INCORPORATION OF MATHEMATICAL MODEL FOR THE OPTIMIZATION OF SOLID WASTE MANAGEMENT IN PRIMARY SECTOR OF KHULNA CITY

Sarmista N Satu*[1] and Islam M Rafizul[2]

[1] *Postgraduate Student, Department of Civil Engineering, Khulna University of Engineering & Technology, Bangladesh, e-mail: sarmistanandi99@gmail.com*

[2] *Professor, Department of Civil Engineering, Khulna University of Engineering & Technology, Bangladesh, e-mail: imrafizul@ce.kuet.ac.bd*

***Corresponding Author**

ABSTRACT

The gradual increase in population, urbanization, and industrialization has made solid waste management in the municipal area a challenging issue as solid waste directly affects the environment and humans. Non-governmental organizations (NGOs) and community-based organizations (CBOs) are responsible for the overall management of the primary collection system for solid waste, which entails door-to-door collection. Mathematical modeling and optimization techniques can help waste management by reducing costs, increasing efficiency in resource allocation, and lessening environmental effects. LINGO is an effective tool for waste management optimization because it offers an intuitive interface for defining and solving complex mathematical models. The primary goal of this study is to characterize the waste that has been gathered through participatory approaches in three categories: biodegradable, recyclable, and non-recyclable waste and to obtain the mathematical model for the primary collection's solid waste management system and the number of the Secondary Disposal Point (SDP) using the Lingo 20.0.1.12 software. Characterization of the plastic fraction of the disposed waste at the SDP using NIR Spectroscopy is another goal of this study. For this study field-based data has been collected from a busy and open SDP, Nirala Point, and a mathematical model has been developed based on the data collected. The LINGO model provides a combination of least-cost and high-capacity disposal point management systems. At the Nirala point, the model SDP, around 140 kg of solid waste per van per day is disposed of, and of that, about 83.71% of waste is compostable, and plastic is 5% of the disposed waste. After the primary and on-site separation by waste collectors 2.5 kg of plastic bottles and 3.5 kg of paper waste are directly going to the recycling center without entering the disposal point. The remaining part of the waste is collected by the secondary disposal truck or container-contained truck provided by KCC and directly disposed of at the landfill site. From the mathematical model developed in the Lingo software with decision variables, objective function, and constraints, the better management system for primary collection of solid waste management has been evaluated. The proposed number of recycling centers and the capacity of this center are optimized in the mixed-integer optimization model. The found plastic fractions from the NIR spectroscopy are PE, PP, PET, PA, PS, PVC, and some unidentified and their percentages of generation per day are 2.14, 0.4, 0.71, 0.16, 0.91, 0.17, 0.52 respectively. This plastic fraction refers to the amount of plastic that is directly disposed of at the landfill site without any further separation. These are mostly used for the storing of household waste and as these wet polythene are not valuable, they are dumped in landfill sites. This study finally includes the necessary field-based data to the mathematical model and gets a management system for the primary sector of Khulna City. This study not only highlights the potential benefits of mathematical modeling but also emphasizes the need for context-specific solutions in urban waste management, a perspective that aligns with the objectives of our research in the primary sector of Khulna City.

Keywords: *Mathematical model, primary collection, Lingo, NIR Spectroscopy, solid waste management*

1. INTRODUCTION

Solid waste management has become a vital issue for a smart municipal area. Municipal solid waste is a reflection of the culture, population, development rate, and socioeconomic conditions of its generation source. Waste is mainly the outlived substances that have no further usage and consist of mainly bio-degradable and non-bio-degradable but these contents are becoming more complicated day by day as plastic and electronics goods spread. Moreover, urbanization places a strain on the management framework (Khan et al., 2022). Proper waste management is very important for the environment, health, and economic reasons. The generation of solid waste in urban areas is accelerated by the increasing population, rapid economic expansion, and high living standards of the community. Solid waste can be defined as the discarded materials that are abandoned, inherently waste-like, deteriorated, or declared waste by the authority, as well as the recycled or reused materials that constitute disposal or that are burned for waste-to-energy purposes. The main fact is that solid waste does not necessarily need to be solid; it can be in liquid, semi-solid, or gaseous form (USEPA, 2021).

