Waste Collection in Urban Areas: A Case Study

Group 10

Introduction

- Waste collection is significant
  - Increasingly evident problem
    - Population growth
    - Urbanization
  - Influence over broader urban management
    - Economic: cost-efficient services
    - Administrative: disposal frequencies, taxes
    - Social&Environmental: direct consequences
- Optimization yields substantial advantages

A Project and Methodology

- Optimization for Networked Data in Environmental Urban Waste Collection (ONDE-UWC)
  - Yields a solution
  - Funded by the Regional Council of Piedmont
  - Applied in Turin, Italy

- GUEST OR
  - Defines project management steps
  - Lean business methodology
  - OR-customized version of GUEST methodology
  - Originated from Politecnico di Torino

3 innovative contributions

1. ONDE–UWC: flexibility in waste management
2. GUEST OR in project management and development
3. Addressing the «disjunction»

Flexibility in waste management

- No fixed disposal frequencies – dynamic schedules
  - Historical data
  - On-vehicle weight systems
  - Network of sensors

- All these are incorporated into a mathematical heuristic optimization algorithm

GUEST OR in Project Man&Devp.

- Different stakeholders with different issues
- Multiple-actor conplex system (MACS)
- Defining a waste collection scenario as such

Addressing the disjunction

- Business solutions v. Technical solutions
- Difficulty to communicate results to nontechnical stakeholders
- A comprehensive framework of implementation will be presented in this paper.

Problem Statement

Problem Statement

- Waste management involves decisions:
  - Strategic: technologies, locations
  - Tactical: fleets, weekly schedules
  - Operational: vehicle routing and scheduling

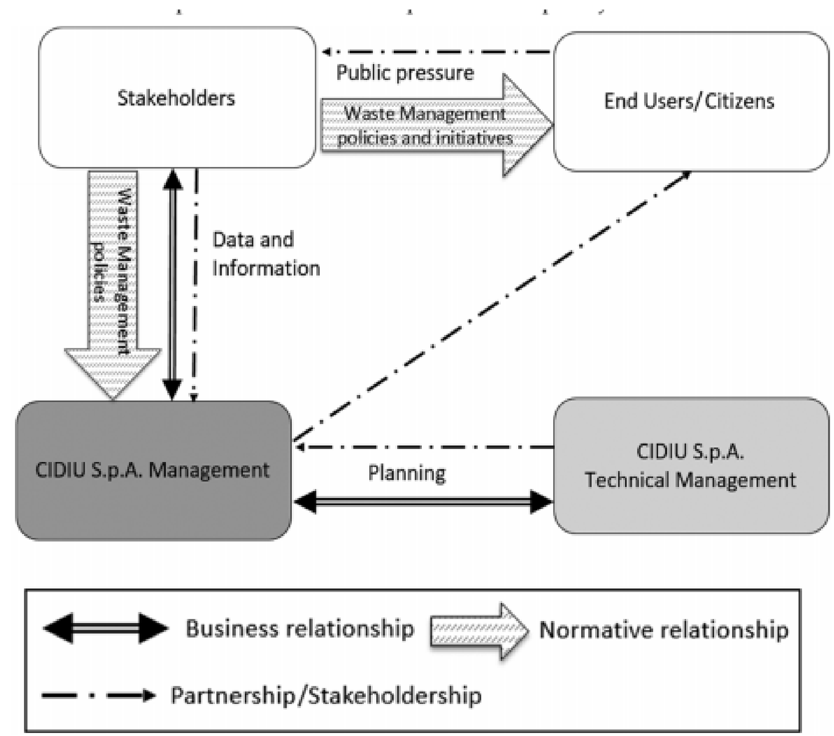
- Waste collection problems require multiple frameworks
- Predetermined set of dumpsters
- Districts require benchmarks for service levels and frequencies to be met

Waste Management in Urban Areas: A Multiple-Actor Complex System

GUEST methodology aims to implement a project correctly and develop a solution by always considering the stakeholder requirements.

- MACS of Waste Management:

-Cidiu S.p.A Management:
-Responsible for waste-collection service.
-10 municipalities
  - Information flow from and to stakeholders such as local administrators.
  - Normative relationship with stakeholders, business relation with technical management of Cidiu.

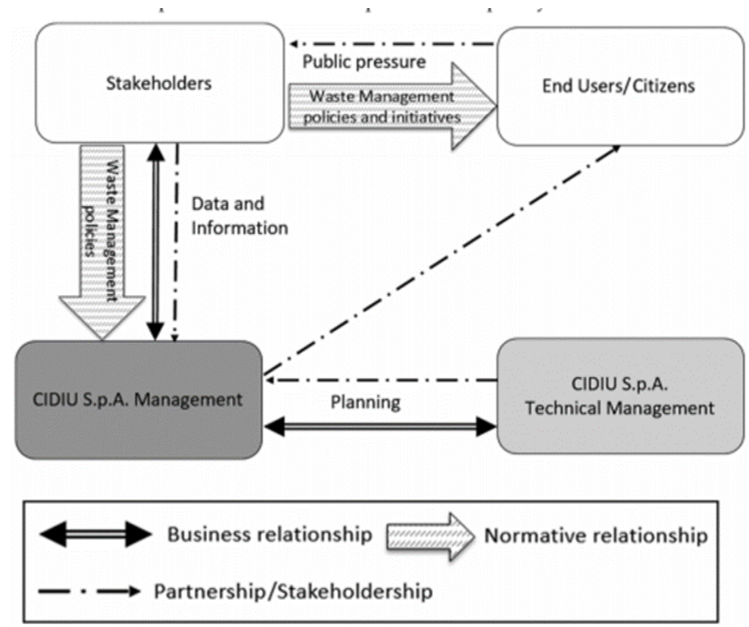


- Cidiu S.p.A Technical Management:

-Chief Operating Officer(COO) and Team Leaders

-Weekly operations of services. Routes, shifts, disposal activities

-Team leader formulates and COO advises.



