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A smart framework for municipal solid waste collection management: A case study in Greater Cairo Region

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A B S T R A C T

Around 28 million tons of municipal solid wastes (MSW) are annually generated in Egypt, with 40% in Greater Cairo Region (GCR). Although, the government aims at improving the MSW service coverage and collection efficiency, formal collection service is still limited and operates with low transportation efficiency resulting in illegal waste collection and dumping. This research aims at providing optimized collection systems to accommodate various housing levels and considering the available resources. As a case study, the collection routes in Al-Mostakbal City, are optimized by selecting the appropriate location and containers order. Meanwhile, the pick-up time is optimized using the appropriate vehicle type, fleet size, and rounds. In addition, dynamic routing is applied using developed production models. A simulation model is developed to assess various improvement scenarios and recommend the effective one for various schemes. The outcome is a highly-efficient framework; with potential to be extended to cover other urban areas.

1. Introduction

Around 28 million tons of municipal solid wastes (MSW) are estimated to be generated annually in Egypt, according to generation rates ranging between 0.75 and 1.25 kg/capita/day [1]; the official MSW composition in Egypt is 56 % organics, 13 % plastics, 10 % paper and cardboard, 4 % glass, 2 % metals, and 15 % other material [2]. However, MSW composition varies significantly through the different governorates, where the organic fraction municipal solid waste (OFMSW) can range between 41 % and 70 % across different governorates [3]. The current MSW management practices in Egypt, according to the latest official statistics, are based on open dumping (81 %), a small recycling share (12 %), and only 7 % landfilled [2]. The Egyptian government has ambitious plans to enhance MSW management; such plans aim at increasing the MSW collection coverage and efficiency from 20 % and 60 %, respectively, in 2016 to reach 80 % and 90 %, respectively, by 2030 [4]. Furthermore, there are plans for increasing the recycling rates of the collected MSW to 80 %, through which: 60 % of the collected MSW will be recycled for compost and refuse-derived fuel (RDF) production, and the remaining 20 % will be thermally treated for energy production [1]. These plans and goals are supported by the Egyptian waste management law 202/2020, which calls for the closure of the illegal dumpsites in Egypt within two years of law enforcement [5].

A significant challenge facing developing the MSW management sector in Egypt is that MSW collection services are limited, and often operate with low efficiency, as lower service coverages encourage illegal waste routes and dumping. Noting that collection costs amount up to 90 % of the MSW management budget [6], and securing sufficient finance for MSW management in Egypt is another major obstacle in enhancing the current MSW management situation. A pay-as-you-throw fee, implemented as fixed fee defined geographically per neighborhood and collected with the electricity bills, is the financial instruments applied for MSW management. However, these collected fees only partly cover the MSW management financial needs, which amounted to approximately 7.2 billion EGP per year in 2021 [7].

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To overcome such challenges with the continuously increasing MSW generation rates, the circular economy approach become a high priority on the political agenda for enhancing waste management systems and ensuring their sustainability. The circular economy approach encourages an essential paradigm-shift from the depletive 'produce-consume-dispose' model of the linear economy to the 'reduce-reuse-recovery-recycle-redesign-remake' model [8]. Hence, the circular economy approach promotes sustainable waste management practices, however, this paradigm shift shall be supported by reverse logistic infrastructures. In this context, considerable emphasis has been paid to smart technologies in the streams of the Internet-of-Things (IoT) and artificial intelligence (AI) [9].

Based on housing levels, the districts can be divided into three categories; high level such as compounds, medium level such planned districts, and low level including unplanned districts. These categories are distinct from the social perspective involving the road network, landscape, culture, security, reasonable walking distance, and ability to separate MSW at source. In addition, there are various economic differences among these categories comprising the available resources in terms of communication infrastructure, containers type, and collection vehicles type.

In this paper, a framework is developed to optimize the MSW collection management considering the characteristics of every category. In addition, the developed framework is applied in El-Mostakbal City, Egypt as a case study and found applicable to be extended to other parts in Greater Cairo.

2. Previous research

Collecting waste is one of the most critical phases of the cycle of waste management (Bautista and Pereira 2006), playing a central but often underestimated role in the municipal solid waste management system [10]. Waste collection is a highly visible municipal service that involves large expenditures and operational problems; resulting in high investment and operational and environmental costs [11]. In fact, due to the massive fuel consumption and labor involved, solid waste collection is usually the most polluting and costly component of MSW management (MSWM), representing 50–90 % of the total costs [10,12].

According to Hickmann, the keys to assuring an optimal solid waste collection system is a combination of equipment selection, maximum productivity and effective routing [13]. Stearns in [14] determined that route-related factors most directly affect the productivity of residential solid waste collection systems. These route related factors include:

(1) Containers: number, type, size, weight limitations
(2) Distance between collection stops
(3) Quantity and quality of waste per stop
(4) Haul distance to disposal site
(5) Collection route topography
(6) Delays in traffic and container accessibility to crew
(7) Road conditions in terms of speed limits and load limits

Through new computer technologies, advances in sensors, data transfer technologies and Internet of Things (IoT), data-driven smart waste collection processes will replace old inefficient collection processes. It will cause a shift from fixed routing and fixed collection intervals to collection according to real demand, supported by smart algorithms and innovative web-applications to improve routing and collection productivity.

Such applications of smart waste management technologies fall under the smart cities' umbrella and aims to achieve sustainable development goals and minimize the waste management sector's associated greenhouse gases emissions [15,16]. From this point of view, AI smart bins can optimize MSW collection schedules, while waste collection vehicles equipped with smart monitoring technologies can dynamically optimize the waste collection routes [17].

The development of advanced IoT (Internet of Things) has enabled the usage of smart waste bins. Municipal authorities are then capable of overseeing and managing the waste bins and to make decisions regarding the optimal waste collection route planning and scheduling [12].

Iot enables installing sensors in the smart bins. A variety of sensors, including sensors to monitor the filling levels of the bins, to weigh the trash bin, to measure the volume of waste in the bin, to identify the type of waste, and to detect hazardous gases produced by waste, can be utilized. This data is gathered and sent to a cloud server, where it is evaluated to determine the status and quantity of waste in each bin [18,19].

Hence, AI based smart waste management systems can support increasing the MSW collection service coverage in an efficient, cost-effective, and environmentally sound manner, whilst allowing sustainable waste management practices and promoting circular economy models.

The smart waste management systems is planned to be applied in the new cities such as the New Administrative Capital City where the required infrastructure and IT facilities exist in addition to the resources availability [20]. However, there are a lot of challenges in the time being to apply such smart systems in most of GCR districts. Therefore, there is a need to develop a smart framework for the MSW collection management considering the different dimensions including the economic and social dimensions, besides the environmental one.

However, implementing such ideas come along with some almost insurmountable challenges related to implementing such technologies in a diverse environment such as Greater Cairo region with different household types and consumption patterns and a big lack of nearby disposal sites. Therefore, the question arises of how to implement such smart technology-based solutions solutions in such complex and challenging environments.

3. Objectives

The main goal of this research is to develop a framework for sustainable and smart MSW collection management considering the environmental, social, and economic perspectives. This goal is divided into a group of objectives as follows:

- Recommending the MSW collection system relevant to the residence category by selecting the appropriate vehicle type, fleet size, rounds, and containers size and location.
- Increasing the MSW coverage efficiency by minimizing the pick-up time and optimizing the collection routes.
- Increasing the MSW recycling efficiency, wherever possible, by implementing and facilitating the at-source separation.
- Decreasing the environmental impact by minimizing the fuel consumption and over saturated containers occurrence.