To address these issues, this research project aims to incorporate mathematical modeling techniques to optimize solid waste management in the primary sector of Khulna City. Mathematical modeling offers the potential to enhance decision-making processes by providing data-driven, cost-effective, and environmentally friendly waste management solutions. By developing a mathematical model tailored to the unique characteristics of the primary sector, we seek to optimize waste collection, transportation, and disposal strategies, thereby promoting sustainable practices that align with the broader goals of urban development in Khulna. Khulna, located in the southwestern part of Bangladesh, is the gateway to the Sundarbans, the largest mangrove forest in the world, and plays a critical role in the national economy. As the primary sector of the city drives economic activities ranging from agriculture to small-scale industries, it becomes the focal point for waste generation, necessitating innovative strategies to optimize waste management. Waste management in Khulna's primary sector faces challenges such as limited resources, increasing waste quantities, and environmental degradation (Harijani & Mansour, 2022).

The objectives and approaches used in the development of solid waste models have differed during the past 20 years. Among these objectives have been the prediction of solid waste generation, the selection of facility sites, the enlargement of facility capacity, the management of the facility, vehicle routing, system scheduling, waste flow, and overall system operation (Badran et. al, 2006). Several programming techniques have been applied, such as goal programming, fuzzy programming, grey programming, quadratic programming, stochastic programming, two-stage programming, interval-parameter programming, dynamic programming, non-linear programming, and geographic information systems (Nganda, 2007).

One of the poorly performed services in developing nations is solid waste management (SWM); ineffective systems are caused by a lack of resources, population growth, urbanization, and the use of antiquated methods. The SWM issue is made worse by improper planning and insufficient data regarding the production and collection of solid waste. Making decisions requires formulating solutions that take into account various objectives and approaches. It might be difficult to develop SWM solutions that meet environmental or economic goals because of the many alternatives available for SWM and the interactions between them (Akbarpour et.al., 2016). Paul et.al.,(2019) demonstrated the value of developing a mathematical model for a municipal Integrated Solid Waste Management (ISWM) system that closely mimics waste management by accounting for trash generation rates, composition, transportation modes, processing techniques, and profits from waste processing. The limitations encompass the connections between waste flows and mass balance, the capacity of processing units, landfills, transport vehicles, and the quantity of journeys. LINGO optimization software solves the linear programming model by incorporating many functional parts, and alternative waste management methods are taken into consideration during analysis. As a result, this model can be used as a decision support tool to assess different waste management options and identify the most affordable set of technologies for the collection, processing, and disposal of solid waste. Limitations encompass the connections between waste flows and mass balance, the capacity of processing units, landfills, transport vehicles, and the number of journeys. LINGO optimization software solves the linear programming model by incorporating many functional parts, and alternative waste management methods are taken into consideration during analysis. As a result, this model can be used as a decision-support tool to assess different waste management options and identify the most affordable set of technologies for the collection, processing, and disposal of solid waste (Paul et.al., 2019).

Transportation cost optimization with a mathematical model will be more feasible and give a more optimal solution (Akbari et.al., 2022). A municipal solid waste management system has a minimum of two objectives to run a model one is the minimization of the transportation and fixed establishment costs and another is to get revenue from the recycling trend and waste to energy facilities. Many mathematical models have been developed to get to know the suitable and easy system (Valizadeh et.al., 2022). Furthermore, the waste management mathematical model's social aim function optimized the number of new jobs created by the development of various facilities. The waste service tax, household discount coupons, the kinds of greenhouse gases that contribute to global warming, and the limitations on air pollution in transfer stations have all been taken into account in these models (Saadatlu, et.al., 2022).

