A paradigm shift in solid waste collection systems design and operation

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ABSTRACT

A new solid waste collection model, called MST, has been developed. It is a result of combining System Thinking and Aggregation Theory and it takes into account real world constraints such as collection frequency, labor shifts and both preventive and corrective maintenance.

MST is a paradigm shift in solid waste collection systems design and operation. It makes possible a more efficient utilization of resources (vehicles and labor) and it is robust against variability sources. MST is the result of having challenged and invalidated a deeply rooted assumption in all models developed up to date.

Simulation and Design Of Experiments were used to compare MST against existing models. Experimental results show significant reduction in the number of trips (Up to 33%), crews (Up to 49%) and vehicles (Up to 40%), which means dramatic operation cost and investment improvements.

Keywords: Waste Collection, System Thinking, Aggregation Theory, Simulation.

1. BACKGROUND

Variability is a key element in every solid waste collection system. Every day, corrective actions must be taken in order to mitigate its negative effects, which increase operating cost due to the need for more trips, crews, overtime and vehicles. Main variability sources are:

- Total daily amount of waste generated in the collection area.
- The geographical distribution of waste and its weight.
- Vehicles and crews unavailability.
- Unexpected route obstacles.

Even though variability is always affecting operations, very few studies have come up with models that consider it. Everett et al. (1996a), Everett et al. (1996b), Everett et al. (1997) and Wilson et al. (2001) introduced probabilistic models, only for design purpose, that estimate collection times and vehicles and crews required to operate a system.

Also a few research were done applying System Thinking and System Dynamics. Most of these studies used those methodologies just for qualitative analysis or to make long term decisions. Painter et al. (2001), Sudhir et al. (1997) and Mashayekhi (1993) are very interesting models for qualitative or strategic purposes.

Many other methodologies were used to model solid waste collection systems. Angelelli et al. (2002), for instance, used Vehicle Routing Problem algorithms, and Mansini et al.(1998) used linear programming. Tchobanoglous et al. (1994) summarized deterministic models widely used in real world and Hurtado (2004) presents an extensive literature review sorted by deterministic or stochastic models, strategic or tactical decisions, etc.

In spite of the variety of goals and methodologies applied, researches regarding solid waste collection systems showed the same key elements in the way they are designed and managed:

- Collection frequency depends on the waste generation rate and its maximum allowed exposure time.
- Each collection team (vehicle and crew) has an assigned route, where they must collect all the garbage in one shift.
- The number of routes that are being collected at the same time depends on the available number of vehicles.
- Collection area is divided into routes taking into account vehicle capacity, variability in waste generation rates and collection frequency (FR). The number of routes needed in a collection area can be calculated as follows:

$$NR = \left\lceil \frac{TR \times TBA}{CV\,(1 - BCV)} \right\rceil \qquad [1]$$

Where *NR* is the number of routes the collection area is divided in, $\lceil X \rceil$ is the nearest integer equal to or greater than *X*, *TBA* is the amount of waste generated each day in the collection area, *TR* is the collection time interval (1/FR), *CV* is the vehicle capacity, *BCV* is the capacity buffer which is kept in every vehicle in order to deal with variability in the waste volume or weight generated on a route.

The design and operation of a solid waste collection system based on these key elements strongly limit the system ability to deal with variability. In the context of this research, every system designed and operated following these key elements is called “Traditional Model (MT)”.

Aggregation Theory is well known and its practical consequences are widely described in literature:

- In order to meet a system goal, less resources are needed as more functions they share.
- The more aggregated the system goals are, the less buffers are needed for its resources in order to protect the system against variability.
- The less local optima goals the elements of a system must meet, the better the system ability to mitigate negative impact of variability is.

The contradictions between the way a waste collection system is designed and operated (MT) and the practical consequences derived from Aggregation Theory motivated a research focused on challenging basic assumptions existing in the MT model. As a result, several models were developed and one of them, MST, is introduced in this paper. Other models can be found in Hurtado (2004).

2. SYSTEMIC TIME CONSTRAINED MODEL (MST)

As it is known, every model is based on assumptions. A basic assumption in the MT model that was challenged and invalidated is: **"In order to meet the collection frequency, it is necessary to divide the collection area into routes"**. This assumption jeopardizes the system's ability to deal with variability.

