Smart Waste Management System as a Sustainable Social Enterprise Model

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Abstract— **Smart and sustainable solid waste management in metropolises with systemic methods and other environmental issues are important factors in the development of urban management and circular economy. Extensive progress has been made towards reducing the environmental and human health impact of the generated solid waste in households. Under such a context, the major challenges are to reduce waste generation and optimize waste collection process in a way that lies within the circular economy. A Norwegian municipality has been investigated as a case study for this research. In this regard, a sustainable social enterprise model for solid waste management has been proposed. It has two key points; one is optimal waste collection and other is to observe effects of optimal route planning for achieving sustainable development goals (SDGs). Furthermore, the data analysis has been done to observe the waste generation patterns in different areas of the investigated municipality and how can this be used for future placement and sizes of waste bins. The proposed solution is profitable for a circular economy as the optimal route planning will help to reduce fuel consumption, cost, and time used for waste collection. The social enterprise model (SEM) accomplishes the revenue and achieves the key performance indicators (KPIs) for sustainable development goals.**

Keywords— Capacitated Vehicle Routing Problem, Circular Economy, Key Performance Indicators, Optimal Waste Collection, Social Enterprise, Sustainable Development Goals, Vehicle Routing Problem.

I. INTRODUCTION

The term *circular economy* can be defined as an economic system based on business model which substitute the 'end-of-life' concept in the allover production, distribution, and consumption phase [4]. Although it is often mistaken with recycling. Smart and sustainable waste management system is one the most important factor in the development of a circular economy.

In the past, waste generation in connection with the production and consumption of other products was considered as a necessary evil. On the contrary to that today's world has accepted the negative impact of unnecessary waste generation and insufficient treatments towards waste management. With the apparent awareness many projects such as circular economy, zero waste, close cycle, waste avoidance, reuse, and recycling have attributed to achieve an ideal world mainly without waste [3,4]. The European economy is generally linear by configuration, results in preventable ecological and human well-being impacts, inefficient utilization of natural assets and over-dependency on assets from outside Europe. Moving to a circular economy would mitigate these weights and concerns, and convey economic, social, and environmental advantages [3].

A Solid Waste Management System (SWMS) consists of the parts which fulfill overarching concept of waste management hierarchy. It includes sorting, collection, transportation, and recycling shown in Figure 1[5]. With the urbanization, the waste transportation along with its collection is one of the major issues in SWMS. It is largely addressed by many researchers world-wide to find the optimal solution.

In this paper, a Sustainable Social Enterprise Model (SSEM) for SWMS has been proposed in such a way that the waste generation analysis and optimal waste collection accomplishes two key points of a SSEM. The focus of this research is on the methods to improve the sustainability development goals (SDGs) proposed by European Commission report. To present the idea, we have investigated a Norwegian municipality and did a spatial and temporal data analysis to achieve the key performance indicators (KPIs) proposed by SDGs described in Figure 2. Section I includes introduction and a brief review on related work. Section II describes the existing practices in the investigated municipality. SEM and SDGs are discussed in section III and section IV illustrates the waste generation analysis based on historic data. Section V includes optimal waste collection methods and finally, the conclusion and future work is discussed.

II. LITERATURE REVIEW

In this paper, our focus is on smart waste management system to build a sustainable social enterprise model (SSEM) for a Norwegian municipality. According to Investopedia [8], a Social Enterprise Model (SEM) can be defined as a business model that has specific social objectives that serve its primarily purpose. SEM seeks to maximize profit though maximizing benefits to the society and environment [8]. Therefore, a Sustainable Social Enterprise Model (SSEM) can be described in terms of sustainability that is about an organization's capacity to be persistent over time [11].