Development of many mathematical models and assessments for solid waste has been done in many countries and also in Bangladesh. Mathematical models that are developed for Khulna City mainly focus on greenhouse gas emissions or forecasting the future waste generation or waste to energy but a mathematical model for the waste management system is needed that will preliminary set the goal for a clean and systematic city. This research is mainly focusing on the management of solid waste management in the primary sector and this is fulfilled by an integer linear programming model and integrating the collection, disposal, fixed establishment cost, and transportation cost. The other objectives are finding the composition of plastic fraction by NIR Spectroscopy machine and characterization of the waste that has been disposed of in the STS.

2. METHODOLOGY

This study was conducted in Khulna City to get a proper solid waste management system for the primary sector of the waste collection which is mainly the door-to-door collection up to secondary transfer stations. This work was done in two ways firstly field-based data collection was done then a mathematical model was developed in LINGO software to find a suitable systematic system with optimized cost.

2.1 Existing Policy Practices in the Khulna City

2.1.1 Study Area

Khulna is a littoral city with around 1.89M households in the Khulna city corporation area of 42.65 km^2 (https://bbs.portal.gov.bd/sites/default/files/files/bbs.portal.gov.bd/page/b343a8b4_956b_45ca_872f_4cf9b2f1a6e0/2023-11-20-05-20-e6676a7993679bfd72a663e39ef0cca7.pdf) which is the target area for this study. It is situated at a longitude of 89.34° East and latitude of 22.49° and due to its geographical location, it is vulnerable to the floating people coming for livelihood in the city corporation area from the neighbourhoods. The city corporation area has many access points to the city as it is surrounded by the Bhairab and Rupsha rivers which opens the city to many gateways and the city has consisted of 31nos. municipal wards that are shown in Figure **1** (Rahaman et. al., 2018). These floating people have a bad impact on the solid waste management system. The conservancy sector of Khulna City Corporation is predominantly responsible for the waste management of Khulna City but the primary collection of waste flow is mainly supported by participatory organizations such as NGOs/CBOs or some informal waste workers whose livelihood is supported by this work including the preliminary separation.