MST is a model that meets the following key requirements:

- It takes advantage of Aggregation Theory, so it allows a much better use of resources.
- It ensures to meet collection frequency at every point in the collection area.
- It meets labor shifts duration.
- It works always the same way. Actions to mitigate consequences of variability are inherent to the model.

2.1 Elements of MST

Route

There is only one route that covers all the collection area. All the teams move through the same route.

Team buffer

It is a place where available vehicles and crews are waiting for a trip to be assigned. There is only one team buffer. Figure 1 shows teams movement through the collection area.

Capacity control mechanism

Each vehicle in operation has a capacity control mechanism. Its function is to coordinate the team replacement as soon as a vehicle in operation completes its capacity. It is like a traffic light (Green, Yellow and Red). The team buffer manager must not take any action as long as every capacity control mechanism is in Green. The yellow zone in an operating team means that the team buffer manager must start preparation of a new one. As soon as that operating team enters the Red zone, the replacement team is launched to replace the operating team when its capacity is full. Figure 2 shows the zone sizing and colours for the capacity control mechanism.

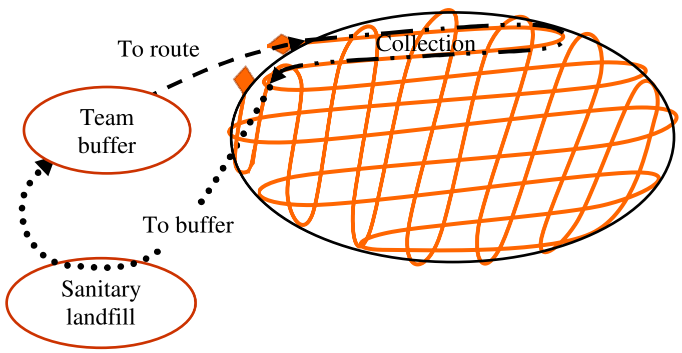
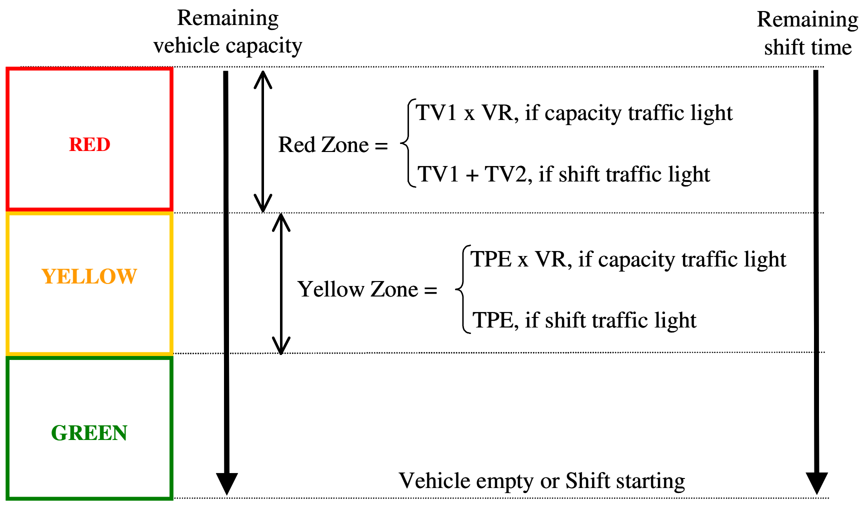


Fig. 1 – Route and team buffer



TV1: Average travel time from team buffer to route.
TV2: Average time from route to team buffer (It include the unloading time at the sanitary landfill).
VR: Collection speed (tons/hour)
TPE: Average time a team needs to be ready lo be launched.

Fig. 2 – Zone sizes for both capacity and shift control mechanisms

Shift control mechanism

Each crew in operation has a shift control mechanism. It controls the team replacement when a crew's regular time is over. Although the size of the zones are calculated with other equations, it works the same way as the capacity control mechanism (Figure 2).

Logical circuits

As it was already described, there is only one route that covers all the collection area. To meet the collection frequency, the route must be crossed at the same time by several teams separated a distance equivalent to the collection period (TR). Each one of these teams is a logical circuit, which is controlled separately through both the capacity and shift control mechanisms. They are called "Logical Circuits" because each one is moving through the same route.