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Figure 1. Solid waste Management System [adopted from Nasar et al [6]]

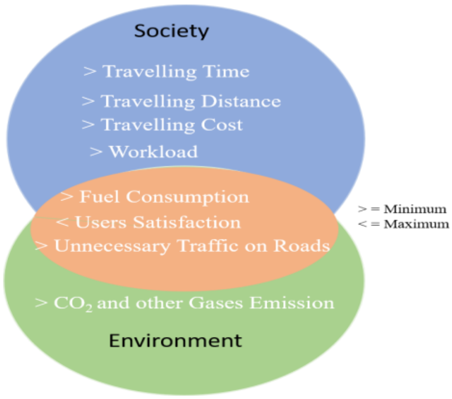

Figure 2. Social Enterprise Model (SEMs) with achieved KPIs proposed by SDGs

In SSEM, impact and financial sustainability of an enterprise cannot be separated. As the waste collection and its transportation is one of the major problems of a SWMS. In this paper, different routing planning models considering various scenarios have been proposed to achieve a smart waste management system as a SSEM. As a smart SWMS will have positive impact on the society and environment. A smart SWMS will help to achieve KPIs proposed by SGDs related to waste management system.

Since past few decades, different techniques have been proposed to solve waste management issues in an economically developing society [2]. In earlier years, to solve a transportation problem the Travelling Salesman Problem (TSP) has gained major attention for researchers [12]. With the advancement of ICT technologies for the past decade, solving transportation problem with TSP is not efficient solution anymore, especially in case of multiple deposit sites. Studies shows that a waste collection and transportation problem can be represented by the number of routes and number of deposit sites [13]. Therefore, researchers have proposed various optimization techniques based on the requirement of users such as Travelling Salesman Problem (TSP), Multi-Objective TSP (MO-TSP), Vehicle Routing Problem (VRP), Capacitated Vehicle Routing Problem (CVRP), Ant Colony Optimization (ACO), Artificial Bee Colony Optimization (ABCO) etc. [6]. In [6], Nasar et al. have proposed optimal transportation with MOO-TSP and various scenarios are taken into consideration. The limitation of TSP and MOO-TSP is that these algorithms can give solution for only single vehicle at a time. Hence, to address a problem where there are multiple routes with multiple vehicles, the VRP and CVRP are the best solutions. Due to its vital role in organizing distribution networks and logistics in many sectors such as garbage collection, mail delivery, snow sloughing and mission sequencing, VRP has gained immense interest of many researchers. To solve VRP and its types such as CVRP, the exact method based on linear programming techniques and heuristic techniques have received broad interest of researchers [14].

I.A. Hameed and Yuan et al. in [12, 15] propose to use Genetic Algorithm (GA) to solve VRP. It is observed that solving VRP with GA is quite efficient and overcome the route-finding complexities. Nonetheless Othman et al. in [16] propose ACO to solve VRP. By declining the parameters used for stopping criteria, the performance of algorithm has enhanced. Hence, to find the best value for each of them, the control parameters are measured and the ACO's performance on VRP is evaluated [16]. According to [17], Li et al. propose a hybrid GA-ACO approach to solve VRP. The objective of this approach is to reduce service cost without exceeding vehicle capacity. The GA algorithms is performed by selection, crossover, and mutation then ACO's pheromones update is performed to move away from local optima [17]. Zhang and Lee in [18] solved CVRP with Artificial BCO, originated from swarm intelligence. ABCO has exploited inherent features of swarm intelligence to improve the ability of traditional ABC for route-directed problems. Hence after studying various research papers from around the world, it is concluded to solve the route planning and waste collection problem with VRP and CVRP.