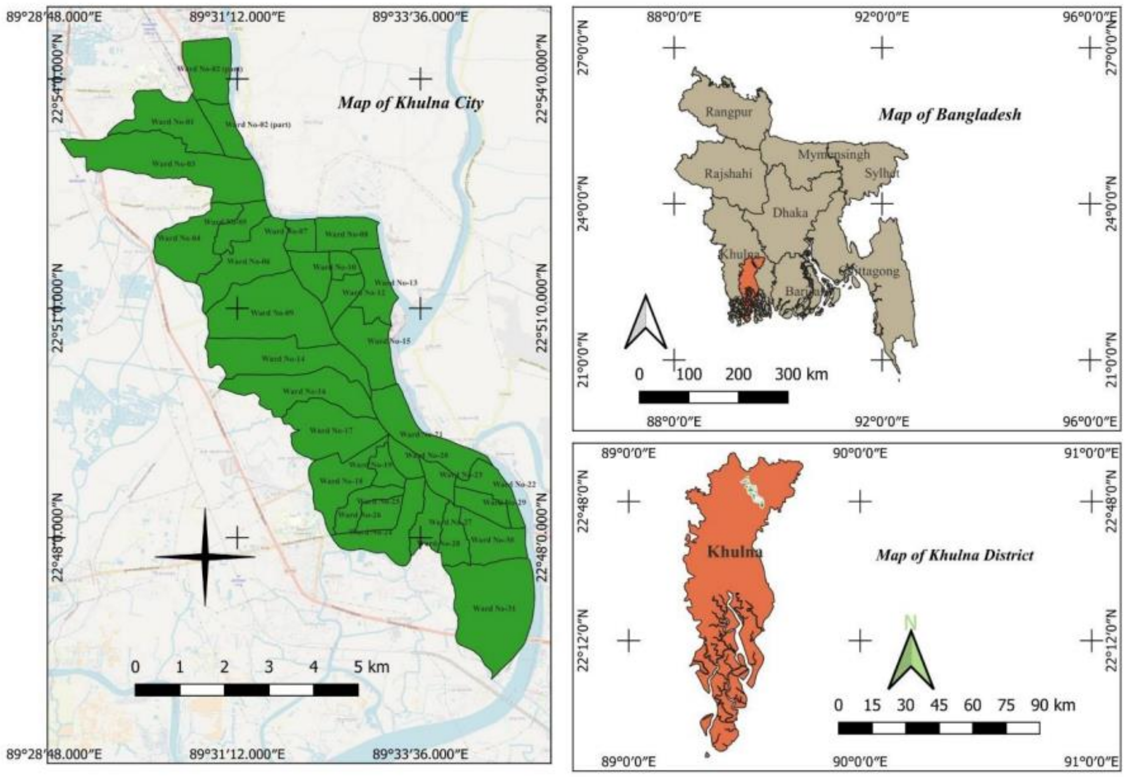

Figure 1:Map of Khulna City (Rafew et al., 2023)

2.1.2 Secondary Dataset Collected from Literature and Survey

According to Noman et al., (2023), in 2023 around 1000 tons/day of municipal solid waste was generated which is a huge amount to handle and for households, the generated waste is 641 tons per day. From a questionnaire survey and data collection conducted by SCIP Plastics Project the waste collection rate per HH on average is 3 kg/day/HH so around 515 tons per day has been collected through the primary collection with the help of participatory approaches. So approximately 20% is still not collected by participatory approaches and most importantly the collected waste is not fully separated. Locally some recyclable wastes (plastic bottles, papers, metals) are separated by waste collectors or some local boys (Tokai) and those are sold to the Vangari shops and then after another part of separation, those are sold to the Recycling shops. But these are not enlisted in Khulna City Corporation, they work in the informal sector. All theses secondary data sets shown in Table **1**.

Table 1: Secondary Dataset Used for the Mathematical Model

Data	Symbol	Value
Number of Households in Khulna City	i	188579 nos.
Number of Containers in Khulna City	j_1	56 nos.
Number of In-house STS	j_2	7 nos.
Number of open STS	j_3	18 nos.
Capacity of Container	s_{j1}	5000 kg (5 ton per container)
Capacity of In-house STS	s_{j2}	22400 kg (22.4 ton per STS)

Total Capacity of STS	$L_{j1}+L_{j2}+L_{j3}$	57000 kg
Amount of waste generated from household level	W_i	641000 kg per HH per day (as in average 4 kg per HH per day)
Amount of waste deposited in 56 container	W_{j1}	230000 kg per day
Amount of waste deposited 7 In-house STS	W_{j2}	154000 kg per day
Amount of waste deposited in 18 Open STS	W_{j3}	540000 kg per day
Cost of waste collection in each location	c_i	BDT 100
Cost of disposing waste at each location	d_j	BDT 500

2.2 Field-Based Data Collection

Waste collection in every area is done in two parts, the first is primary collection and the other part is secondary collection system. The first part is done from households to Secondary Disposal Points (SDPs) and the secondary collection is from SDPs to landfill sites. Participatory approaches like NGOs/CBOs are involved in the primary collection that includes the household, institutional, commercial, and street wastes that are disposed of in three types of Secondary Transfer Stations (STS): Open STS, In-house STS, and Container. As open STSs have no definite limit for waste volume a busy STS of that kind has been taken as a model to know the scenario well and the generation rate at this point. Nirala point has been taken as the model.

2.2.1 Waste composition

The solid waste collected from Household (HH) by non-motorized van was collected before being disposed of at STS and total waste was taken for the waste composition. Usually, 140 kg or more of that waste is collected by a van per trip and 70 kg has been taken for composition for feasible and easy handling. Waste was separated in the field manually and weight was weighed which has been shown below in *Figure **2*** and *Figure **3***. Plastic bottles and polythene were separated for carrying to the waste laboratory for further NIR spectroscopy tests.