In other words, several teams are moving through the same route separated by a distance equivalent to TR. That distance is called "distance between circuits (DER)" and it is equal to the average linear speed (VL) divided by the collection frequency (FR). So, DER = VL / FR.

The number of teams that must be moving through the route at the same time (NER), separated by DER kilometres is:

$$NER = \left\lceil \frac{LRU}{DER} \right\rceil \qquad [2]$$

Where $\lceil X \rceil$ is the nearest integer equal to or greater than X, LRU is the route length and DER is the distance between circuits.

During the operation, there is always one team collecting at each logical circuit. All logical circuits share the same route and the same team buffer.

Frequency control mechanism

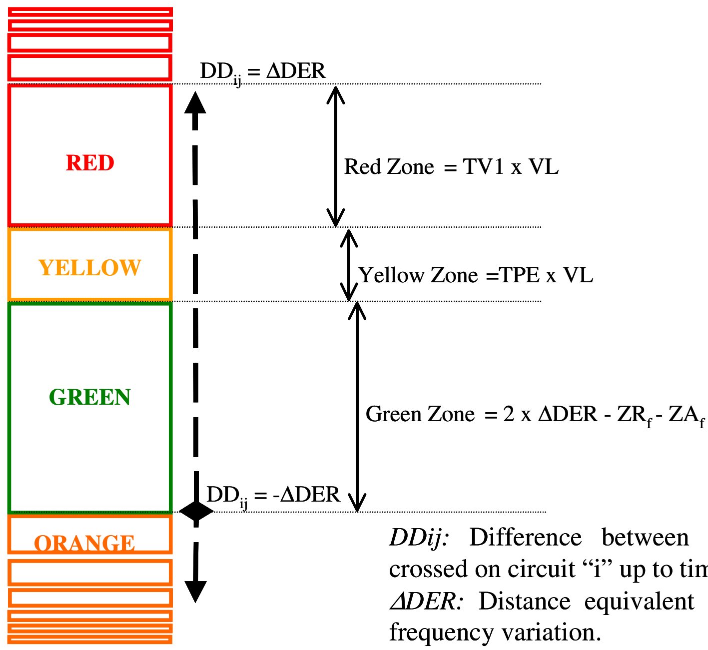
As it was explained earlier, each team in operation has two feedback loops that guarantee capacity and crew time availability on the road. In addition, circuits share the same route and team buffer. All these elements make possible to take advantage of Aggregation Theory.

The frequency control mechanism is the element that coordinates all circuits in order to guarantee the collection frequency at each point in the route. There is a frequency control mechanism for each logical circuit.

It is like a traffic light, but in this case with four zones (Orange, Green, Yellow and Red) because it must correct delays and advances.

While a circuit is in the Green zone, the team continues collecting in the normal way. If the circuit is in the Yellow zone, the team continues in the normal way while another team at the buffer is prepared to help in the case the circuit goes to the Red zone. As soon as the circuit enters the Red zone, the prepared team is launched in order to help the delayed team, which means collection speed is doubled.

If a circuit goes to the Orange zone, it means the collection is going faster than required. So the team must stop and wait until the circuit enters the Green zone again. If there is more than one team collecting at this circuit, the last to have entered stays on the road. Figure 3 shows the frequency control mechanism.



DDij: Difference between standard and current distances crossed on circuit "i" up to time "j".
ΔDER: Distance equivalent to maximum allowed collection frequency variation.

Fig. 3 – Zone sizes for frequency control mechanism

Vehicles in the system

The number of vehicles in the system (NTV) must be enough to guarantee one team at each circuit continuously. A way to estimate it is:

$$NTV = \left\lceil NER \times \frac{TTME}{TRE} \right\rceil \quad [3]$$

Where $\lceil X \rceil$ is the nearest integer equal to or greater than *X*, *NER* is the number of logical circuits, *TTME* is the average round trip duration and *TRE* is the average team collection time in a trip.