4. Methodology

To achieve the research objectives, a framework is developed at two levels. The first level is the detailed level which is suitable where enough data are available, or can be collected, regarding the current MSW collection management for the required district/area; otherwise, the second level, which is the generic level, is suitable.

4.1. Detailed framework

To apply this framework in certain district/area, the following data should be available:

- Details of the current MSW collection process in terms of collection fleet size, type, and capability, collection time plan (i.e., times of day and days of week), and intermediate and final stops (i.e., disposal stations).
- Road network characteristics in terms of road alignment and hierarchy, width, speed, direction, sidewalks, and truck route restrictions if any.
- Socio-economic characteristics including land use type and density, population and income level for residential land use at the smallest level (e.g., building), and working period for non-residential land use.

In addition to the abovementioned data, the following data to be collected through surveys if not available:

- Container's location, size, type, catchment area, and walking distance.
- Current route of every collection vehicle in each round including the route start, end, intermediate stops, and services containers in order.
- MSW composition for the separation purposes.
- Average pick-up time for each vehicle type per container type.
- Average density of MSW per container type.
- Average saturation level (i.e. volume to capacity ratio) for each container at the times of collection.
- Average density of MSW per container type.

In this case, the framework involves the following steps:

(1) Develop a MSW production model at the available land use unit (e.g., building, population) based on the average container saturation level, average density, catchment area, land use characteristics. This model can be developed using regression analysis, rates, or category analysis (i.e. cross classification). If the accuracy of such model is not high, the input data to be updated and then the model to be redeveloped. The average saturation level can be updated using sensors if applicable, mobile applications, collection team remarks, or by survey.
(2) Conduct the sorting analysis if the separation at source is applicable. In this case, a representative sample for each land use type/category should be collected and analyzed.
(3) Evaluate the current routes in terms of a group of Key Performance Indicators (KPI) such as pick-up time, in-vehicle time, total collection time, travel distance, network duplication, and average walking distance.
(4) Identify the drawbacks of the current MSW collection management system to be able to propose the improvement scenarios.
(5) Suggest a set of improvement scenarios to raise the fleet and recycling efficiencies, and to minimize the environmental impact as well as the pick-up time and walking distance.
(6) Optimize the routes in each scenario to minimize the in-vehicle time and then to minimize the travel distance and network duplication. The route optimization aims at minimizing the in-vehicle time by re-arranging the serviced containers in this route knowing the skim matrix among all containers as well as other stops in the route. Similar to salesman problem, the route is theoretically not allowed to pass through any serviced container more than one time. However, the topology of road network and containers location (e.g., dead-end local streets) may require to pass through some serviced container more than one time to serve other containers. This optimization can be implement using genetic algorithm (GA) or branch and bound technique taking the network size into consideration as discussed later in the case study.
(7) Consider as much as possible the on-demand routing using sensors at the containers if applicable; otherwise, using the developed MSW production model.
(8) Evaluate and compare the improvement scenarios based on the same KPI to select and recommend the appropriate scenario for the study area and awareness level in the light of available resources.

4.2. Generic framework

This framework is suitable for planning phase for new districts or existing districts where no enough data available regarding the MSW collection management. This type of framework is developed based on the Authors' experience as summarized in Table 1.

5. Case Study: El Mostakbal City

The study was conducted in El-Mostakbal City, a gated compound at the east of Greater Cairo Region, representing a typical middle-income neighborhood. The city is divided mainly into three sectors; 1, 2, and 3. Sector 1 is subdivided into two clusters; economic and investment residence. The study is specifically applied on the economic residence of Sector 1 which contains 235 occupied residential buildings. Based on collected data through continuous one week, the current situation of MSW in the city is analyzed

Table 1
A Generic Framework for Sustainable MSW Collection Management.

District	High Living Level	Medium Living Level	Low Living Level
Item			
At-Source Separation	Recommended	Not recommended	Not applicable
Collection Vehicle	Hoist truck with mechanical loading/unloading, compaction, and separation	Hoist truck with mechanical loading/ unloading, and compaction	Medium Pick-up vehicle with two assistants
Containers	0.5–1 m^3 size distributed at 25 m walking distance with sensors	1–2 m^3 size (up to 50 m walking distance)	2–4 m^3 size (up to 100 m walking distance)
Demand Estimation	Using sensors	Developing MSW production models and updating using mobile applications	Developing MSW production models and updating seasonally
Rounds	Each container to be serviced once every 1–4 days according to sensor signal	Each container to be serviced once a day	Each container to be serviced 1–2 times daily
Routes	Optimized dynamic routes	Optimized static routes for each week.	Optimized static routes for each season.

through three main aspects as discussed in the following three subsections. Accordingly, a set of improvement scenarios are proposed and discussed at the end of this section.

5.1. MSW production rate

The MSW amount of each building was observed where the saturation level (i.e., volume-capacity ratio) was recorded just before unloading, through a continuous one week in September 2022, and then averaged. The average saturation level ranges between 10 % and 147 % where 25 containers are oversaturated. In addition, the density is measured for a random sample of 60 medium boxes and found 85.9 ± 18.9 kg/m^3. This low density can be explained in the light of compaction and sorting absence where the wood, glass, and cardboard causes significant gaps within these narrow containers. However, it is recommended to update this density using a larger sample size.

The daily MSW production ranges between 4.1 and 60.5 kg/building with an average of 33.1 kg/building and standard division of 7.4 kg/building. This wide variation (22 %) refers to the high effect of socio-economic attributes. Fig. 1 illustrates the buildings and containers location as well as the daily MSW production of each building.

The socio-economic characteristics of buildings were collected in terms of number of occupied apartments, existing population, and income level in terms of number of private cars for the existing population. Each building has 28 apartments; however, the number of occupied apartments, during the survey time, ranges between 1 and 26 with an average of 18.8. Similarly, the existing population ranges between 4 and 129 with an average of 87.3 person/building. Moreover, the number of private cars for the existing population ranges between 1 and 40 with an average of 26.2 car/building.

The building production is analyzed in relation to its socio economic attributes; apartments (APR), population (POP), and cars (CAR) in addition to household size (HHS) and household cars (HHC) as depicted in Table 2. All attributes give positive correlations which is logic; however, all attributes achieve low correlation which leads to weak estimation.

Therefore, the person production rate is analyzed in relation to the same attributes where the person production rate ranges between 0.16 and 1.03 with an average of 0.39 kg/person and standard division of 0.11 kg/person. This wide variation (30 %) refers to the high effect of socio-economic attributes.

As shown in the bottom half of Table 2, all attributes give negative correlations which may be logic; however, HHS and HHC achieve low correlations unlike other attributes. In addition, Apartments, cars, and population are statistically correlated to the person production due to the acceptable values of *t*-statistic and p-value.