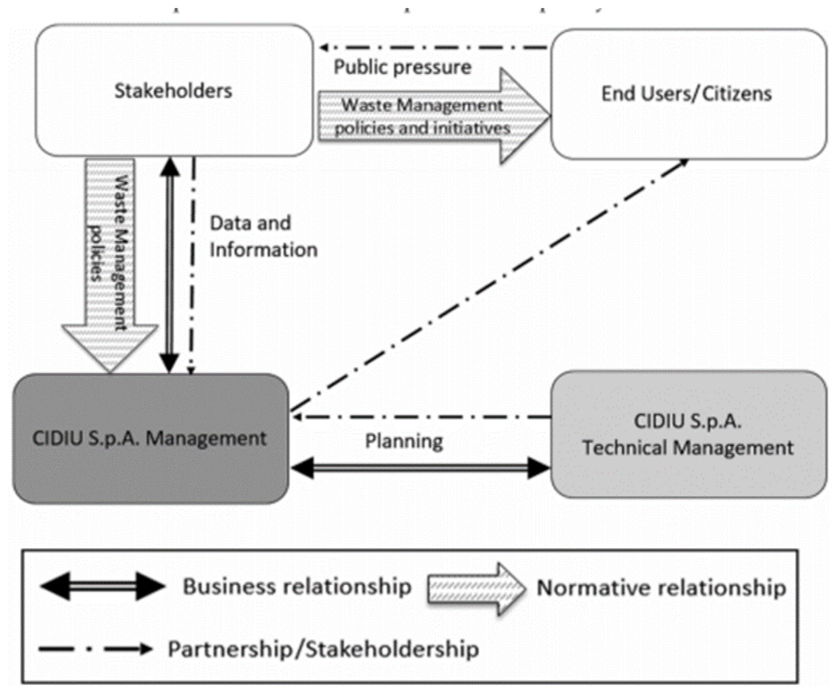
- End Users:

–Citizens

–Generate and collect waste.

–Cost of taxes imposed by administrators are within their interest.

–Public pressure to stakeholders.

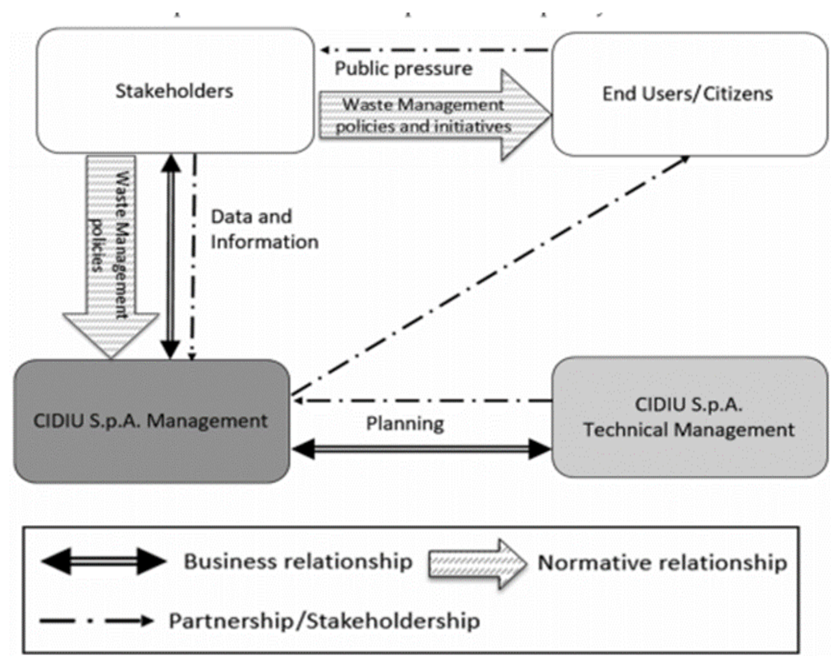


- Stakeholders:

-Local and regional administrators.

-They manage urban waste-collection services, collect taxes, generate reports periodically.

-Use the data gathered by the waste-collection firms.