TTME and *TRE* are estimated by the following equations:

$$TTME = TV1 + TV2 + TRE \quad [4]$$

$$TRE = Mín\left(\frac{CV}{VR}; TURNO - TET - TV1 - TV2\right) \quad [5]$$

Where *Mín(X1; X2)* is the lowest value between *X1* and *X2*, *TET* is the average time a crew is waiting at the team buffer to be assigned to replace an operating team, *CV* is the vehicle capacity, *VR* is the average collection speed, *TURNO* is the shift duration, *TV1* is the average time from the team buffer to the route and *TV2* is the average time from the route to the team buffer (It includes the unloading time at the sanitary landfill).

2.2 Operation of MST

Operation starts launching NER teams to the route, one to each circuit, which will start collection separated by DER. Figure 4 shows the start-up system condition.

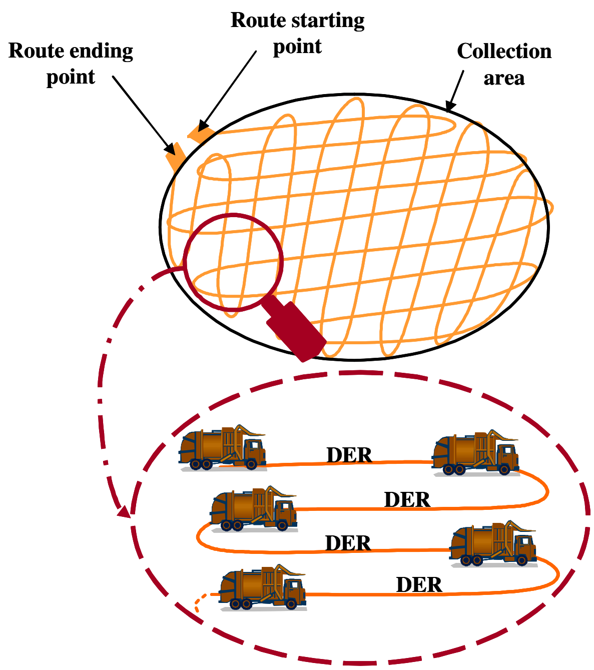


Fig. 4 – Start-up teams location

Once collection has started, the capacity control mechanism and the shift control mechanism are used as the launching criteria for replacement teams. Frequency control mechanisms are used as the launching and exiting criteria for support teams.

A “replacement team” is a team that is launched to replace another one whose capacity is full or it has been on the road more time than available. A “support team” is a team that is launched to help a circuit to recover the time lost due to variability existence.

A team must leave the route and go to the sanitary landfill whether its capacity is full, or its shift is over, or the frequency control mechanism is in Orange and it has been supported by another team.

As an example, figure 5 shows the dynamics of a capacity control mechanism.