Therefore, the stepwise regression is applied to select the best attributes. Equation (1) presents the best multiple regression model for the MSW person rate (MSW_{PR}) in terms of number of occupied apartments and population in the building. This equation informs that the daily person production in a building equals 0.864 kg minus 0.0097 kg per occupied apartment and 0.0033 kg per existing capita. Despite, the two attributes are statistically significant as p-value and *t*-statistic are acceptable, the coefficient of determination (R^2) for this model is 0.45. In addition, the intercept is very high compared to the other coefficients.

$$MSW_{PR} = 0.864 - 0.0097\,APR - 0.0033\,POP \quad (1)$$

To improve the model, the piecewise regression is applied where the population attribute is divided into 3 pieces by two thresholds at 73.4 and 92; while, the apartment attribute is divided into two pieces by one thresholds at 18 car/building resulting in

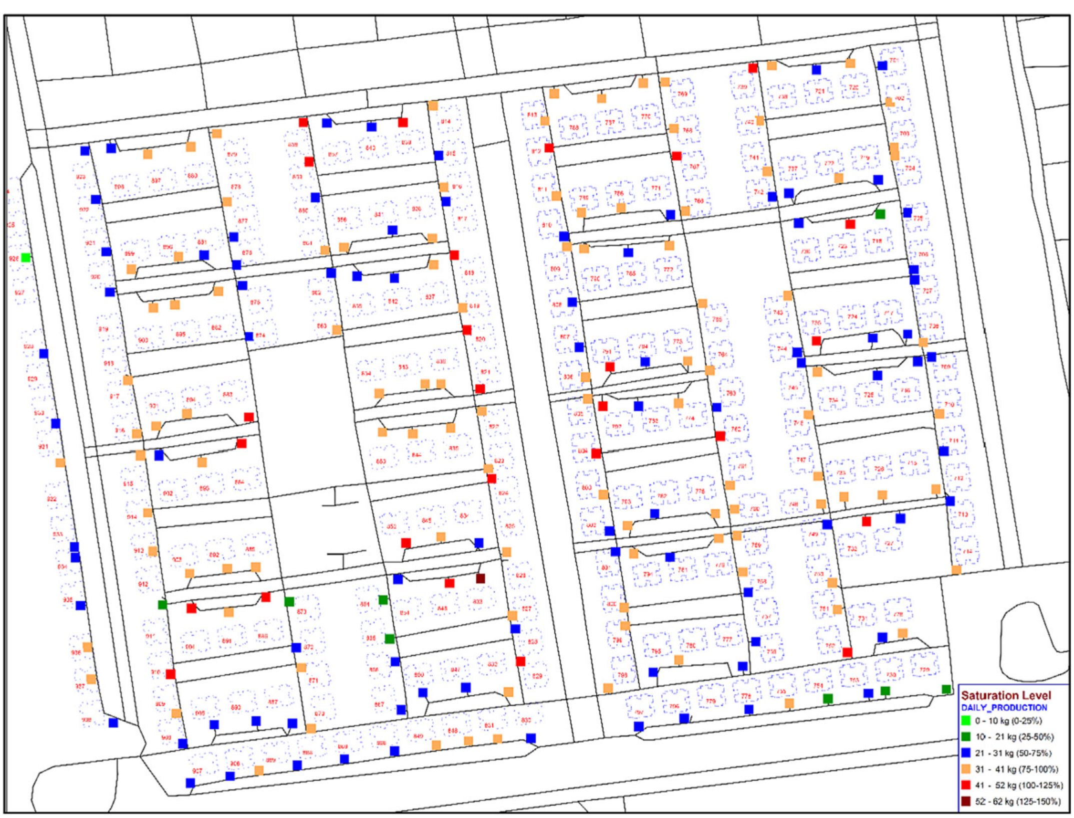

Fig. 1. Containers Location, Saturation Level, and Daily Production.

Table 2
Analysis of Variation (ANOVA) of MSW production.

Daily MSW \ Attributes		APR	CAR	POP	HHS	HHC
Building Production	Correlation	0.06	0.09	0.13	0.15	0.10
	t Stat	0.96	1.33	1.93	2.35	1.47
	P-value	0.34	0.18	0.05	0.02	0.14
Person Production Rate	Correlation	−0.63	−0.53	−0.66	−0.20	−0.02
	t Stat	−12.25	−9.42	−13.30	−3.07	−0.30
	P-value	0.00	0.00	0.00	0.00	0.77

total six categories. Equation (2) shows the multiple regression model for each piece where the model is continuous and R^2 for this model is 0.51.

This production model is very useful in studying the future scenarios (i.e., planning phase) at certain horizon years or when the city will be fully occupied.

$$\begin{cases} MSW_{PR} = 1.085 - 0.012POP - 0.006APR \forall POP \le 73, APR \le 18 \\ MSW_{PR} = 0.756 - 0.012POP - 0.002APR \forall 73 \le POP \le 92, APR \le 18 \\ MSW_{PR} = 0.846 - 0.012POP - 0.003APR \forall POP \ge 92, APR \le 18 \\ MSW_{PR} = 0.897 - 0.002POP - 0.006APR \forall POP \le 73, APR \ge 18 \\ MSW_{PR} = 0.569 - 0.002POP - 0.002APR \forall 73 \le POP \le 92, APR \ge 18 \\ MSW_{PR} = 0.712 - 0.002POP - 0.003APR \forall POP \ge 92, APR \ge 18 \end{cases} \tag{2}$$

This equation estimates the daily person production according to the category of occupied appartments and population. For instance, if a building has less than 18 occupied appartments and less than 73 capita, the daily person production equals 1.085 kg minus 0.012 kg per existing capita and 0.006 kg per occupied apartment.

Although this model is more accurate than the ordinary multiple regression model shown in Equation (1), it may be more difficult for practitioners. For practitioners' usage, the average rate is calculated within the above six categories and found 0.479, 0.379, 0.343, 0.406, 0.371, and 0.333, respectively. However, R^2 in this case is 0.03 which is very weak.

As the accuracy of production estimation is not high, it is recommended for the best operation/management to use sensors at containers to identify the dynamic production instead of using static models/equations/rates. Otherwise, the piecewise model is recommended with urgent update every season to reflect the seasonal change in the socio-economic attributes and consumption.

5.2. Sorting analyses

A sorting analyses campaign were conducted for the generated MSW at El-Mostakbal City (i.e., all sectors and all residence levels) on a time span of seven consecutive days to track the MSW composition variations across a normal working calendar week. Sorting analyses were conducted according to the American Standard Test Method for Determination of the Composition of Unprocessed Municipal Solid Waste (ASTM-D5231) [21]. The method identifies the weight of a representative sorting sample of unprocessed MSW to be range between 91 and 136 kg to represent the characteristics of a vehicle load of MSW; and the number of samples were identified according to a confidence level of 90 % and using food waste as the governing component. The sorting sites at El-Mostakbal City are at the primary stage of waste generation, right after collection from containers, and before transporting to the transfer stations, and without any scavenging activities. Furthermore, the sampling points were selected to represent three sub-segments (low, middle, high) of the middle-income segment; such categorization were based on the three sub-divisions in the compound buildings, which is reflected on the residential units' areas and prices. Sorting analyses were conducted for each sampling points in quadruplicates each day. The sorting analyses were conducted in line with the Egyptian code of Design Principal and Implementation Conditions for Municipal Solid Waste Management Systems [22]. Hence, MSW at the identified sites were sorted according to the twenty-one material categories identified by the Egyptian Code, as presented in Table 3.

MSW sorting analyses were conducted for seven consecutive days, in quadruplicates each day, at three sites sorting samples at the primary stage of waste generation, before any scavenging activities, and the sample weight composition is presented in detail in Table 4. The results did not indicate any significant variations between the middle-income sub-divisions as the confidence intervals were intersecting for all the MSW materials expect for plastics that represented a higher weight fraction in the low-middle income segment. Furthermore, the results show the organics and plastics are the main components of MSW in Greater Cairo representing 55 ± 7 % and 16 ± 2 %, respectively, as illustrated in Fig. 2. With respect to organics amount in the generated MSW, the results of the study are in line with the available studies on waste composition in Egypt; 56 % according to the Egyptian Ministry of Environment (MoE) [2], and 59 ± 12 % as reported by Abdallah et al. (2020) [3]. With respect to plastics, this study reports

Table 3
Waste Material Categories according to the Egyptian Code.