ONDE-UWC Value Propositions:

Figure A.1. Value Proposition of Cidiu S.p.A. Management

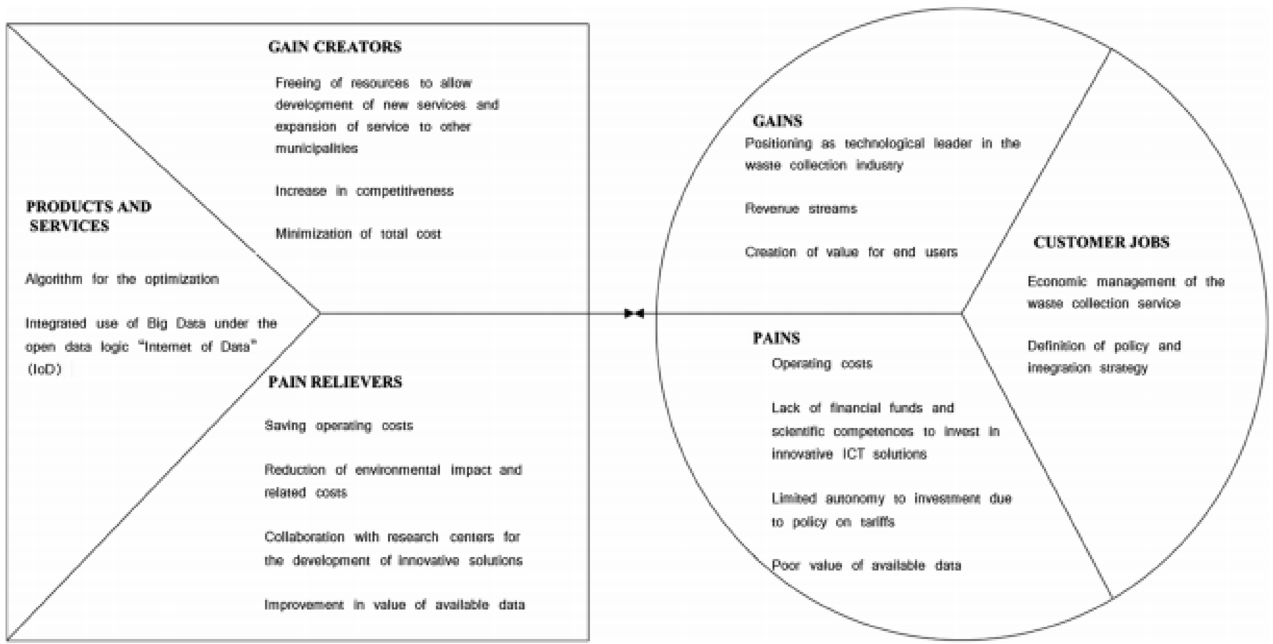
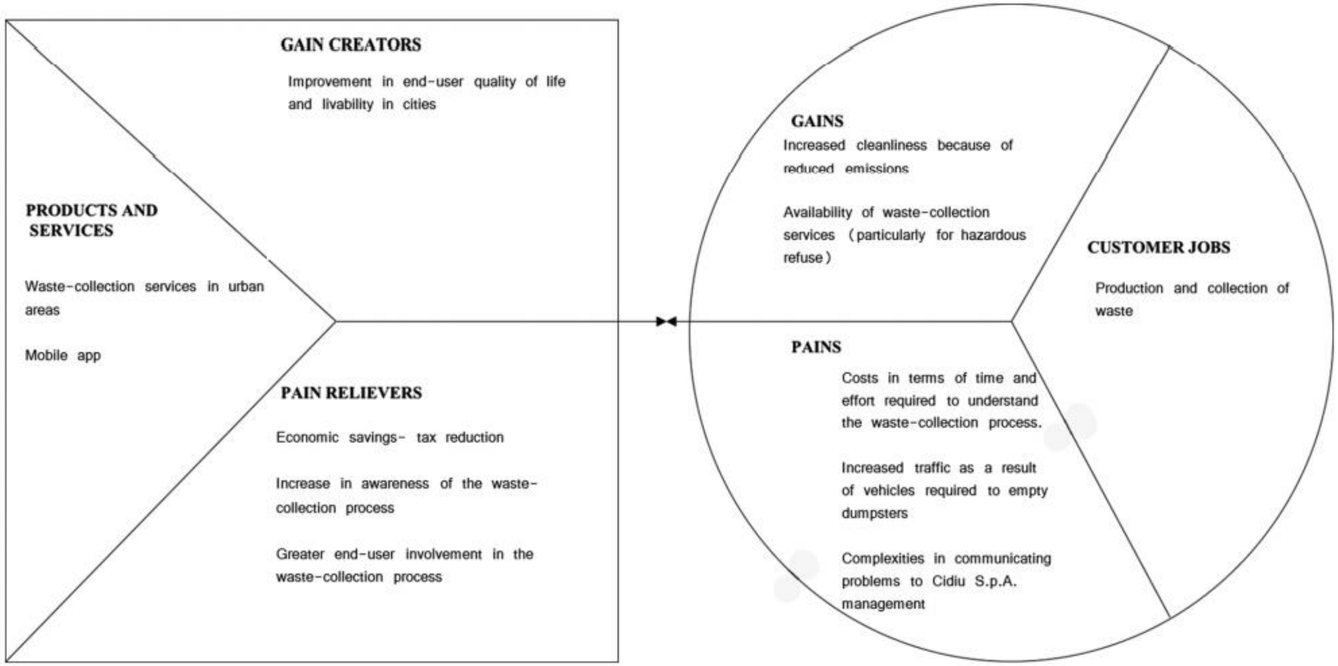
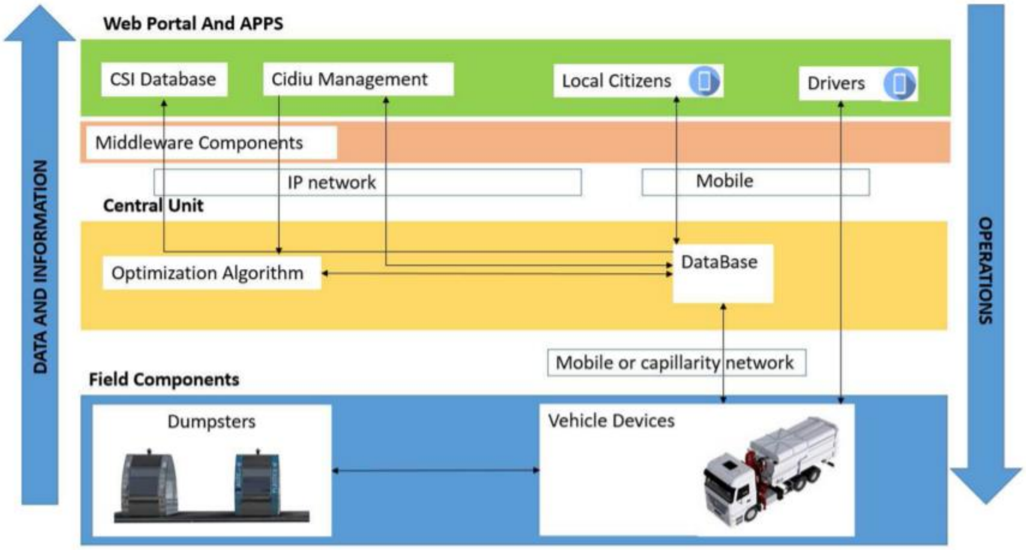