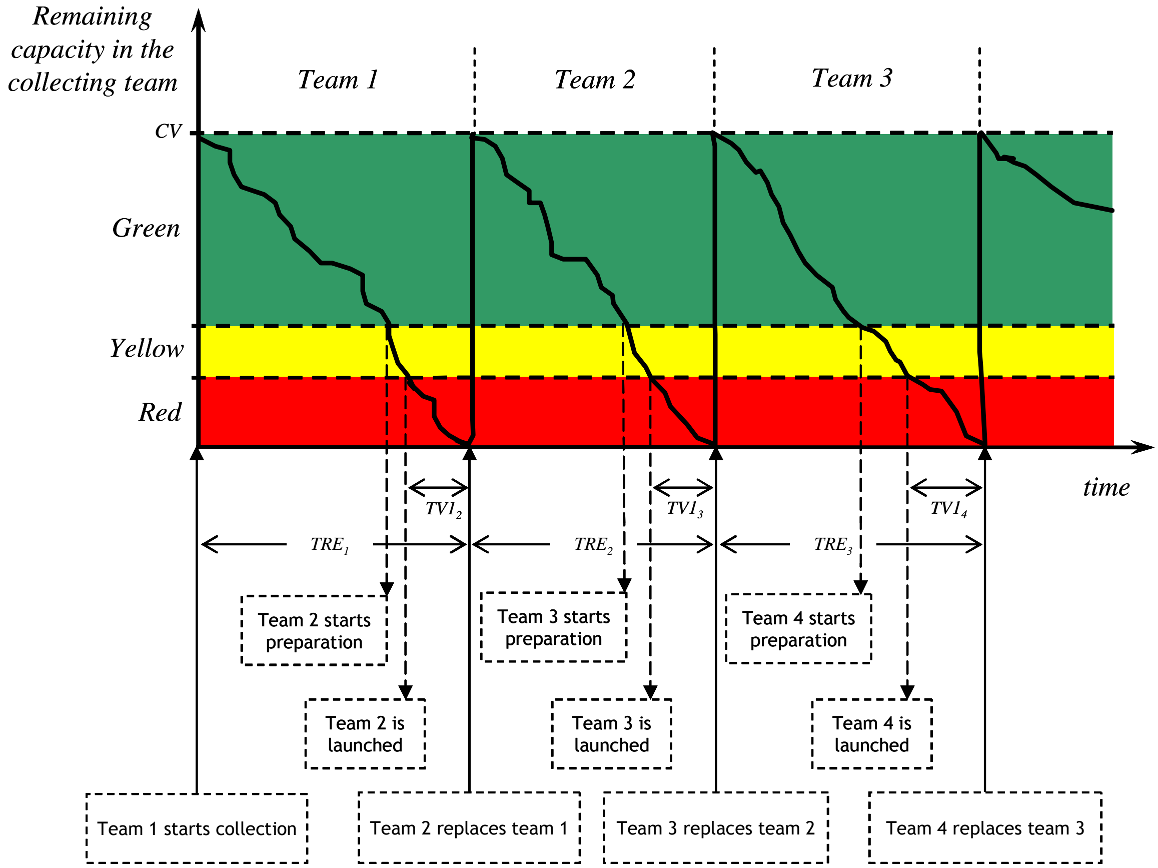


Fig. 5 – A capacity control mechanism in operation

All teams leaving the route must go to the sanitary landfill, unload the collected waste and return to the team buffer and wait their next assignment, which could be to the same circuit or to another one.

MST makes possible a continuous flow of vehicles, crews and garbage.

3. ADDING PREVENTIVE AND CORRECTIVE MAINTENANCE TO MST

Just minor changes to the previously described equations are required in order to add maintenance considerations to MST.

3.1 Preventive maintenance

Preventive maintenance can be considered easily by adding the average maintenance time at the garage (TMP) to the definition of the average round trip duration (TTME). TMP is the average time in queue (Waiting for maintenance) and the average service time.

$$TTME = TV1 + TV2 + TRE + TMP \qquad [6]$$

Thus, adding preventive maintenance increases the total number of vehicles (NTV).

3.2 Corrective maintenance

Vehicle failures are inherently managed by the MST model because the frequency control mechanism will immediately detect the problem and it will automatically take the necessary corrective actions. However, due to the fact that vehicles will be unavailable during some time, more vehicles are needed to guarantee the system operation. This means that the equation to estimate the number of vehicles in the system (NTV) must be modified accordingly.

Under the assumption of pure random failure probability, equation (5) is modified as follows to consider vehicle unavailability in the estimation of the total number of vehicles in the system (NTV):

$$TRE = Mín\left(\frac{CV}{VR}; TURNO \times \left(\frac{MTTF}{MTBF}\right) - TET - TV1 - TV2\right) \qquad [7]$$

Where *MTBF* is the mean time between failures and *MTTF* is the mean time to failure.

4. EXPERIMENTAL RESULTS

Discrete event simulation and 2^k factorial design of experiments were used as experimental methodology to compare MT and MST models. Table 1 describe factors and levels.

Table 1 – Factors and levels for experiments

Factor	Description	Level 1	Level 2
F1	Collection period (TR = 1/FR)	1 day	3 days
F2	Waste generation rate in the area (TBA)	100 tons/day	1000 tons/day
F3	Collection speed (VR)	Normal(1.5; 0.15) tons/hour	Normal(2.5; 0.25) tons/hour
F4	Vehicle capacity (CV)	7 tons	14 tons
F5	Shift duration (TURNO)	8 hours	10 hours

TV1 and TV2 were considered exponentially distributed random variables. The mean of TV1 was 0.5 hours and the mean of TV2 was 1 hour.

Each crew works 8 hours as regular working hours. If a crew works more than 8 hours, the difference is considered overtime. For instance, whenever TURNO is 10 hours, each crew may work about 2 extra hours.