Figure 2:Mixed SW from a van was collected on a sheet and then the weight of the total SW was found

(a) (b) (c) (d) (e)

Figure 3:Composition of waste (a) Biodegradable Waste (b) Plastic Bottle (c) Polythene and Plastic Sheet (d) Paper (e) Medical Waste

2.2.2 Plastic Fraction with NIR Spectroscopy

Plastic bottles and polythenes were washed well and dried in the oven to get rid of the water which was required for NIR spectroscopy as shown in Figure ***4***.

After washing, the polythene and Plastic were kept in the oven for 3 hours at 105°C to dry up the water and make it testworthy. After drying up weight was measured again and the lost waste was considered

Figure 4: Washing up the plastic, polythene, and bottle.

Figure 5:Measuring the weight of plastic

Figure 6: Plastic Fraction Identification by NIR Spectroscopy

as the dust and others. The Plastic fraction was identified by the NIR Spectroscopy machine (Figure **6**) of the separated plastic by different categories manually like polythene, food packaging, hard poly bags, bottles, caps, levels, boxes, brushes, pens, toys, and many others. The fraction of plastic with their specific name found from the linked-up phone with the NIR Machine was noted down. The weight was measured and noted down again against the specific fraction of plastic that was scribbled down beforehand as shown in Figure **5**.

2.3 Mathematical Model Development

The mathematical model was developed with LINGO software by focusing on the existing waste management system to develop the waste management system of primary collection.

2.3.1 Objective Function

Two objectives were taken into consideration for the primary collection of solid waste one was about the capacity and the number of the STS or SDP and another was about the minimization of the cost required for the waste management system and can be expressed by the following Equation **1**.

$$\text{Maximize Total Capacity} = \sum(\mathbf{j}, \mathbf{Lj} * \mathbf{y}) \qquad (\mathbf{1})$$

In this model, the objective function of total capacity seeks to maximize the total waste disposal capacity. The model will optimize the decision variables ‘y (Locations)’ to maximize the total disposal capacity, considering the constraints related to waste generation, collection capacity, and disposal decisions by the following Equation **2**.

$$\text{Minimization of Total Cost} = \sum(\text{Locations}, \text{c}(\text{Locations}) * \text{x}(\text{Locations}) + \text{d}(\text{Locations}) * \text{y}(\text{Locations}) * \text{W}(\text{Locations})) \qquad (2)$$

This objective is to minimize the total cost for the primary collection of solid waste including the cost of collecting waste and the cost of disposal. It captures the trade-off between the cost of collecting waste and the cost of disposing of waste at each location. The optimization process will find the values for the decision variables that minimize this total cost while satisfying the specific constraints.

2.3.2 Sets, Variables, and Data Declaration

For a mathematical model declaration of Sets, variables, and data are important and that were declared and a simplified flow is shown by Figure **7**.

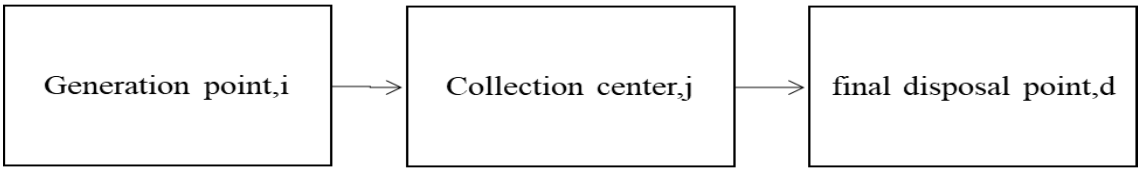

Figure 7:Flow of waste

Sets:

Locations of waste generation or collection point = i = Total number of households in Khulna metropolitan city = 188579 nos.
Location of waste disposal point = j

In-house STS = j1 = 7 nos.

Open STS = j2 = 18 nos.

Container = j3 = 56 nos.

Sets are declared as,

```
SETS:
  Locations /i, j1, j2, j3/;
  Collection_Locations /i/;
  Disposal_Locations /j1, j2, j3/;
ENDSETS
```

Data:

Capacity of the van = 300 kg

Cost of collecting waste at each location = c_i

Cost of disposing waste at each location = d_j

Maximum waste collection capacity at each location = L_i

Maximum waste disposal capacity at each location = L_j

Amount of waste generated at each location = W_i

Some data has been collected from secondary sources and this help is taken from SCIP Plastics Project, Dept. of Civil Engineering, KUET, Khulna.