Figure A.3. Value Proposition of End Users

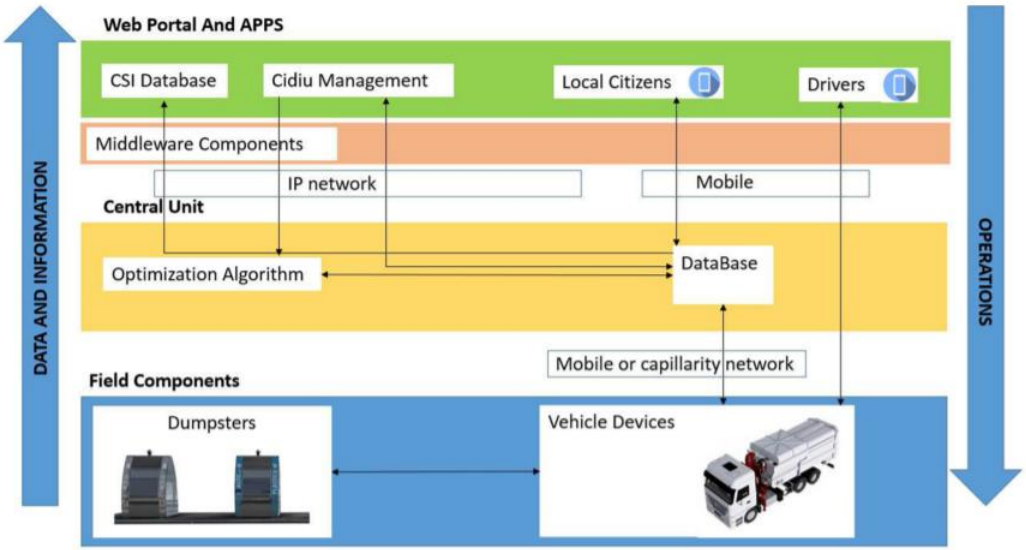


Solution Implementation



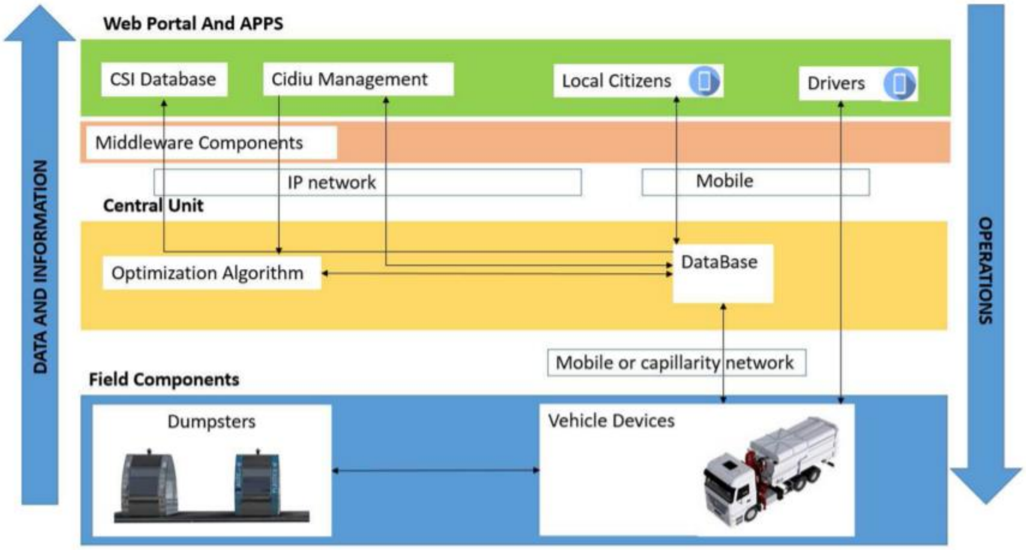
- **Central Unit:** Information management and optimization.
- **CSI (Consorzio per il Sistema Informativo) Database:** Data related to waste collection in the region

