP served 13 collection points in five fully used trips over 54.5 km, solved to proven optimality in seconds with free software. It beat the Clarke–Wright heuristic by 8.6% and nearest neighbour by 2.3%, and the larger lever was vehicle capacity: moving from 8-tonne to 12-tonne vehicles cut optimal distance by 29%.

Two practical conclusions follow:
First, ward-scale route optimisation no longer needs expensive solvers or specialists, and the binding constraint is data: if BMC published collection-point locations, quantities and routes, models like this one could be run on measured inputs. Second, fleet decisions and routing decisions should be made together, since the value of high-capacity vehicles is only realised when routes are redesigned around them.

Declaration on the Use of Generative AI:
Generative AI tools were used to assist with literature search, drafting, coding the optimisation model and formatting. The author reviewed, edited and verified all content, data, calculations and references, and takes full responsibility for the work.

## REFERENCES

[1]. Benjamin, A. M., and J. E. Beasley, “Metaheuristics for the waste collection vehicle routing problem with time windows, driver rest period and multiple disposal facilities,” Computers & Operations Research, vol. 37, no. 12, pp. 2270–2280, 2010.
[2]. Bonomo, F., G. Durán, F. Larumbe, and J. Marenco, “A method for optimizing waste collection using mathematical programming: A Buenos Aires case study,” Waste Management & Research, vol. 30, no. 3, pp. 311–324, 2012, doi: 10.1177/0734242X11402870.
[3]. Free Press Journal, “BMC begins integrated waste collection system in Worli, Prabhadevi,” Aug. 6, 2026.

[4]. Ghose, M. K., A. K. Dikshit, and S. K. Sharma, "A GIS based transportation model for solid waste disposal: A case study on Asansol municipality," Waste Management, vol. 26, no. 11, pp. 1287–1293, 2006.

[5]. Joshi, V., A. Sharma, and D. Kumar, "Optimization model for collection and transportation of municipal solid waste in Jaipur city," Science & Technology Asia, vol. 26, no. 4, pp. 134–142, 2021.

[6]. Kim, B. I., S. Kim, and S. Sahoo, "Waste collection vehicle routing problem with time windows," Computers & Operations Research, vol. 33, no. 12, pp. 3624–3642, 2006.

[7]. Municipal Corporation of Greater Mumbai, "Refuse transfer station and landfill management," Solid Waste Management Project Overview. [Online]. Available: https://portal.mcgm.gov.in

[8]. Praja Foundation, Report on the Status of Civic Services, Environmental and Climate Issues in Mumbai. Mumbai, India: Praja Foundation, 2026.

[9]. Tavares, G., Z. Zsigraiova, V. Semiao, and M. G. Carvalho, "Optimisation of MSW collection routes for minimum fuel consumption using 3D GIS modelling," Waste Management, vol. 29, no. 3, pp. 1176–1185, 2009.

[10]. Wy, J., B. I. Kim, and S. Kim, "The rollon–rolloff waste collection vehicle routing problem with time windows," European Journal of Operational Research, vol. 224, no. 3, pp. 466–476, 2013.

[11]. Yalçınkaya, S., and H. İ. Kaleli, "Optimizing municipal solid waste collection with GIS-based high-density routing and zoning," Transportation Research Part D: Transport and Environment, vol. 148, Art. no. 105012, 2025, doi: 10.1016/j.trd.2025.105012.