No.	Material Category	Description
1	Paper	Includes printer and copy paper, newspapers, magazine paper, advertisements, books, notebooks
2	Cardboard	All types of cardboard
3	Plastic (PET)	Transparent soda and mineral water bottles
4	Plastic (HDPE)	Glassware detergents, dark food packages
5	Plastic (PP)	Food packages (yoghurt, fast food, cheese, etc.)
6	Plastic (LDPE)	Plastic bags and plastic used for packaging and foam plates
7	Plastic PVC	Irrigation hoses and water, drainage, and gas pipes
8	Plastic (PS)	Containers and cutlery (Food takeaway containers, cutlery, egg tray)
9	Glass	Glass bottles, jars, and glass parts
10	Iron	Tin cans and containers, and iron plates
11	Aluminum	Aluminum plates, foil, cans
12	Organic Waste	Food residues, animal waste
13	Agricultural Waste	Trim trees residues, straw, and wood
14	Textiles	Carpets, clothing, cloth bags, and covers
15	C&D Waste	Building repair waste mixed with MSW
16	Electrical Equipment	Automotive electronics, wires, other electronics
17	Hazardous & Medical Waste	Dry batteries, paint cans and insecticide, syringes, blood bags and medical cotton
18	Rubber Waste	Car tires
19	Wooden Waste	Wood
20	Compounds	Diapers, Tetra Pak, etc.
21	Other	Street sweeping, any waste that is not classified under the above items.

Table 4
MSW Sorting Analyses at the Primary Stages of Waste Generation.

MSW Material	Low- Middle Income			Middle- Middle Income			High- Middle Income			Mean		
Organics	52.4 %	±	9.5 %	55.0 %	±	3.6 %	57.5 %	±	8.4 %	55.0 %	±	7.2 %
Plastic	19.3 %	±	1.8 %	14.9 %	±	0.9 %	14.9 %	±	1.8 %	16.4 %	±	1.5 %
Diapers	9.3 %	±	5.3 %	11.2 %	±	1.6 %	6.7 %	±	5.5 %	9.1 %	±	4.1 %
Cardboard	8.5 %	±	2.5 %	7.6 %	±	2.5 %	6.3 %	±	3.2 %	7.5 %	±	2.7 %
Street Waste	4.6 %	±	4.4 %	5.3 %	±	4.0 %	8.9 %	±	10.1 %	6.3 %	±	6.2 %
Glass	2.1 %	±	1.4 %	1.8 %	±	0.9 %	1.0 %	±	0.8 %	1.7 %	±	1.0 %
Paper	1.1 %	±	0.4 %	1.5 %	±	0.9 %	2.0 %	±	1.1 %	1.5 %	±	0.8 %
Textiles	1.0 %	±	0.7 %	1.4 %	±	1.2 %	1.2 %	±	0.9 %	1.2 %	±	0.9 %
Aluminum	1.6 %	±	0.8 %	0.8 %	±	0.2 %	1.0 %	±	0.5 %	1.1 %	±	0.5 %
Wood	0.0 %	±	0.1 %	0.1 %	±	0.3 %	0.3 %	±	0.9 %	0.2 %	±	0.5 %
Rubber	0.1 %	±	0.2 %	0.4 %	±	0.9 %	0.0 %	±	0.0 %	0.2 %	±	0.4 %
Iron	0.0 %	±	0.0 %	0.0 %	±	0.0 %	0.0 %	±	0.1 %	0.0 %	±	0.0 %
Total	100 %			100 %			100 %			100 %		

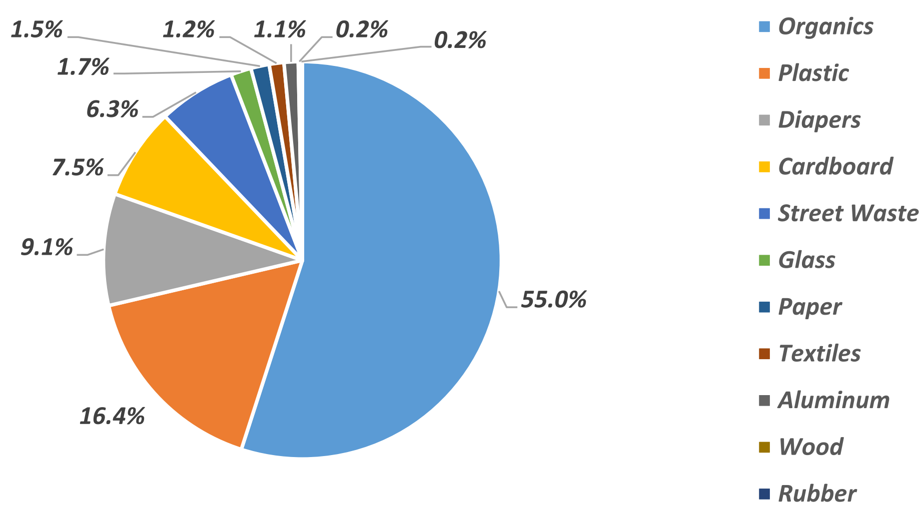

Fig. 2. MSW Composition at the Middle-Income Neighborhood Category.

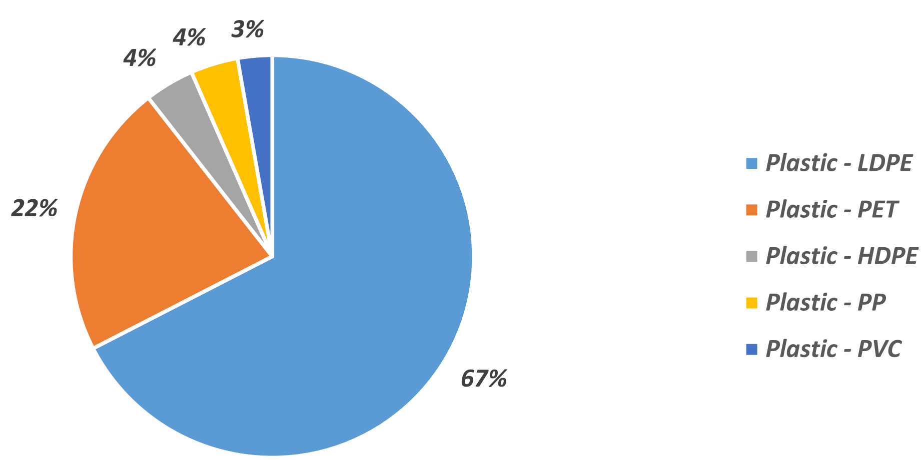

Fig. 3. MSW Plastics' Composition at the Middle-Income Neighborhood Category.

higher amounts than the previous studies on waste composition; 13 % reported by MoE in 2016 [2], and 11 ± 4 % according to Abdallah et al. (2020) [3]. The composition of the MSW plastics is illustrated in Fig. 3, which indicates that the dominant plastic materials are LDPE (67 %) and PET (22 %). Noting that LDPE are used for plastic bags, packaging and foam plates, and PET is used in transparent soda and mineral water bottles, the increase in the plastic compositions indicates the continuously increasing amounts of disposable plastics and packaging materials.