Solution Implementation



- **Enabling Technologies:** The internal and external technologies that enhance the decision-making process
- **Middleware Components:** Allows data exchange between the enabling technologies and the communication network.
- **The IP Network and Mobile network:** Channels used by the application. The central unit manage

Solution Implementation



- The timing of each operation differs
- the optimization algorithm is run three times each day

Computational Tests and Results

- Applying GUEST OR methodology: Development time is reduced to less than one month from the beginning of the project

- Without GUEST OR, it was 4 months.

6 Key Performance Indicators

- Average number of third shifts during a week of activity (nTS)
- Average number of vehicles used daily (nV)
- Average percentage of waste volume at the moment of collection (WV%)
- Total routing time (TRT)
- Average fulfillment percentage of the vehicles (FV%) for each time shift during which a vehicle is used
- Average number of dumpsters visited during each time shift in which when a vehicle is used (nVD)

Before and After the Algorithm (Heuristic) is Applied

Table 1. For Each KPI, We Compare the Solution Before and After Using Our Proposed Algorithm

KPIs	Cidiu S.p.A. solution	Simulated solution
nTS	1.44 (0.5)	0 (0)
nV	3 (0)	2 (0)
WV%	0.28 (0.10)	0.70 (0.05)
TRT	4.35 (0.5)	5.24 (0.3)
FV% (%)	54 (10)	87 (5)
nVD	62.3 (12)	68.5 (12)

Comparison between Heuristic and Optimal Solution Obtained by CPLEX

Table 2. Comparing Cidiu S.p.A.'s Optimal Solutions and the Solutions Generated Using our Proposed Approach

No. of dumpsters	nTs [%]	rC [%]	Optimal time [s]	Heuristic time [s]
10	0 (0)	0 (0)	43.43 (1.64)	2.76 (0.65)
20	0 (0)	0 (0)	150.43 (10.89)	3.73 (0.56)
30	0 (0)	1.75 (1.38)	443.64 (15.92)	8.56 (0.84)
40	0 (0)	2.69 (1.43)	890.67 (30.53)	13.36 (0.74)
50	0 (0)	3.32 (2.34)	1842.86 (45.65)	26.27 (2.45)

Notes. We computed all values by using six time periods and two types of waste. Column 1 shows the number of dumpsters; column 2 shows the percentage difference in the number of time shifts (nTs); column 3 shows the percentage difference in the routing cost (rC); and columns 4 and 5 report the computational time of CPLEX and our proposed heuristic.

Waste Collection Systems in Turkey

The concept of transfer centers has been emerged in Istanbul to reduce waste logistic costs, decrease traffic load and save time. Domestic solid wastes collected daily by district municipalities throughout Istanbul are transferred to larger vehicles at 8 solid waste transfer stations serving in various parts of the city and transported to disposal sites.

- Reduce traffic load.
- Reduce CO_2 Emissions, noise and visual image pollution.
- Save fuel, labor and time.
- Reduce transportation costs due to being economy-friendly systems.
- Reduce need for tools and equipment for waste collection.

Waste Collection Systems in Turkey

5.1. The Weighted Sum Method

The oldest and most widely used method of combining objectives. Ease of use and user preferences are advantages to reflect on the model. All effective solution to generate value in the field and has the condition of being convex objective functions.

Let $\lambda \geq 0$

$$Min\ \{\sum_{k=1}^{p} \lambda_k f_k(x): x \epsilon X\} \quad (1)$$

5.2. The ϵ-Constraint Method

Unlike the weighted sums instead of combining the objectives, this method adds to one of the others when optimizing the objective constraints. The solution that found is at least a weakly efficient solution. Convexity does not need the requirement. Determining the stage of the constraint values are cumbersome.

$$f_k(x) \leq \epsilon_k, \quad k=1,\ldots,p, \quad j \neq k \quad (2)$$
$$\text{Min } f_j(x) \quad (3)$$

5.3. The Hybrid Method

In the hybrid method, the weighted sum of the objective function under constraints imposed on all objective function minimization. Convexity does not need the requirement. User preferences may reflect the model. But just reach the point that can be supported by a linear function.

$$f_k(x) \leq f_k(x^0), \quad k=1,\ldots,p \quad (4)$$
$$Min\ \sum_{k=1}^{p} w_k f_k(x) \quad (5)$$

5.4. The Elastic-Constraint Method

Epsilon constraints set for inclusion in the methods of the constraints in the objective function is difficult to solve the problem. Elastic constraint method, ε-constraint loosening the constraints allowed deviation due to a penalty. There are computational difficulties associated with penalty function. The decision-makers are not taken into account the weight of preference.

$$f_k(x) - s_k \leq \varepsilon_k, \quad k=1,\ldots,p, \quad j \neq k \quad (6)$$
$$s_k \geq 0, \quad k=1,\ldots,p, \quad j \neq k \quad (7)$$
$$Min\ \sum_k f_j + \sum_{k \neq j} M_k S_k \quad (8)$$