III. METHODOLOGY

A. A Case Study of Norwegian Municipality

As mentioned earlier, we have investigated a Norwegian municipality as a case study and analyzed the data collected from local waste bins. This paper is based on a smart circular city project by U4SSC [7]. According to U4SSC report [7], the total number of inhabitants is 82488 in the investigated municipality with the inflation rate 3.1%. After studying the current practices for SWMS in detail, we have presented a SSEM based on data analysis of waste generation and optimal waste collection with the help of VRP and CVRP algorithms. In the investigated municipality, there are different types of waste bins used for waste collection and for each type of bin, a specific type of truck is used. As a polit study in [5], a conceptual model has been proposed for the same municipality to improve current practices. The proposed model promises to provide better services for waste management system. In [6], we have addressed waste collection and transportation problem. An optimized solution based on multi-objective optimization problem, is proposed for the discussed problem. Whilst this paper focuses on SSEM for waste management based on data analysis and optimal route planning which proposes to achieve social and environmental sustainability. With the help of Vehicle Routing Problem (VRP) and Capacitated-VRP, optimal waste collection solutions are proposed that will help to achieve a sustainable environment with least waste in a municipality.

Table 1. Estimated duration covered by V_N vehicles from b_i to b_j

Constraints	V_0	V_1	V_2
Travelling duration (hrs)	1.12	1.11	1.108
Routes	$b_0 \rightarrow b_9 \rightarrow b_3 \rightarrow b_0$	$b_0 \rightarrow b_2 \rightarrow b_8 \rightarrow b_1 \rightarrow b_4 \rightarrow b_7 \rightarrow b_0$	$b_0 \rightarrow b_6 \rightarrow b_5 \rightarrow b_0$

Table 2. Estimated distance covered by V_N vehicles from b_i to b_j

Constraints	V_0	V_1	V_2
Travelling distance (km)	61.46	43.45	60.64
Routes	$b_0 \rightarrow b_5 \rightarrow b_0$	$b_0 \rightarrow b_7 \rightarrow b_0$	$b_0 \rightarrow b_2 \rightarrow b_8 \rightarrow b_4 \rightarrow b_1 \rightarrow b_6 \rightarrow b_3 \rightarrow b_9 \rightarrow b_0$

The data analysis of waste generation helps to achieve social and economic sustainability as it helps the service providers in placement of new waste bins where it is needed. It helps in prediction of waste generation that can play an important role in waste collection and route planning.

B. Waste Generation Analysis

Figure 3 illustrates the behaviour of waste generation in different regions of investigated municipality during the months of a year. This waste generation graph helps the service providers to place more waste bins if needed. Whilst Figure 4 shows the speed of increasing waste volume per month in various waste bins. It will help the service provider to predict the volume of waste in each bin and schedule trips for waste collection accordingly. The expenditure for waste collection and transportation is analysed in Figure 5. This bar graph represents cost that will help to make predictions and decisions while scheduling the waste collection trips and for hiring truck drivers to make these trips around the municipality. In this paper, we have done regression analysis of cost per trip with time and distance separately. Figure 10 & Figure 11 shows the regression analysis between cost consumption, time and distance taken for each trip. In here, cost is dependent variable while time and distance are independent variables. The mathematical expression to calculate linear regression is:

$$y = a + bx_i + e_i \qquad \text{Eq. (1)}$$

Where x_i is *a* line with slope *b* and y_i-intercept *a*. e_i represents error or unobserved deviations and *{i=1……n}*. The linear regression slopes in both Figure 10 & Figure 11 confirm the goodness to fit.

C. Optimal Route Planning and Waste Collection

The waste collection and transportation are addressed by VRP, CVRP optimization algorithms, and Google Maps platform is used for visualizing optimal routing for different number of vehicles.

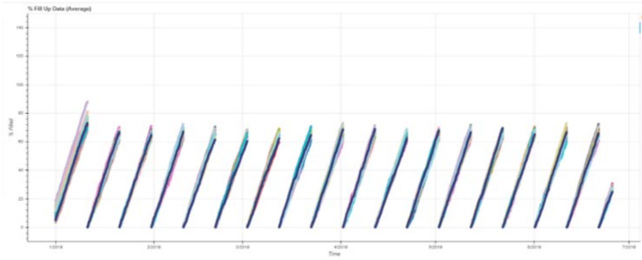

Figure 3. Fill-up behaviour of waste w.r.t time in different waste bins around the municipality