Variables:

Amount of waste collected from each location = x

Binary decision variable (1 if waste is disposed at the location, 0 if not) = y

The model defines binary decision variables for trash disposal, denoted by y, and decision variables x for the quantity of waste collected from each location.

2.3.3 Constraints Development

Some constraints against the single objective function are mandatory to justify and get an accurate result. The two models for two different objectives have some common constraints as constraints are based on the waste generation, collection capacity, and disposal capacity or system.

For the maximization of the capacity of disposal point constraints taken and hence expressed by the following Equations **3** to **6**:

Waste Generation (Locations) = $\sum (Locations, x(Collection\_Locations)) = E = W(Collection\_Locations)$ (3)

Collection Capacity (Locations) = $x(Collections\_Locations) = L = s(Locations)$ (4)

Disposal Decision (Locations) = $\boldsymbol{x(Collection\_Locations) = L = y(Disposal\_Locations) * W(Collection\_Locations)}$ (**5**)

For the minimization of the cost of the primary collection of waste, the developed constraints are expressed by the following Equations **6** to **11**:

Waste Generation (Locations) = $\sum (\boldsymbol{Locations, x(Collection\_Locations)) = E = W(Locations)}$ (6)

Collection Capacity (Locations) = $\boldsymbol{x(Collection\_Locations) = L = s(Locations)}$ (**7**)

Disposal Capacity (Locations) = $\boldsymbol{x(Collection\_Locations) = L = r(Collection\_Locations)}$ (**8**)

Disposal Decision (Locations) = $\boldsymbol{x(Collection\_Locations) = L = y(Disposal\_Locations) * W(Collection\_Locations)}$ (**9**)

Non Negativity (Collection_Locations, Disposal_Locations) $\approx \boldsymbol{x, y \geq 0}$ (**10**)

All Disposal Location Used $\approx$ $\boldsymbol{Disposal\_Locations, y(Disposal\_Locations)) = E = CARD(Disposal\_Locations)}$ (**11**)

Here =E= indicates the equality constraints and =L= indicates the less than or equal constraints but it can also be indicated as '=' and '<=' respectively. This constraint mentioned in equations (**3**) and (**6**) ensures that the total amount of waste collected from all locations x(locations) equals the amount of waste generated at each location W(locations). Equations (**4**) & (**7**) indicate that this constraint enforces that the amount of waste collected from each location (x (locations)) does not exceed the maximum collection capacity at that location (L (locations)). Disposal decision constraints in equations (**5**) & (**9**) ensure that the amount of waste collected from each location is subject to the binary decision variable (‘y (locations)’), indicating whether the waste is disposed of at that location. For non-negative decision variables equation (**10**) is used that ensures the values of x and y must be positive values. To ensure that all the disposal location is declared in the set section must be used so that in the optimization process number of disposal locations should not be compromised. "AllDisposalLocationsUsed" guarantees that the cardinality (number of elements) of the set of disposal sites (CARD(Disposal_Locations)) is equal to the sum of binary decision variables for disposal locations. This essentially mandates that all disposal sites be utilized.

These constraints collectively define the relationships and limitations in the waste management system. The model aims to optimize the binary decision variables (‘y (locations)’) to maximize the total waste disposal capacity while adhering to the constraints related to waste generation, collection capacity, and disposal decisions.

3. RESULTS AND DISCUSSIONS

3.1 Observation of Field Data

Collected solid waste per van per day is around 140 kg of this specific van moreover many vans have the capacity of 300 kg. A total of 60 van trips are completed in the model SDP, Nirala Point. Amount of separated paper and plastic before coming SDP 3.5 kg and 2.5 kg respectively.