5.5. The Benson Method

The basic idea is choosing a suitable solution $x^0 \in X$ point of the are to find pareto effective value depending on this point. $l_k = f_k(x^0) - f_k(x)$ is added as non-negative deviation variables. The sum of the deviation variable is minimized. Benson method's constraints are more flexible than epsilon-constraint method. Its implementation is easy. This method needs an initial appropriate solution.

$$f_k(x^0) - l_k - f_k(x) = 0, \quad k=1,\ldots,p \quad (9)$$
$$l_k \geq 0, \quad k=1,\ldots,p \quad (10)$$
$$Min\ \sum_k l_k \quad (11)$$

5.6. The Augmented Weighted Tchebycheff Function Method

In which ρ is sufficiently small positive number. y_k^*: k^{th} reference value for the objective function (ideal point) and p is the number of objectives. In recent years, methods based on the tchebycheff metric has been the most popular multi-purpose tool used in solving the general problem.

$$\text{Min Max } [w_k (f_k(x) - y_k^*)] + \rho \sum_{k=1}^{p} (f_k(x) - y_k^*) \quad (12)$$
$$\alpha \geq w_k (f_k(x) - y_k^*), \quad k=1,\ldots,p, \quad x \epsilon X \quad (13)$$
$$Min\ \alpha + \rho \sum_{k=1}^{p} (f_k(x) - y_k^*) \quad (14)$$

5.7. The Conic Scalarization Method

The basic idea is to use the support cone instead of finding the pareto efficient support hyperplanes value. It does not require the condition of convexity over the objective functions and appropriate solution area. It was developed to solve the general problem multipurpose. Decision makers reflect the preferences and wishes of the mathematical model.

$$Min\ \alpha \sum_{k}^{p} \left| f_k(x) - a_k \right| + \sum_{k \neq j} w_k (f_k(x) - a_k) \quad (15)$$

Waste Collection Systems in Turkey

6. APPLICATION

In this study, a route plan has developed to collect the medical wastes in hospitals in Eskişehir regularly. Eskişehir map is given in (Figure.1) below. There are 6 hospitals in Eskişehir. A vehicle collect the medical wastes from these 6 hospitals and carry them to the depot to recycle. 6 hospitals and the depot is shown in (Figure.1) with red spots.

Figure 1. *Location of Hospitals and the Depot in Eskişehir*

6.1. Mathematical Model

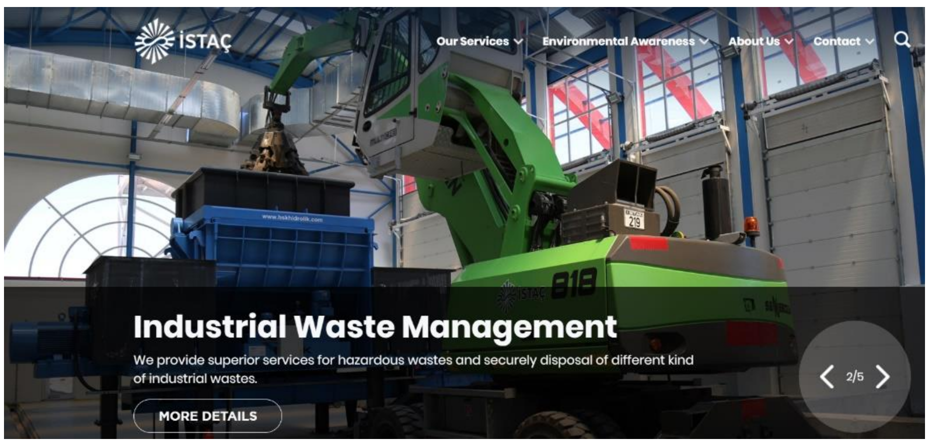
The mathematical model has similarities with travelling salesman. There is no vehicle capacity in this mathematical model. There are two objective functions. These are; minimization of total carrying distance and minimizing of average speed at the hour.

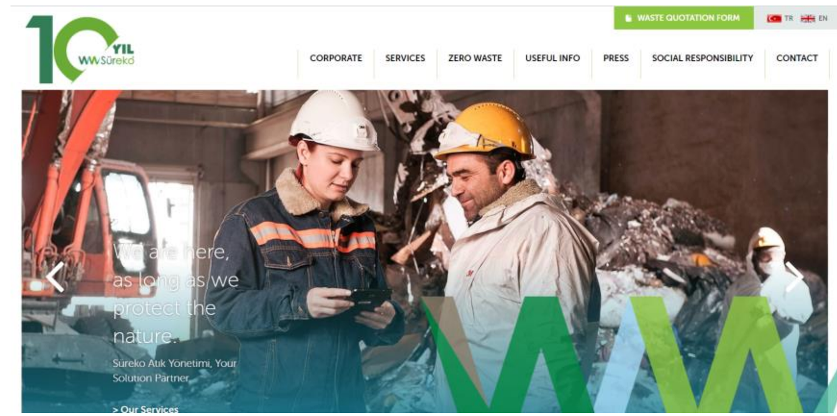
i,j: Transportation node index, i=1,2,3,…7 and j=1,2,3,…,7 customer nodes and i,j=1 is delivery center or depot node.
d_{ij}: Carrying distance from node i to node j.
R: A set of intermediate nodes.
u_i: It has any real value of the node i.
v_{ij}: The maximum speed limit can be entered from the way node i to node j.