Maximum allowed variation in collection period was 10%, so each point in the route must be visited once in each interval [0.9xTR; 1.1xTR].

All the values were chosen based on data available from literature and actual solid waste collection systems.

The following measurements were used to compare the system performance:

- Average number of trips in a day (V).
- Average number of crews in a day (T).
- Average overtime in a day (HE).
- Total number of vehicles in the system (Ve).

Table 2 shows experimental results. There is a clear improvement in the system performance when it is managed following MST model instead of MT model. Numbers in parenthesis are confidence intervals.

MST makes possible reductions in the number of trips (Up to 33%), crews (Up to 49%) and vehicles (Up to 40%), which means important operation cost and investment improvements. The bigger the collection area, the greater the improvement is.

On the other hand, overtime increases. In most countries, overtime has a very low impact on costs in comparison to the important reduction on trips and crews. However, MST has a parameter that regulates the trade off between the number of crews and overtime. More details about this issue can be found in Hurtado (2004).

5. CONCLUSIONS

MST (Acronym of the Spanish words "Modelo Sistémico con restricciones de Tiempo", which means "Systemic Time-constrained Model") is a new model to design and operate solid waste collection systems. Experimental results showed significant improvements in a system when it is managed applying MST model instead of MT model, which makes sense because:

- MST takes advantage of Aggregation Theory. So, it allows a much better resource utilization.
- MST ensures to meet collection frequency at every point in the collection area.