Table 2: Waste percentages of the disposed waste at the SDP

Required Field			**Quantity (kg)**	**Percentage (%)**
Compostable Waste			**58.6**	83.71
Recyclable	Paper		**5.7**	8.14
	Plastic	PE	**1.496**	2.14
		PP	**0.278**	0.40
		PET	**0.498**	0.71
		PA	**0.112**	0.16
		PS	**0.634**	0.91
		PVC	**0.121**	0.17
		Unidentified including the washable waste	**0.361**	0.52
	Total Plastic		**3.5**	5.00
	E-waste		**0.04**	0.06
	Aluminium			0.00
	Others Metal			0.00
Non-recyclable	Glass		**0.5**	0.71
	Medical Waste		**0.04**	0.06
	Textile (diaper, sanitary pad)		**0.24**	0.34
Dust and Others			**1.38**	1.97
Total Waste			**70**	100.00

The Table **2** represents the data set found from the manual sorting of the solid waste collected by a van in a single trip and the fraction of different types of plastic from the NIR spectroscopy. The three main categories of waste separation in this sorting were bio-degradable, recyclable, and non-recyclable waste. Here the non-recyclable waste includes glass, medical waste, and textiles including sanitary pads and diapers that are disposed of directly at the landfill site. Plastic, aluminum, and other metals have been taken into consideration as recycling wastes. This data collection and waste sorting give insight view of the amount of waste disposed at the STS at a time and give the estimation of how much waste is disposed of in an open STS. As the main focus relies on the primary sector of waste collection, the amount found from one STS gives the validation of the secondary data taken from literature work and also helps to decide on the number of STS of different types finally design of the STS depends on the fraction of waste disposed on the STS. The amount of biodegradable and other fractions will determine the amount of waste that will fit the compost center, recycling center, combusting, and landfill. These data will be useful for the future extensions of this research for the overall management system that includes the secondary collection and all the material flow paths as well.

Figure **8** shows the plastic fraction that has been detected by the NIR spectroscopy and mainly this plastic has been disposed of at the STS and directly goes to the final disposal point. Too much single-

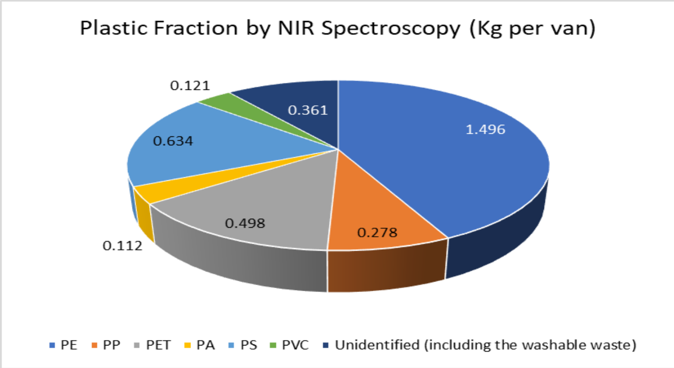

Figure 10:Comparison Between Existing Data and Optimized Data

use plastic is disposed of at the STS and this will become an effective input for incineration and pyrolysis as among 5%, 2.14% contains PE.

3.2 Mathematical Model Evaluation

For the maximization of the capacity, some secondary data set was taken to know the scenario of the existing management system and also to provide the data set to the mathematical model as parameters. The secondary data that has been used in the mathematical model is shown in Table ***1***.

Table 3: Maximization of Capacity

	Types of Container	Before Optimization	After Optimization
Capacity (STS) (tons)	Container (56)	5	5
	In-house (7)	22.4	22.6
	Open (18)	30	31.44