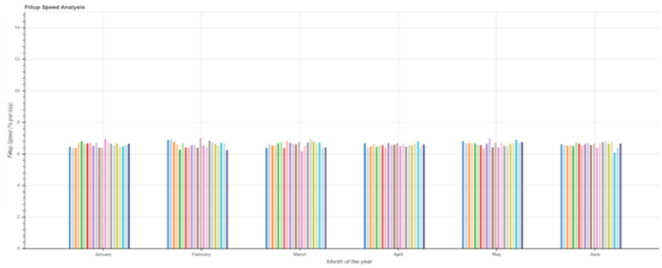

Figure 4. Waste generation speed in different bins around different regions

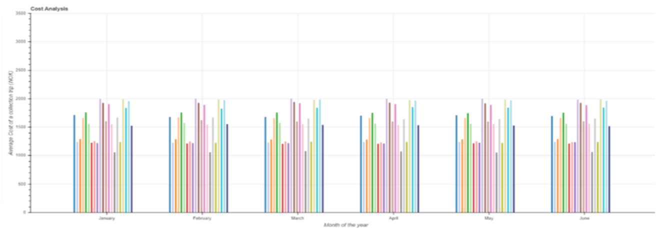

Figure 5. Cost analysis for waste collection and transportation

Figure 6. Optimized routes via VRP with minimum duration for V_N and $N = 0,1,2$

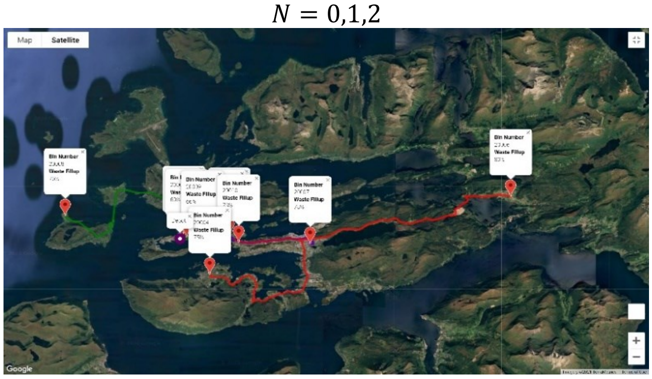

Figure 7. Optimized routes via VRP with minimum distance for V_N and $N = 0,1,2$

Table 3. Estimated distance covered by V_N vehicles with equal vehicle capacity D_k, from b_i to b_j

Constraints	V_0	V_1	V_2
Capacity of V_N (tons)	**15**	**15**	**15**
Travelling distance (km)	44.43	56.39	64.2
Routes	$b_0 \rightarrow b_7 \rightarrow b_2 \rightarrow b_0$	$b_0 \rightarrow b_3 \rightarrow b_9 \rightarrow b_1 \rightarrow b_4 \rightarrow b_0$	$b_0 \rightarrow b_6 \rightarrow b_5 \rightarrow b_8 \rightarrow b_0$
Waste load (tons)	$w_0 \rightarrow w_4 \rightarrow w_7 \rightarrow w_7$	$w_0 \rightarrow w_4 \rightarrow w_5 \rightarrow w_7 \rightarrow w_{12} \rightarrow w_{12}$	$w_0 \rightarrow w_4 \rightarrow w_7 \rightarrow w_{15} \rightarrow w_{15}$

Table 4. Estimated distance covered by V_N vehicles with unequal vehicle capacity D_k, b_i to b_j

Constraints	V_0	V_1	V_2
Capacity of V_N (tons)	**10**	**20**	**15**
Travelling distance (km)	63.56	49.94	55.9
Routes	$b_0 \rightarrow b_6 \rightarrow b_5 \rightarrow b_0$	$b_0 \rightarrow b_4 \rightarrow b_7 \rightarrow b_2 \rightarrow b_0$	$b_0 \rightarrow b_3 \rightarrow b_9 \rightarrow b_1 \rightarrow b_8 \rightarrow b_0$
Waste load (tons)	$w_0 \rightarrow w_4 \rightarrow w_7 \rightarrow w_7$	$w_0 \rightarrow w_5 \rightarrow w_{14} \rightarrow w_{20} \rightarrow w_{20}$	$w_0 \rightarrow w_4 \rightarrow w_5 \rightarrow w_7 \rightarrow w_{15} \rightarrow w_{15}$