5.3. Current collection management

MSW is collected in Sector 1 through a container per each building, as previously illustrated in Fig. 1; each container comprises two adjacent medium boxes of 240 L each. The MSW collection fleet comprises six vehicles: five small pick-up vehicles and one medium pick-up vehicle; all with manual loading and no compaction. The six vehicles collect MSW through six collection routes as illustrated in Fig. 4.

Fig. 4. Current MSW Collection Routes.

The number of buildings for each vehicle depends on its size. While, the medium pick-up serves 64 buildings, the small vehicle can serve up to 47 buildings. Each vehicle is assigned to serve daily specific buildings through only one collection round at 7:00 AM. All routes start and end at a central point in the city (i.e. intermediate hub) as illustrated at the right side of Fig. 4.

The six vehicles are tracked using GPS sensors to record the arrival and departure times at each served building. The trip length ranges between 5.119 km for route and 13.730 km for route 3; while, the total time ranges between 68 min for route 5 and 171 min for route 4. A macro simulation model is developed using Visum software to study the improvement scenarios as discussed latter. To calibrate such model, Open Street Map and Google Maps are used to identify the road network and its characteristics (alignment, direction of traffic, and speed). The recorded in-vehicle times are used to validate the model and found acceptable.

The average pick-up time (i.e., loading/unloading and cleaning) is 2.6 min/building with a standard division of 0.5 min/building. This average pick-up time is 2.8 min/building for the small pick-up vehicles and 2.1 min/building for the medium pick-up vehicle. This variation is due to the presence of additional assistant to the driver in case of medium pick-up vehicle. Table 5 summarizes the current routes characteristics.

The current collection management is good in terms of buildings grouping, pick-up time, and cleaning after collection. On the other hand, the main drawback of the current situation is the time consuming due to manual loading, and the significant portion of overlap paths between the six collection routes. Furthermore, the small capacity of vehicles, lack of compaction, and insufficient assistants increase the number of the collection vehicles and routes, as well as the collection time.

Operationally, the pick-up time for small pick-up vehicles can be decreased if two assistants are working with the driver as in the medium pick-up vehicle case. In addition, the total network duplication can be decreased by replacing the small pick-up vehicles by medium ones. Moreover, the route duplication, in-vehicle time, and total time can be reduced by re-sorting the route buildings. Furthermore, the routes can be optimized to be more efficient if the route buildings are identified dynamically using sensors or at least using production models.

Environmentally, collection process will be more eco-friendly if the medium boxes at the buildings with oversaturated containers (i.e., daily production higher than 41 kg) are replaced by larger ones, provided by additional boxes, or serviced through two rounds daily. In addition, the recycling efficiency can be improved if additional boxes are added for at-source separation purposes according to the results of aforementioned sorting analysis.

Table 5
Current Waste Collection Routes Statistics.

Route	Vehicle	Buildings Count	Network Length (km)	Travelled Distance (km)	Network Duplication (km)	In-Vehicle Time (min)	Pick-Up Time (min)	Total Trip Time (min)
1	S1	44	5.570	5.811	0.241	18	124	142
2	S2	46	6.004	9.794	3.789	34	132	167
3	S3	44	7.228	13.730	6.503	36	124	160
4	M1	64	8.743	11.211	2.468	38	134	171
5	S4	19	4.599	5.119	0.520	15	53	68
6	S5	18	6.091	6.250	0.160	19	51	70
Sum		235	38.234	51.916	13.681	161	618	779

5.4. Improvement scenarios

Based on the analyses of the current situation of MSW collection, a set of improvement scenarios are proposed as briefly described in Table 6 and discussed in more details through the following subsections. Each scenario tries to improve its base scenario from additional perspective; therefore, its requirements includes the requirements of the base scenario. The base scenario for each scenario is the previous scenario except for the base of fifth scenario which is the third scenario. It is worth noting that scenario 4 (i.e., on-demand scenario) is not the base of scenario 5 where the on-demand routing is not efficient for scenarios 5 and 6 due to the large-size or multiple-building containers.

5.4.1. Scenario 1: re-Routing

This scenario includes revision of the current six collection routes to minimize travel distance and travel time, while retaining the collection operation as in the current scenario (i.e., same vehicles, assistants, loading, and pick-up time). The in-vehicle time is optimized by rearranging the order of served containers by each vehicle.

First, integer GA is applied to optimize the routes based on the traditional salesman problem [23]; however, the computer consumed two hours per route without achieving a satisfactory results. The main problem is the long route in terms of number of serviced containers as well as the size of road network in terms of nodes and links. Second, the developed program for route optimization by Alsobky et. al. [24] is applied to optimize the MSW routes; however, the computer consumed more than two hours per route without achieving a satisfactory results due to the same problem.

Therefore, a new algorithm is developed specifically for this research using Matlab software according to the branch and bound technique based on the skim (i.e. time) matrix among the serviced containers in addition hub location as follows:

(1) Starting at the hub location, all connected containers to this location are forming possible routes of just two locations.
(2) The in-vehicle times of all these possible routes are calculated. Each possible route is branched to include additional connected container and then the in-vehicle times of branched possible routes are updated.
(3) The previous step is repeated till each possible routes involved all serviced containers and then corresponding route time is updated.
(4) The hub location is added at the end for all possible routes and then the corresponding route time is updated.
(5) To limit the computer run time within a reasonable period (e.g., few minutes), the number of possible routes should not exceed a reasonable threshold (e.g., 1,000 routes). The bounding criteria is implemented based on the route time. In particular, the routes of highest times are excluded. This step is necessary only for the long route involving more than six containers. For instance, if the route involves 10 containers the number of possible routes by Permutations, without repetition, is 10! (i.e., 3,628,800 possible routes); while, the number of possible routes involving six routes is only 720.
(6) The possible route of least route time is selected to be the optimum route.

As Visum software calculates the skim matrix for zones and main zones only (i.e., not for nodes), another algorithm is developed in this research to calculate the shortest path for each pair of containers based on Dijkstra technique and then calculate the skim matrix among containers. The statistics of implementing the re-routing scenario are presented in Table 7.

Implementing the re-routing scenario reduced the travel distance by 28 %, from 51.916 km to 37.285 km, and consequently the network duplication is reduced by 93 %, from 13.681 km in the current situation to 0.924 km. In addition, the in-vehicle time is reduced by 30 %, from 161 to 112 min. Though that the in-vehicle time and travel distance are significantly improved in the re-routing scenario compared to the base scenario (current situation), yet the pick-up time is similar to that of the base scenario since it is based on the same pick-up mechanism. Hence, there is still a need to improve the pick-up time.

5.4.2. Scenario 2: Medium Pick-up vehicles

In this scenario, the collection fleet is replaced by 4 medium pick-up vehicles serving 4 collection routes and covering all the serviced residential buildings. Accordingly, the pick-up time is 2.1 min/building for all pick-up vehicles assuming two assistants are working with the driver. Additionally, the in-vehicle time and the travel distance are optimized similarly to the first scenario by rearranging the order of served buildings by each vehicle. Fig. 5 shows the buildings to be serviced by each vehicle in addition to the optimum route for each vehicle.

