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Development and Validation of a Holistic Sustainable Solid Waste Management Model

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ABSTRACT: Increasing amounts of solid waste (SW), in big urban centers, has turned into an insurmountable challenge for the municipal authorities. Complexity of solid waste management (SWM) system further compounds the problem. Apart from the above, the major challenge of this study is lack of proper mechanism to collect, damp, and recycle the SW produced in developing countries. To deal with the issue, numerous efforts were made in the past to develop models to predict system behaviour. The major shortcoming in these models was their limited scope because only few components of SWM were considered. There is a need to develop a comprehensive model. In this paper, a major contribution in the field of SWM is the development of a comprehensive model that helps in decision and policy making in the said sector. This prescribed model encompasses all the six components and sub-components of SWM viz. (1) generation, (2) onsite handling, storage, and process, (3) collection, (4) transport and transfer, (5) processing and recovery (material recovery facility (MRF), refuse derived fuel (RDF), composting), and (6) disposal. In addition, sustainability variables such as social, environmental, and economic variables need to be incorporated in the model being essential to run SWM on a sustainable basis. This paper presents this comprehensive model. The six components/sub-components were divided into ten sectors. These sectors have 40 sub-models and 290 variables. The structural, behavioral, and face validation tests are performed. The results indicate that these tests increased the creditability and confidence of the model for future use by the decision-makers to plan and implement the policies regarding an effective and sustainable SWM system.

Keywords: Sustainable solid waste management, System dynamics modelling, Validation tests

I. INTRODUCTION

The major research problem for this research is poorly managed SW systems in urban centers that includes the unsustainability of SWM systems, and omission of sustainability variables and their linkages to the municipal SWM system. Previous studies were just focused on the few sustainability variables by considering the single element of SWM system. The present study will help the decision and policy makers in making sustainable policies in this sector by considering the prescribed comprehensive model. As per World Bank study (2019), it was revealed that around 2.01 billion metric tons of municipal SW was generated [1]. The total quantity is expected to rise to 3.4 billion metric tons by 2050. Reasons would be population growth, rapid urbanization, and accelerated globalization [2, 3]. Poorly managed waste has alarming consequences for public health, local and global environment, and the economy [4-6]. Big urban centers are specifically hard hit in terms of environmental degradation, social inclusion [*Social inclusion is the process of improving the terms on which individuals take part in society. So here it means the people participation in SWM sector. People take part in this sector through services (e.g., awareness programs related to recycling and source segregation of waste etc.), and markets (e.g., labor, or sale of recyclables, RDF, and compost)*]., and economic sustainability [6]. In minimizing these impacts and achieving the United Nations sustainable development goals, proper management, treatment, and disposal of municipal SW requires special attention.

Why most of the SWM systems are malfunctioning and are unsustainable? The prime reason is that these are designed using a linear approach. In linear approach, only few variables (generation rate, collection efficiency, etc.) are considered on which the entire system (generation; storage; collection including vehicles, crew, and equipment; disposal (land filling); recycling/recovery (MRF, RDF, composting), etc.) is designed and operated. Many variables, which play a cardinal role to make the system efficient and sustainable are ignored [6]–[8]. It is further elaborated in the following paragraph.

The operations of SWM system on few variables, stated above, is a pitfall in optimizing, making it efficient and sustainable. For example, generation rate is calculated solely based on population; whereas other variables which affect generation rate are ignored. Among others, these variables include (1) migration, (2) economic growth, (3) household size, (4) employment, (5) recycling trends, and (6) living standard. These variables are not incorporated due to time and data constraints. "Dynamic" nature of the problem is also ignored i.e., the constantly changing values of variables with time.

Linear approach has another major drawback. It is unable to deal with the complexity introduced by the feedback of various variables [7], [9]. This complexity in a system refers to the use of some portion of that system's output as input for their future behavior. Therefore, a holistic approach is required that can model the cause-and-effect relationships of the various variables in each component of SWM system.