Table 5. Estimated duration covered by V_N vehicles with equal vehicle capacity D_k, from b_i to b_j

Constraints	V_0	V_1	V_2
Capacity of V_N (tons)	**15**	**15**	**15**
Travelling duration (hrs)	0.884	1.20	1.17
Routes	$b_0 \rightarrow b_7 \rightarrow b_2 \rightarrow b_0$	$b_0 \rightarrow b_3 \rightarrow b_9 \rightarrow b_1 \rightarrow b_4 \rightarrow b_0$	$b_0 \rightarrow b_6 \rightarrow b_5 \rightarrow b_8 \rightarrow b_0$
Waste load (tons)	$w_0 \rightarrow w_9 \rightarrow w_{15} \rightarrow w_{15}$	$w_0 \rightarrow w_4 \rightarrow w_5 \rightarrow w_7 \rightarrow w_{12} \rightarrow w_{12}$	$w_0 \rightarrow w_4 \rightarrow w_7 \rightarrow w_{15} \rightarrow w_{15}$

Table 6. Estimated duration covered by V_N vehicles with unequal vehicle capacity D_k, from b_i to b_j

Constraints	V_0	V_1	V_2
Capacity of V_N (tons)	**10**	**20**	**15**
Travelling duration (hrs)	1.16	1.02	1.17
Routes	$b_0 \rightarrow b_3 \rightarrow b_9 \rightarrow b_1 \rightarrow b_0$	$b_0 \rightarrow b_2 \rightarrow b_4 \rightarrow b_7 \rightarrow b_0$	$b_0 \rightarrow b_6 \rightarrow b_5 \rightarrow b_8 \rightarrow b_0$
Waste load (tons)	$w_0 \rightarrow w_4 \rightarrow w_5 \rightarrow w_7 \rightarrow w_7$	$w_0 \rightarrow w_6 \rightarrow w_{11} \rightarrow w_{20} \rightarrow w_{20}$	$w_0 \rightarrow w_4 \rightarrow w_7 \rightarrow w_{15} \rightarrow w_{15}$

The following are considerations for optimization problem in the investigated case:

1. Number of trucks, number of bins/nodes, starting and stopping points are known.
2. Both optimization algorithms are solved using PYTHON libraries, Google Maps API KEY, Google Distance Matrix API [10].
3. However, distances and actual estimates of travelling time are retrieved from the Google Maps Platform using a Google Distance Matrix API for multiple origins and destinations. Google Maps API provides maps, street view, traffic, places, geographical locations, routes etc.
4. For both optimization problems, greedy descent algorithm is used by route solver which provides shortest route length with minimum time or minimum distance.
5. Each waste collection vehicle has some specific capacity for collection. Therefor the capacity constraint is included besides time and distance in CVRP.

1) Vehicle Routing Problem (VRP)

Let $G = (B, E)$ where $B = b_1, b_2, \ldots, b_n$ is a set of nodes representing nodes/bins with the depot location at nodes v_1 and E is a set of edges connecting all the nodes. With every edge $(i, j), i \neq j$ is associated with a non-negative distance matrix $C = c_{ij}$. In some cases, it can be interpreted as traveling time or traveling cost with different nodes. According to G. Laporte [19] and M. Zirour et al. [14], the mathematical representation of VRP:

Let x_{ij} be an integer variable which may take value $\{0,1\} \forall \{i, j\} \in E\{\{0, j\}: j \in B\}$ and value $\{0,1,2\} \forall \{0, j\} \in E, j \in B\}$. When a route including a single city, j is selected in the solution then $x_{0j} = 2$. The integer program representation of VRP is as follows:

$$Min \sum_{i \neq j} x_{ij} d_{ij} \quad \text{Eq. (2)}$$

$$Min \sum_{i \neq j} x_{ij} t_{ij} \quad \text{Eq. (3)}$$

Subject to:

$$\sum_{j} x_{ij} = 1, \forall\, j \in B, \quad \text{Eq. (4)}$$

$$\sum_{i} x_{ij} = 1, \forall\, i \in B, \quad \text{Eq. (5)}$$

$$\sum_{i} x_{ij} \geq |K| - v(K), K: K \subseteq B, |K| \geq 2, \quad \text{Eq. (6)}$$

$$x_{ij} \in 0, 1, \forall\, i, j \ \in E; i \neq j \qquad \text{Eq. (7)}$$

Equation 4,5,6 & 7 define a modified assignment problem i.e. assignments on the main diagonal are banned. Constraints in eq (6) are sub-tour elimination constraints: $v(K)$ is an appropriate lower bound on the number of vehicles required to visit all nodes of K in the optimal solution [20]. Table 1 & Figure 6 shows the estimated minimum time covered by vehicles V_N where $N = 0,1,2$ and duration is calculated in hours (hrs). While Table 2 & Figure 7 illustrates the estimated distance in kilometers (km) covered by vehicles V_N where $N = 0,1,2$. The vehicles V_N starts from depot site and return to the same site where b_0 represents depot.

2) Capacitated Vehicle Routing Problem (CVRP)

According to R. Fukasawa et al. [20] and M. Zirour et al. [14], the CVRP can be represented as given below:

Let $G = (V, E), d, q$ *and* D define a CVRP instance that have nodes b_0 as a depot and the remaining nodes in N as customers.

$$Min \sum_{e=(u,v)\in E} d(e) x_e \qquad \text{Eq. (8)}$$

Subject to:

$$Min \sum_{e\in\sigma(\{0\})} x_e = 2, \forall\, u \in N\{0\}, \qquad \text{Eq. (9)}$$

$$\sum_{e\in\sigma(\{0\})} x_e \geq 2k^* \qquad \text{Eq. (10)}$$

$$\sum_{e\in\sigma(K)} x_e \geq 2k(K), \forall\, K \in N\{0\} \qquad \text{Eq. (11)}$$

$$x_e \leq 1, \forall\, e \ \in E\sigma(\{0\}), \qquad \text{Eq. (12)}$$

$$\sum_{l=1}^{P} q_l^e \lambda_l - x_e = 0, \forall\, e \ \in E, \qquad \text{Eq. (13)}$$

$$x_e \in \{0,1,2\}, \forall\, e \ \in E, \qquad \text{Eq. (14)}$$

$$\lambda_l \geq 0, \forall\, l \ \in \{1, \ldots \ldots, p\} \qquad \text{Eq. (15)}$$

Where x_e represents the number of times that edge e is traversed by a vehicle and if e is adjacent to the depot, its value is assumed 2 corresponding to a route with a single customer [20]. λ_l normally represents possible routes and each λ_l parameter is associated with one of the all-possible *q-routes* satisfying the capacity constraint [20]. Where *q-route* is a back-and-forth distance between depot and the node with maximum demand D [20]. The proposed solutions for waste collection are data-driven and categorized by highly adaptive routes, considering the demand and volume of waste collected in each bin b_N. While b_0 denotes depot site and in CVRP, same as VRP, the vehicles starting point is depot site. Table 3,4 & Figure 9 shows the calculated routes with minimum distance for vehicles V_N where $N = 0,1,2$. The capacity D_k of every vehicle is same in Table 3 and is unequal vehicle capacity for table 4. Whilst Table 5,6 & Figure 8 indicates the calculated routes with minimum time for vehicles V_N where $N = 0,1,2$. While the vehicle capacity is equal is Table 5 and unequal in Table 6.