The results of this scenario indicates that replacing the small pick-up vehicles by medium sized ones of shorter pick-up times, and re-routing to consider only 4 collection routes, reduced the travel distance by 42 %, from 51.916 km to 29.989 km, and consequently reduced the network duplication by 92 % from 13.681 km in the current situation to 1.127 km. Furthermore, this led to reducing the in-vehicle time by 42 %, pick-up time by 22 %, and collection time by 26 % improvement, compared to the base scenario.

Table 6
MSW Collection Improvement Scenarios.

SN	Scenario	Description	Requirements
1	Re-Routing	Reselection of serviced buildings per route- Revision of routes for more effective travel distance and collection time	Maps/instructions
2	Medium Pick-up Cars	Replacing the small pick-ups by medium pick-up ones on a reduced number of routes to Scenario No. 1 routes	Less number of routes than in Scenario No.1 + Replacing the small cars by medium pick-up cars
3	Two Rounds	Collection through two rounds divided among Scenario No. 1 routes at different times of day: 7:00 AM + 3:00 PM.	Previous as in Scenario No. 2 but splitting routes into 2 shifts
4	On-Demand	Dynamic based on real demand/smart containers and divided among Scenario No.1	As in Scenario No. 3 but dynamically (varied from time to time) + dynamic rates/sensors per container
5	Central Collection points for each 3–4 buildings	Same as Scenario No. 3 with fixed routes but with central points of collections for each 3–4 buildings	As in Scenario No. 3 + shifting to central locations
6	Source Separation and in-vehicle compaction	Collecting the separated MSW at home by specific car + compaction	As in Scenario No. 5 + hoist trucks with mechanical loading of containers with compaction
6′	No source separation and in-vehicle compaction	Collecting the separated MSW at home by specific car + compaction	As in Scenario No. 5 + hoist trucks with mechanical loading of containers with compaction

Table 7
Current Waste Collection Routes Statistics.

Route	Vehicle	Buildings Count	Network Length (km)	Travelled Distance (km)	Network Duplication (km)	In-Vehicle Time (min)	Pick-Up Time (min)	Total Trip Time (min)
1	S1	44	5.469	5.576	0.108	18	124	142
2	S2	46	5.633	5.730	0.098	18	130	148
3	S3	44	7.164	7.516	0.352	21	124	145
4	M1	64	7.819	8.114	0.295	26	134	160
5	S4	19	4.597	4.669	0.072	13	53	66
6	S5	18	5.679	5.679	0.000	17	51	68
Sum	235	36.361	37.285	0.924	112	615	728	

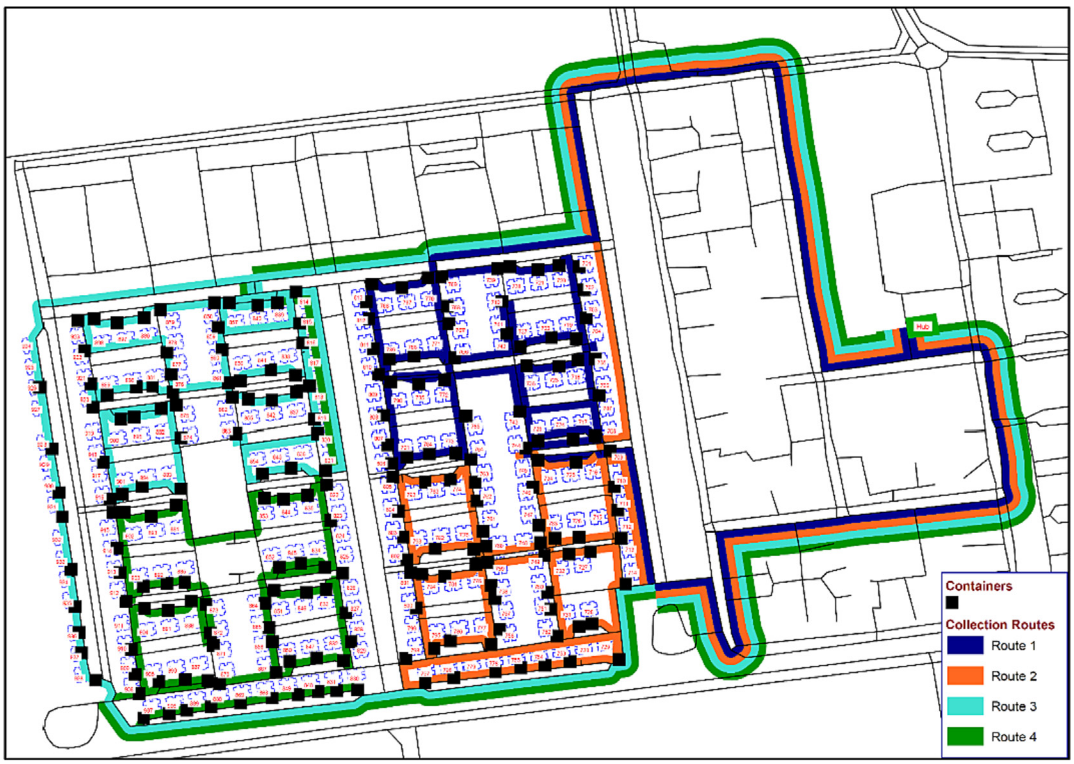

Fig. 5. re-Routing Considering Four Medium Pick-up Vehicles.

Nevertheless, operating the collection fleet once a day may not be efficient considering the increasing waste generation amounts, and that the transfer station to which the collected MSW is transported is only one hour drive far from the compound. Hence, operating the collection fleet twice (e.g., 7:00 AM and 3:00 PM) may be more efficient in terms of MSW collection, and avoiding waste accumulation in the compound.

5.4.3. Scenario 3: Two rounds

This scenario is based on the same vehicle types and routes developed in the second scenario, yet with splitting the MSW collection into 2 rounds/shifts per day instead of 1 round as in the current, first, and second scenarios. Furthermore, for each shift, two medium pick-up vehicles will be operating the collection, considering all the residential buildings.

The main edge of this scenario is that only two medium pick-up vehicles are required to reach the same improvement developed in the second scenario (i.e., reducing the travel distance and in-vehicle time by 42 %, each, pick-up time by 22 %, collection time by 26 %, and network duplication by 92 %). While this scenario is similar to the second in terms of in-vehicle time, travel distance, pick-up time, and collection time, operating the vehicles two shifts daily, instead of only one, is more efficient in terms of fleet size and employees.

It is worth noting that all the proposed scenarios so far operate the pick-up vehicle to serve daily specific buildings regardless the MSW production of these buildings which is less efficient compared to dynamic (i.e., on-demand) collection. Therefore, there is a need to study a scenario for dynamic/on-demand collection considering the daily varying MSW production per residential building.

5.4.4. Scenario 4: On-Demand collection

This scenario is the dynamic version of the third scenario, where the served buildings by each pick-up truck varies from day to another based on the production demands. Wireless IoT based sensors to be used to provide real time fill up level of each container. These sensors are communicating through wireless network to central management system responsible for dynamically monitoring garbage fill level of containers and on-line dispatching of pick-up vehicles, also via on-board units equipped with wireless communication, with dynamic routing to allow for effective and on-demand collection routing. Fig. 6 illustrates the On-Demand collection process along with an example for a bin level sensor installed in South Korea.