$$\min F1 = \sum_{i=1}^{7} \sum_{j=1}^{7} d_{ij} x_{ij} \qquad (16)$$
$$\min F2 = \sum_{i=1}^{7} \sum_{j=1}^{7} v_{ij} . x_{ij} \qquad (17)$$
$$\sum_{i=0}^{N_k} x_{ij} = 1 \qquad \forall j=1,2,\ldots,7 \qquad (18)$$
$$\sum_{i=0}^{N_k} x_{ij} = 1 \qquad \forall j=1,2,\ldots,7 \qquad (19)$$
$$u_i - u_j + n. x_{ij} \leq n - 1 \qquad \forall i \neq j \in R \qquad (20)$$

The equations of (16) and (17) are the objective functions of the mathematical model. (18) and (19) constraints are specified to visit each nodes at least once. Equation (20) denotes the sub-tour elimination constraint. This type of sub-tour elimination constraints, using Gomory cutting planes approach developed by Miller, Tucker and Zemlin in 1960[20]. These constraints took the tour of the state model to inhibit the formation of approximately (n^2-3n+2) lead to the addition of one constraint[21]. In particular, the use of this Miller, Tucker and Zemlin constraints in oversized model is much easier and routing problems is one of the constraints to improved well-received tour blocking.

Waste Collection Systems in Turkey





Technological Constraints

- A dumpster should always be less than 80% full (C.12)
- A working day includes 3 shifts; 6 hours each (C.18)
- Each truck can collect only a specific type of garbage (C.8)
- For each turn (route and time), each dumpster is visited at most by one truck (C.4)

Geographical Data

- Distances between all dumpsters
- Computed using Google
- Constructed a graph; dumpsters as nodes
- Each node is connected to other nodes by arcs

Parametric Sets

- V_1: Set of availabe trucks $i \in V_1$
- V_2: Set of garbage types $s \in V_2$
- V_3: Set of time shifts $t \in V_3$
- V_4: Set of dumpster $j \in V_4$
- V_4 also includes depot ($j=1$) and the dumps ($j=J-s,\ldots,J$)

Parameters

- C_{it}: *Cost of using truck i in shift t (Same for first two shifts and double for third shift)*
- C_{max}: *Maximum duration of a shift (6 hours)*
- $d_{j_1 j_2}$: *Time taken by a truck to travel from dumpster* j_1 *to* j_2
- *C : Maximum volume of a vehicle*
- l_s: *Extra capacity for garbage type s depending on applicability of a press*
- Θ_{jt}: *Volume of waste that arrives at dumpster j at time t (also the quantity of waste at the beginning of shift t)*
- *a: time taken by drivers to collect the waste from dumpster*
- *α: Percentage of dumpster capacity that cannot be exceeded (80%)*
- *λ: Parameter that weighs importance of routing w.r.t operational costs*
- V_j: *Capacity of dumpster j*

Decision Variables

$$w_{it} = \begin{cases} 1, & if\ truck\ i\ is\ used\ during\ shift\ t \\ 0, & otherwise \end{cases}$$

$$z_{ist} = \begin{cases} 1, & if\ truck\ i\ is\ used\ during\ shift\ t\ to\ collect\ garbage\ s \\ 0, & otherwise \end{cases}$$

$$y_{ijt} = \begin{cases} 1, & if\ truck\ i\ is\ used\ during\ shift\ t\ to\ collect\ garbage\ of\ dumpster\ j \\ 0, & otherwise \end{cases}$$

$$r_{j_1 j_2}^{it} = \begin{cases} 1, & if\ truck\ i\ goes\ from\ dumpster\ j_1\ to\ j_2\ during\ shift\ t \\ 0, & otherwise \end{cases}$$

$$x_{ijt} = Volume\ of\ garbage\ collected\ by\ vehicle\ i\ from\ dumpster\ j\ during\ shift\ t$$

$$x_{ijt} = Volume\ of\ garbage\ collected\ by\ vehicle\ i\ from\ dumpster\ j\ during\ shift\ t$$

$$V_{jt} = Volume\ of\ waste\ present\ in\ dumpster\ j\ at\ the\ end\ of\ shift\ t$$

Objective Function

$$\text{minimize} \sum_{i=1}^{I} \sum_{t=1}^{T} c_{it} w_{it} + \lambda \sum_{i=1}^{I} \sum_{t=1}^{T} \sum_{j_1=1}^{J} \sum_{j_2=1}^{J} d_{j_1 j_2} r_{j_1 j_2}^{it}, \qquad \text{(C.1)}$$

- Objective function minimizes cost
- First component is sum of fixed cost for activating truck *i* in shift *t*
- Second is the routing cost

Constraints

$$\text{subject to } w_{it} \geq y_{ijt}, \quad \forall i, j, t; \tag{C.2}$$

$$M y_{ijt} \geq x_{ijt}, \quad \forall i, j, t; \tag{C.3}$$

Constraints linking variables together

$$\sum_{i=1}^{I} y_{ijt} \leq 1, \quad \forall j, t; \tag{C.4}$$

One truck for a dumpster j in shift t

Constraints

$$x_{ijt} \geq V_{jt} - M(1 - y_{ijt}), \quad \forall\, i, j, t; \qquad \text{(C.5)}$$