Table 2 – Experimental results

Run						MT							MST						
Run	F1	F2	F3	F4	F5	V		T		HE		Ve	V		T		HE		Ve
1	1	1	1	1	1	20.5	(1.0)	20.5	(1.0)	0.8	(0.8)	6	15.1	(0.5)	14.9	(0.2)	0.9	(0.7)	5
2	1	1	1	1	2	20.4	(1.2)	16.7	(3.8)	2.1	(1.7)	6	17.5	(1.1)	12.8	(3.8)	7.3	(4.0)	5
3	1	1	1	2	1	15.3	(0.7)	15.3	(0.7)	2.7	(1.4)	6	11.3	(0.4)	11.3	(0.3)	2.9	(1.5)	4
4	1	1	1	2	2	11.7	(0.9)	11.7	(0.9)	11.7	(2.2)	6	9.3	(0.5)	8.8	(0.2)	13.4	(1.2)	4
5	1	1	2	1	1	20.1	(0.8)	17.0	(0.7)	0.3	(0.7)	4	15.9	(0.5)	13.0	(0.8)	0.9	(1.0)	4
6	1	1	2	1	2	20.0	(0.9)	15.3	(0.3)	0.5	(0.7)	4	16.5	(0.7)	9.2	(0.4)	7.2	(2.7)	4
7	1	1	2	2	1	9.8	(1.0)	9.8	(1.0)	0.8	(1.1)	4	7.7	(0.1)	7.7	(0.2)	1.5	(0.9)	3
8	1	1	2	2	2	9.7	(0.9)	9.2	(1.0)	1.1	(0.9)	4	8.2	(0.7)	7.3	(0.2)	2.6	(1.2)	3
9	1	2	1	1	1	209.9	(5.3)	209.9	(5.3)	7.9	(3.3)	49	151.9	(1.7)	145.0	(0.7)	11.9	(3.5)	38
10	1	2	1	1	2	209.9	(5.4)	164.5	(3.5)	23.9	(4.7)	49	182.3	(3.7)	106.8	(1.7)	131.4	(10.9)	41
11	1	2	1	2	1	142.6	(1.3)	142.6	(1.3)	27.2	(3.5)	58	107.2	(2.1)	106.2	(1.2)	36.5	(5.4)	36
12	1	2	1	2	2	121.2	(2.5)	121.2	(2.5)	125.7	(7.7)	57	85.0	(1.5)	82.4	(1.0)	147.0	(6.6)	34
13	1	2	2	1	1	206.7	(5.5)	166.3	(3.3)	2.7	(2.4)	37	159.0	(2.7)	95.9	(1.4)	17.7	(3.6)	28
14	1	2	2	1	2	206.7	(5.3)	146.5	(0.8)	6.1	(2.0)	37	156.5	(2.7)	76.6	(0.8)	59.3	(5.6)	28
15	1	2	2	2	1	105.7	(3.1)	105.7	(3.1)	8.6	(3.9)	29	75.4	(1.1)	74.1	(0.3)	11.8	(3.3)	23
16	1	2	2	2	2	105.0	(2.9)	95.1	(2.0)	14.8	(2.9)	28	88.7	(1.8)	65.2	(1.0)	50.0	(6.0)	23
17	2	1	1	1	1	21.3	(1.0)	21.3	(1.0)	0.8	(0.9)	5	14.7	(0.4)	14.6	(0.4)	0.8	(0.7)	5
18	2	1	1	1	2	21.3	(0.8)	16.7	(0.7)	2.2	(2.0)	5	16.3	(0.5)	13.2	(0.6)	5.7	(2.7)	5
19	2	1	1	2	1	14.4	(0.3)	14.4	(0.3)	2.7	(1.6)	5	11.2	(0.3)	11.2	(0.1)	3.1	(1.2)	5
20	2	1	1	2	2	12.1	(0.9)	12.1	(0.9)	12.2	(2.1)	5	8.2	(0.3)	8.2	(0.3)	14.5	(1.6)	4
21	2	1	2	1	1	21.0	(0.8)	16.8	(0.5)	0.3	(0.6)	4	15.2	(0.8)	12.4	(1.4)	0.7	(0.9)	4
22	2	1	2	1	2	21.0	(0.8)	14.7	(0.4)	0.6	(1.0)	4	15.1	(0.7)	8.4	(0.4)	7.3	(2.4)	4
23	2	1	2	2	1	10.6	(0.9)	10.6	(0.9)	0.8	(1.1)	3	7.7	(0.1)	7.7	(0.1)	1.7	(1.0)	4
24	2	1	2	2	2	10.5	(0.9)	9.5	(0.6)	1.6	(1.3)	3	7.7	(0.1)	7.6	(0.1)	2.2	(1.0)	4
25	2	2	1	1	1	210.0	(5.1)	210.0	(5.1)	8.0	(2.6)	49	148.0	(1.3)	144.6	(1.2)	11.1	(3.0)	38
26	2	2	1	1	2	210.0	(5.5)	164.8	(3.7)	23.9	(5.2)	49	174.6	(1.9)	104.8	(1.2)	135.4	(5.9)	41
27	2	2	1	2	1	142.1	(0.1)	142.1	(0.1)	27.5	(5.0)	40	107.3	(0.9)	105.7	(0.7)	37.7	(5.8)	36
28	2	2	1	2	2	121.2	(3.4)	121.2	(3.4)	125.2	(7.1)	40	81.7	(1.2)	80.8	(0.6)	153.0	(6.2)	34
29	2	2	2	1	1	207.1	(5.1)	166.4	(3.7)	3.0	(1.8)	37	152.4	(2.7)	93.5	(1.8)	18.3	(4.0)	28
30	2	2	2	1	2	207.1	(4.9)	146.5	(1.2)	6.9	(1.0)	37	149.4	(2.1)	75.1	(1.1)	59.4	(3.9)	28
31	2	2	2	2	1	106.3	(3.7)	106.3	(3.7)	8.8	(2.9)	28	74.2	(0.9)	73.6	(0.5)	11.4	(2.9)	23
32	2	2	2	2	2	105.6	(2.7)	94.9	(2.9)	16.2	(3.7)	28	84.7	(1.9)	65.9	(1.2)	45.5	(7.6)	24

As a result, MST is robust against variability sources found in every solid waste collection system, such as:

- Total daily amount of waste generated in the collection area.
- The geographical distribution of waste and its weight.
- Vehicles and crews unavailability.
- Unexpected route obstacles.

Implementing the MST model as a management methodology in a solid waste collection system requires several paradigm shifts in the people who operate it. In order to be successful, at least these elements must be considered:

- Education and training about the logic of the model.
- A measurement system that induces people to take the right actions.
- A reliable communication system between the headquarters and each team.
- A software to easily follow up the control mechanisms (Capacity, shift and frequency).

All MST details and more experiments comparing it against MT can be found in Hurtado (2004).

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