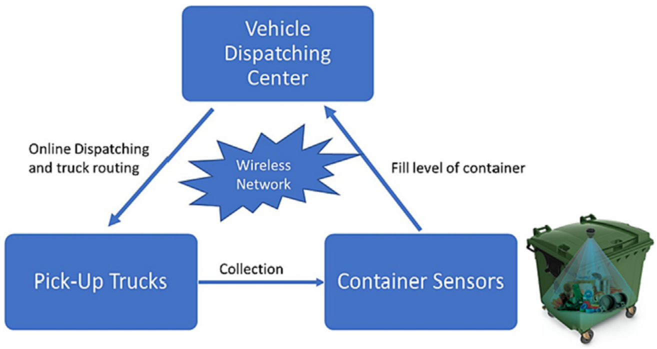

Fig. 6. On-Demand Collection Process.

Since there is no possibility to install sensors in the waste collection containers in the compound at the time being, the authors considered the daily MSW production per residential building as a dynamic variable for the demand. As previously discussed in the current scenario and depicted in Fig. 1, the daily MSW production is observed in terms of the saturation level of containers (i.e., MSW volume to capacity ratio) where 210 containers are up to 100 % and 25 containers exceed 100 %.

The buildings of saturation levels up to 100 % are served once daily, while the buildings of saturation levels exceeding 100 % will be served twice daily. Therefore, the collection route for each pickup vehicle is designed to include the over-saturated containers in addition to about 50 % of the under-saturated containers.

The supremacy of the on-demand collection scenario, compared to the other proposed scenarios, is that no over saturation would occur in the MSW containers, and accordingly no waste accumulation, while retaining the edge of the third scenario regarding the fleet size and employees efficiency. In this scenario, the travel distance, in vehicle time, pick-up time, collection time, and network duplication are reduced by 34 %, 32 %, 14 %, 18 %, and 94 %, respectively, compared to the current scenario.

5.4.5. Scenario 5: Central collection points

This scenario is based on the same number of routes and vehicles as in the third and fourth scenarios, yet with a different routing scheme to serve central collection points for each three to four buildings instead of one collection point per residential buildings as in the previous scenarios. Hence, to implement this scenario, the current containers are supposed to be re-located to central locations to decrease the in-vehicle time. The proposed locations of these central containers were selected to serve a maximum of four adjacent buildings, to maintain a reasonable walking distance for the residents between each building and its central container. More criteria shall be considered before allocating the central containers such as the landscape and wind directions. Fig. 7 shows the proposed location for the central collection points in addition to the new routes for these points considering the vehicles and rounds as developed in Scenario 3.

In this scenario, the travel distance, in-vehicle time, pick-up time, collection time, and network duplication are reduced by 54 %, 57 %, 22 %, 29 %, and 97 %, respectively, compared to the current scenario. However, the drawback of this scenario is that the walking distance for residents will increase from an average of 22 m to an average of 43 m.

5.4.6. Scenario 6: In-Vehicle compaction

In this scenario, the central containers illustrated in the fifth scenario are maintained, yet with replacing the four medium pick-up vehicles by one medium hoist vehicle with mechanical loading and compaction units to serve the central collection points through two rounds (i.e., 7:00 AM and 3:000 PM). Therefore, the medium sized boxes at the central locations will be replaced by bigger ones of capacity ranging between 1,500 and 2,000 L, so that these containers can be unloaded mechanically. The pick-up time of such system is expected to be 0.067 h/container (i.e., 4.0 min/-container). This pick-up time for each central location point means that the pick-up time is about 1.25 min/building which is definitely less than the pick-up time for the current medium pick-up vehicle by which the containers are loaded/unloaded manually.

On the other hand, additional containers hall be used for at-source separation purposes. According to the soring analysis discussed earlier in this section, two additional containers are recommended at the central location; the first one shall be specified for plastic (14.9 %); while, the second one shall be specified for cardboard and papers (9.1 %). Accordingly, the main container shall be specified for organics (55.0 %), unrecyclable materials (16.2 %), and limited recyclable material (4.8 %). In this case, the main container will be serviced every day; while, the additional containers will be services every several days (e.g., four days). Therefore, the average pick-up time will be 6.0 min/building. In addition, using sensors at the additional containers will increase the service period and decrease the average pick-up time. Fig. 8 depicts the optimum routes for this scenario either with or without separation or sensors.

Applying the collection through compacting vehicle with separation (i.e., three container at each central location point) reduces the travel distance, in-vehicle time, pick-up time, collection time, and network duplication by 70 %, 71 %, 30 %, 38 %, and 96 %, respectively, compared to the current operation. While, the in-vehicle compaction without separation will improve the current pick-up time and total collection time by 54 % and 57 %, respectively. It is worth noting that the at-source separation requires awareness and incentives to encourage the residents to separate the MSW at home first according to the abovementioned categories and then throw them in the relevant containers.

Such significant reductions promote this scenario as the optimum, compared to the other proposed scenarios, in terms of the travel distance, in-vehicle time, pick-up time, total collection time, and network duplication, however, it is considered costly in terms of mechanical loading, unloading, and compacting vehicle in addition to the required containers in terms of their numbers and size.

5.5. Recommended improvement scenarios

Based on the abovementioned analysis for the improvement scenarios, Fig. 9 summarizes the improvement of each scenario with respect to travel distance, in-vehicle time, pick-up time, total collection time, and network duplication noting that scenario 6 is with separation; while, scenario 6′ is without separation.

It is clear that all scenarios resolve significantly the current network duplication. Scenario 6 is the best one at all in terms of all operation attributes. In addition, Scenario 6 is considered the most echo-friendly-one in terms of recycling efficiency and fuel consumption. However, this scenario is costly in terms of hoist vehicle and required containers.

If the at-source separation would not be implemented for any reasons, Scenario 6′ is recommended instead. If the compacting vehicle would not be available for any reasons, Scenario 5 is recommended. If the central location points would not be applicable for any reasons, Scenario 3 is recommended. If operating two medium pick-up vehicles for two rounds per day is not working, Scenario 2 is recommended. If replacing the five small pick-up vehicles by two additional medium pick-up vehicles is not valid, Scenario 1 is recommended.

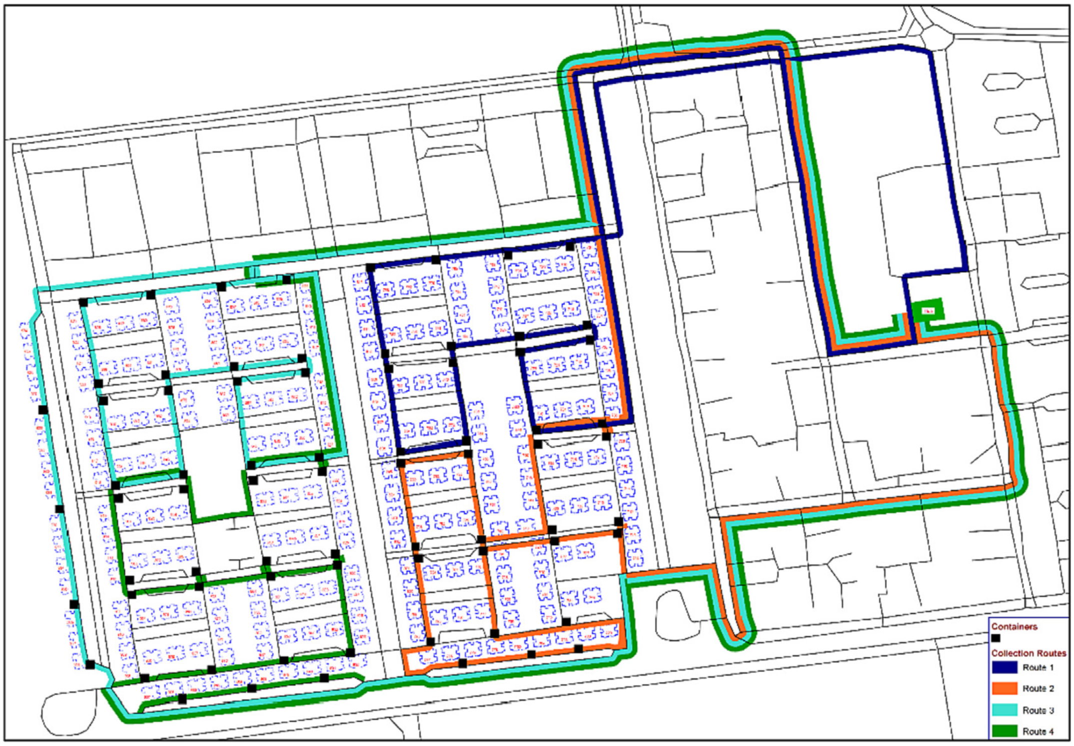

Fig. 7. Locations of Central Collection Points and Corresponding Routes.