Similar to MTZ

$$\sum_{j=1}^{J} x_{ijt} \leq \hat{C} + \sum_{s=1}^{S} l_s z_{ist}, \quad \forall\, i, t; \qquad \text{(C.6)}$$

Truck Capacity Constraint

Constraints

$$Mz_{ist} \geq x_{ijt}, \quad \forall i, s, j \in \mathcal{J}^s, t; \tag{C.7}$$

$$\sum_{s=1}^{S} z_{ist} \leq 1, \quad \forall i, t; \tag{C.8}$$

A truck can collect only one type of waste

$$V_{j0} = \Theta_{j0}, \quad \forall j; \tag{C.9}$$

Incoming waste at t =0 in a dumpster

$$z_{ist} \leq y_{i(J-s)t}, \quad \forall i, t; \tag{C.10}$$

Assigning a truck to a dump

Constraints

$$V_{jt} = V_{jt-1} + \Theta_{jt} - \sum_{i=1}^{I} x_{ijt}, \quad \forall j, t \neq 0; \qquad \text{(C.11)}$$

$$V_{jt} \leq \alpha V_j, \quad \forall j, t; \qquad \text{(C.12)}$$

Flow balance and dumpster Capacity constraint

$$w_{it} \geq w_{i+1,t}, \quad \forall t, i = 1{:}I - 1; \qquad \text{(C.13)}$$

Ordering of trucks for a shift t

Routing Constraints

$$\sum_{j_1=1}^{J} r_{jj_1}^{it} = y_{ijt}, \quad \forall\, t, i, j; \tag{C.14}$$

$$\sum_{j_1=1}^{J} r_{jj_1}^{it} = \sum_{j_1=1}^{J} r_{j_1 j}^{it}, \quad \forall\, t, i, j; \tag{C.15}$$

$$\sum_{j=1}^{J} r_{1j}^{it} = w_{it}, \quad \forall\, t, i; \tag{C.16}$$

$$\sum_{j=1}^{J} r_{j1}^{it} = w_{it}, \quad \forall\, t, i; \tag{C.17}$$

Constraints

$$\sum_{j_1=1}^{J}\sum_{j_2=1}^{J} d_{j_1 j_2} r_{j_1 j_2}^{it} + a \sum_{j=1}^{J} y_{ijt} \leq C_{\max}, \quad \forall i,t; \quad \text{(C.18)}$$

$$\sum_{j_1, j_2 \in S, j_1 \neq j_2} r_{j_1 j_2}^{it} \leq |S| - 1, \quad \forall S \subset \mathcal{J}, S \neq \varnothing; \quad \text{(C.19)}$$

Time Shift constraint for a truck *i*

$$x_{ijt} \in \mathbb{R}^{+}, \quad \forall i,j,t;$$

$$z_{ist} \in \{0,1\}, \quad \forall i,s,t;$$

$$y_{ijt} \in \{0,1\}, \quad \forall i,p,t;$$

$$r_{j_1 j_2}^{it} \in \{0,1\}, \quad \forall i,j_1,j_2,t;$$

$$V_{jt} \in \mathbb{R}^{+}, \quad \forall j,t.$$

Problems with MILP

- Too many variables
- Model becomes large
- CPLEX cannot handle such a tremendous amount of memory (Cidiu uses CPLEX)
- Number of variables of order 2^{IJ^2T}
- 3-phase heuristic

3-Phase Heuristic

Clusterization

- Aggregate dumpsters into clusters
- Consider each cluster as a dumpster
- C4 and C5 remove (multiple vehicles can collect waste from the same clusters)
- $d_{c_1 c_2} = min_{j_1 \in c_1, j_2 \in c_2} \; d_{j_1 j_2}$
- $V_c = \sum_{j \in c} V_j$

3-Phase Heuristic

Building a feasible solution

- Second phase produces a feasible solution for the original problem
- Apply the following algorithm

(a) for each $w_{it} = 1$, where $i \in \mathcal{I}$, $t \in \mathcal{T}$;

(b) create the list *list*0 and insert all dumpsters for each cluster, such that $y_{ict} = 1$ where $i \in \mathcal{I}$, $c \in \mathcal{C}$, $t \in \mathcal{T}$;

(c) remove from *list*0 all dumpsters that have been voided;

(d) sort *list*0 in decreasing order of quantity of waste;

(e) create *list*1;

(f) add, one by one, all the dumpsters of *list*0 into *list*1 until constraints (C.6) or (C.18) hold with equality;

(g) if all the dumpsters in *list*0 have been added, then:

i. if there is a dumpster in *list*1 that is γ full or more, go to step (h);

ii. otherwise, go to step (a);

(h) set to zero the percentage of volume occupied from the waste in each dumpster in *list*1. Then, go to step (a).

3-Phase Heuristic

Postoptimization

- Obtain a much better feasible solution for the original problem
- Refine it by considering it a TSP problem
- Chained-Lin-Kernighan heuristic for asymmetric networks (similar to k-opt)

Question:

"What type of a heuristic is this?"
(Construction, Improvement, Meta)

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