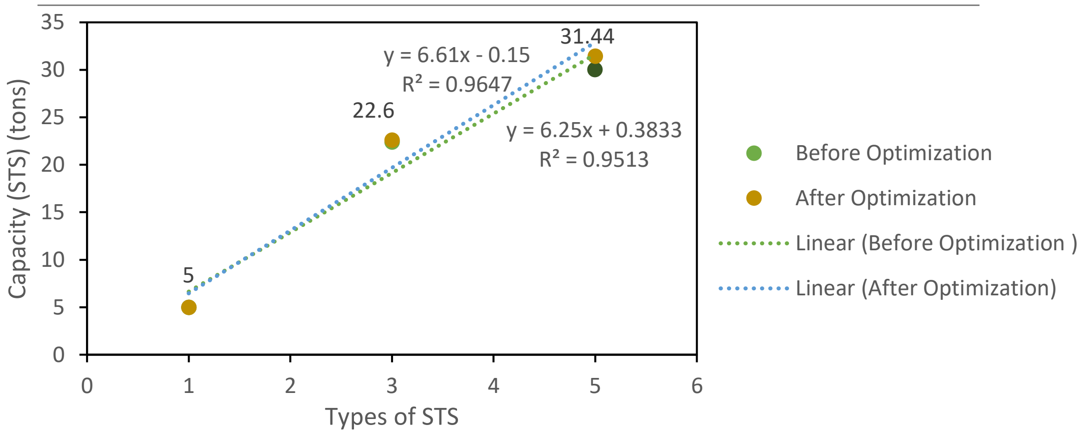

Figure 9: Maximization of Capacity Using LINGO

From *Table **3*** the optimized capacity is found for In-house and Open STS so that will be converted for In-house STS and an extra STS will cover the optimized maximum capacity. Considering the practical scenario and data as the biodegradable is more than 80%, the In-house one will be more effective than the open STS. Figure **9** shows the dataset as presented in the software with input and output data for clear understanding and Figure **10** shows the comparison with the regression coefficient.

Table 4: Result from Cost Optimizations by LINGO

	Before	**After**
Waste Collection Rate (kg/HH/day)	2.73	2
Cost (BDT)	5.15E+07	3.78E+07

For minimization of total cost, the objective value has been found $3.78 \times 10^7\ BDT$ (Table ***4***). After numerous iterations, this data has been found with a 2kg per HH per day generation rate using every disposal point. For minimization of cost along with other constraints, we have to consider the waste collected from each location cause when the waste is well managed all the waste flow path will not be towards STS a huge part will go to the recycling center and composting center and then the rate for waste collection will be less. With 2.73 kg per HH per cost is $5.15 \times 10^7\ BDT$, so approximately 26.6% cost decrease from the previous one.

4. CONCLUSIONS

The waste was categorized into three parts compostable or bio-degradable, recyclable, and non-recyclable waste and the found percentages are 83.71%, 13.2%, and 1.11% respectively. The fraction of plastic fraction that is found in STS after separating valuable plastic is 5%. As polythene bags have been widely used 1.5 % of PE has been found from the NIR Spectroscopy. These results depicted the need for incineration or Pyrolysis to convert single-use plastic into waste. For extension of this research considering percentages of these categories, all possible facilities will be built. From the mathematical model, the optimized value for minimized total cost is found $3.78 \times 10^7\ BDT$ which is 26.6% less than the previous cost. For the maximization of the capacity and well management, by considering all the constraints capacity has been increased for in-house and open STS by 0.2 tons and 1.44 tons respectively. So, making capacity for the open STS about 29 tons each one more In-house STS can be built depending on the field and secondary data (Table **1** & Table **2**). Here the mathematical model is formulated for a low-cost management system with maximum capacity STS only targeting the primary sector. This outcome will make a managed primary collection system and open a door for future work on the overall MSWMS. With these outcomes i.e., percentages of three categories, plastic fraction from NIR, and mathematical model of primary sector further research will be proceeded.

ACKNOWLEDGEMENTS

The author is highly indebted to the members of the SCIP Plastics Project, funded by the German Federal Ministry for the Environment, Nature Safety and Consumer Protection, Department of Civil Engineering, KUET, Khulna for their immense help with the lab facilities and NIR Spectroscopy Machine and other secondary information that was needed to complete the project. In addition, the authors are grateful to Dipl.-Ing. Senta Berner, BUW Research Associate, and Prof. Dr.-Ing. Eckhard Kraft, Faculty of Civil Engineering, BUW, Germany.

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