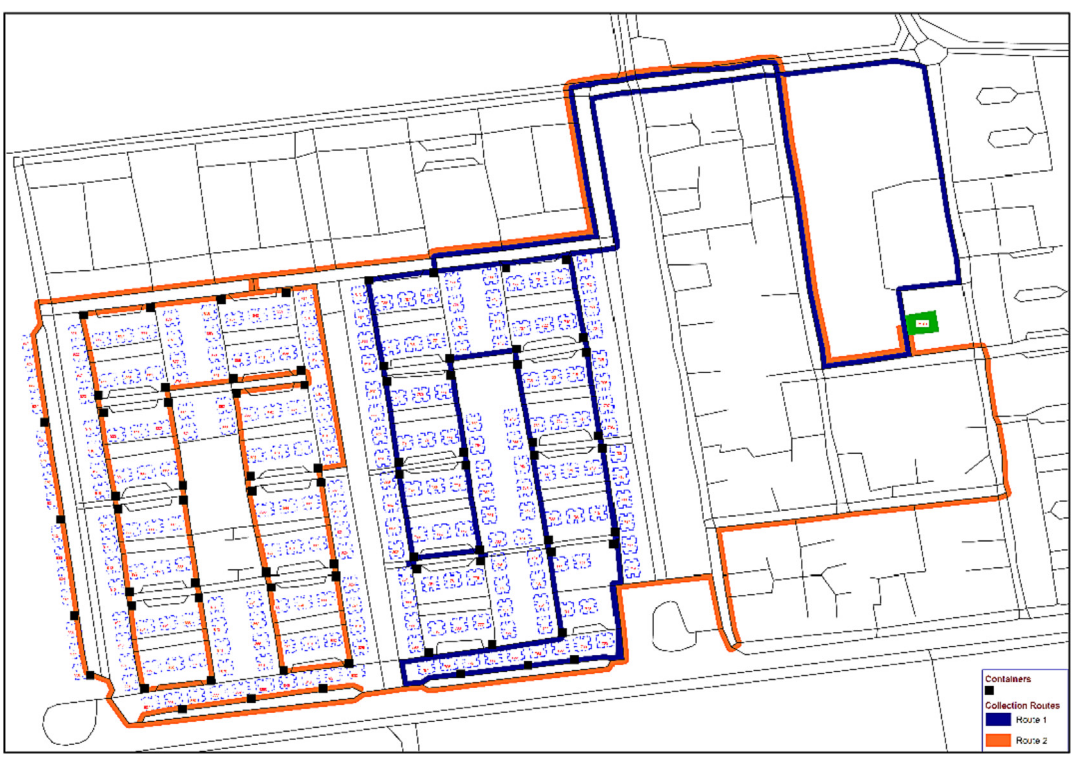

Fig. 8. Routes of Hoist Vehicle with Mechanical Loading and Compaction.

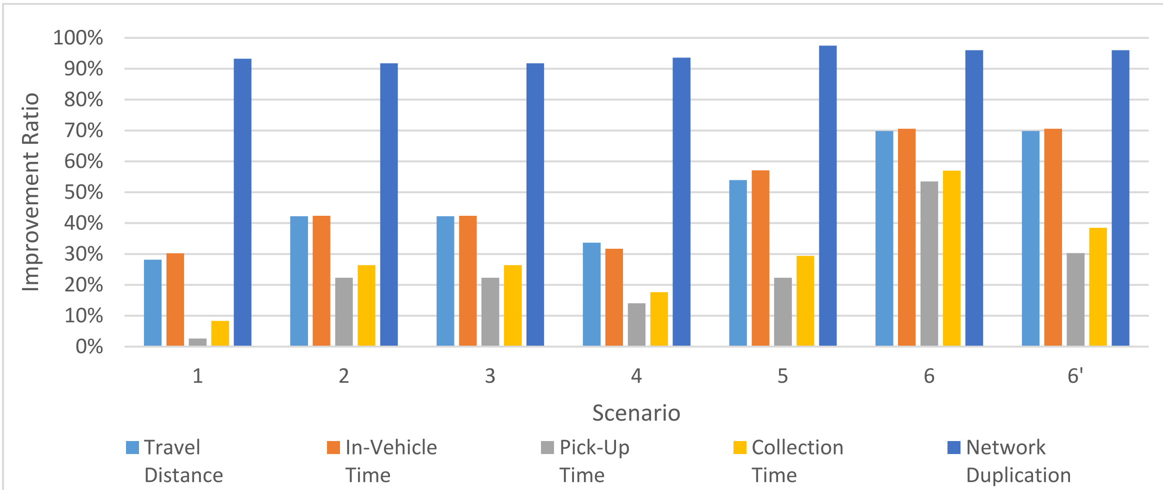

Fig. 9. Improvement Scenarios Comparison.

6. Conclusions and recommendations

This research aimed to develop a smart and sustainable MSW collection system for Greater Cairo using El Mostakbal City as a case study. The research management is to achieve the following:

- Conducted site survey and obtaining the average pick-up time for the most popular collection vehicles and conducted sorting analysis and determining the MSW composition for different living levels within El Mostakbal City.
- Developed a sustainable framework for the MSW collection management suite different types of land uses, living levels, resources, and data availability.
- Developed a routing optimization algorithm suitable for different sizes of road networks and lengths of routes, and numbers of serviced containers.

Several solid waste collection and routing scenarios were tested and assessed using traffic simulation. On the basis of the results and current resources present in GCR, the following recommendation are provided:

(1) Short-term: Solid waste collection improvements through re-routing and replacement of small pick-up vehicles by medium trucks in areas of large solid waste demand.
(2) Medium Term: set-up of central solid waste collection points instead of collection points per building, coupled with re-routing schemes and gradual introduction of hoist trucks with mechanical loading of containers with compaction to replace medium and pickup trucks
(3) Long-term: Demand-responsive smart collection with smart bins/containers at central collection points with/without source separation, taking into account housing levels and introduction of sensor and communication technologies to enable smart detection and dispatching and management of collection vehicles. Such a scenario can be implemented more rapidly in new smart cities as the New Administrative Capital with existing IT and organization resources. Other places in GCR need more time to set up the necessary organizational and IT infrastructure.

Future work will be the expansion and application of smart/sustainable MCW collection into other parts of GCR with connectivity up to formal solid waste processing and disposal facilities to complete the waste collection transport cycle.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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