Figure 8. Optimized routes via CVRP with minimum duration for V_N and $N = 0,1,2$

Figure 9. Optimized routes via CVRP with minimum distance for V_N and $N = 0,1,2$

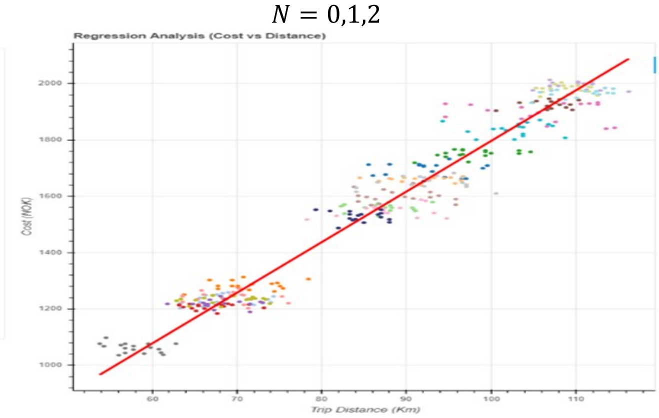

Figure 10. Regression analysis cost per trip w.r.t distance

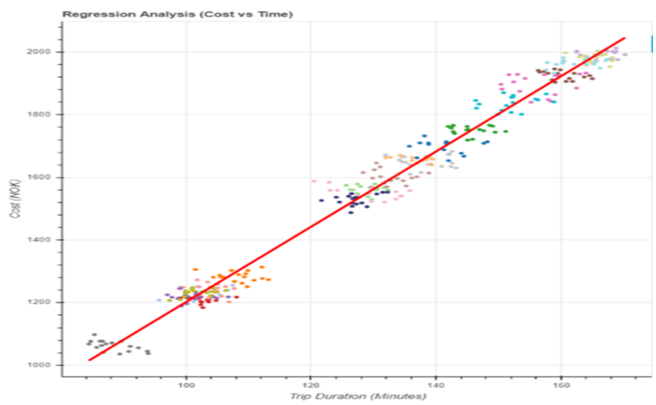

Figure 11. Regression analysis of cost per trip w.r.t time

IV. DISCUSSIONS AND CONCLUSION

In this paper, a Norwegian municipality is investigated for solid waste management system. The data analysis has been done to observe two main factors. One is waste generation patterns in different areas of the municipality. Based on the data analysis about waste volume, generation, filling up speed, and collection cost, optimized methods and solutions are proposed. Furthermore, a SSEM is presented that achieves a for-profit business for service providers and a non-profit business for government and citizens as shown in Figure 2. The optimization algorithms such as VRP and CVRP are proposed whilst considering various constraints to collect waste with minimum cost, time, and distance. With the help of optimal waste collection and proposed SEM, the following points are achieved:

- Advance route planning with highly adaptive and flexible methods i.e., VRP and CVRP
- Waste collection on demand. It will reduce:
  - Fuel consumption
  - Travelling time, and distance
  - Expenditures
  - CO_2 and other toxic gases emissions
- Waste bin placement according to the waste generation analysis.
- Creation of waste maps with toggles such as waste volume, location, capacity etc. This map helps the truck drivers for decision-making.
- With the help of the proposed solutions, various business models can be proposed to achieved sustainability.
- With the advent optimization methods, all the stakeholders can be connected and interlinked on one platform. Where stakeholders in a SWMS are city government, municipality, police, service providers, workers, and citizens.
- The regression analysis as shown in Figure 9 & Figure 10 between time/ cost, and distance/ cost shows the need of frequent waste collection trips in certain areas of the municipality.

These mentioned points help to develop a smart and sustainable waste management system according to SDGs.

In this paper, the optimal routes are calculated with the help of VRP & CVRP. In future, Vehicle Routing Problem-Time Window (VRPTW) can be used to achieve optimization within a time window. For SWMS and for increasing revenue, the smart detection for waste sorting can be introduced.

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