System dynamic (SD) modelling has been proposed as a non-linear modeling approach that incorporates the dynamics as well as complex problems [10]. SD modeling has been successfully used in strategic and policy assessment applications, such as software development, human resources management, distribution supply chain simulation, and product development simulation [11], [12], [13], [14]. Particularly, it is well suited for the simulation of complex systems such as a waste management system[15], [16]. Many efforts have been made by different authors to study SW systems [17], [18], [27], [28], [19]–[26]. Most of the studies, published focus on specific aspects, such as the waste generation (WG) or other components independently while others considered a few interrelationships with other pillars of sustainability such as environmental, economic, and social variables. The studies so far do not take all six components and related sustainability variables. These are the major gaps.

To address the above gaps, and deal with various interdependent variables in SWM system, the SD approach was applied in 1997 for the first time [16]. Several interdependent issues such as public health, environment, present and future costs to society, and the livelihood in the informal recycling sector were addressed. Later fuzzy logic was also added to the SD model for forecasting the SW generation. Results show that the qualitative variables are important for a holistic modelling approach in waste management system. Fuzzy logic seems to offer very promising supplementary tools. It may be used for modelling exogenous elements like influences and thresholds, as well as for the deduction of new rules from simulation results [18]. Most models focused only on the technical and economic aspects of SW system [20], [21], [23].

SD model was also applied in Delhi. It included municipal SW generation, collection, disposal, recycling, treating capacities, electricity generated from municipal SW, and funds required for municipal SWM from 2006 to 2024 [22]. The gap was that the technical and economic aspects of SWM and its linkages were studied, while social and environmental aspects were not considered.

Some researchers developed a model, which was used to forecast environmental, economic, and social performance patterns. However, technical and institutional variables and their linkages to the municipal SW system were omitted [24], [27]. Another gap in all the aforesaid SW models was their specificity to one geographical area restraining their use to other locations [29], [30].

From the foregoing review, it becomes quite clear that the models so far developed are not adequate for addressing the dynamic, complex, and interconnected nature of a SWM system. Hence, there is a need to undertake a study, in which all the components of sustainable SWM may be included using SD modeling. It will help to understand the highly non-linear relationships among various components of SWM and variables that affect the dynamics of the system in a holistic framework. Besides, it would help to forecast the budget, requirement of new treatment facility, economic and workforce shortfall for SWM systems.

Model must not be specific to a geographic place; it must be generalized and encompasses all the possible complexities of sustainable SWM. It may be able to evaluate the possible outcomes even before an SWM system is rolled out. This study will fill all the aforesaid gaps. Therefore, the first objective of this study is to propose a dynamic model of sustainable SWM using Stella Architect that covers all the components of SWM. The second objective is the structural and behavioral testing of the sustainable SWM model by face validity test followed by three other theoretical common methods, namely the dimensional consistency, the extreme conditions, and the behavior sensitivity tests. The validated model will be intended to assist decision-makers in better understanding and developing an efficient waste management strategy. The third objective is to get real-time data output, and the fourth one is to identify sustainability variables for measuring the sustainability of municipal SWM. This paper covers the first two objectives, and the remaining two objectives will be addressed in a later publication.

II. METHODOLOGY

A. SD Model development

Lahore city, with a present population of 12 million (year 2021), was adopted for SD model development. The model was developed on Stella Architect (Version 1.2.2), delta time (DT) was 1and the Euler method was selected as an integration method. The simulation period of 100 years was selected. The conceptual framework of the model is shown in Fig. 1. The model covers all the interconnectedness, feedback, and complexity among all the six components of municipal SWM, and sustainability variables.

The model development is made in a way that it may be used for any city, medium or large size. The model contains 10 sectors i.e., (1) population, (2) gross domestic product (GDP), (3) WG, (4) waste collection (WC), (5) people's willingness (PW) to segregate waste, (6) MRF, (7) recycling plant, (8) compost plant, (9) landfill, and (10) financial. Each sector is built up of small sub-models and variables. More specifically, a total of 40 sub-models and 290 variables are incorporated into the model. Each sector and submodels are discussed below.

Sector: Population. Fig. 2a shows the population sector for the city of Lahore. This sector contains 10 variables viz. population, carrying capacity, immigration rate, emigration rate, birth rate, death rate, immigration, emigration, births, and deaths. The population is a stock, it accumulates what flows into it minus what flows out of it throughout simulation i.e., 100 years.

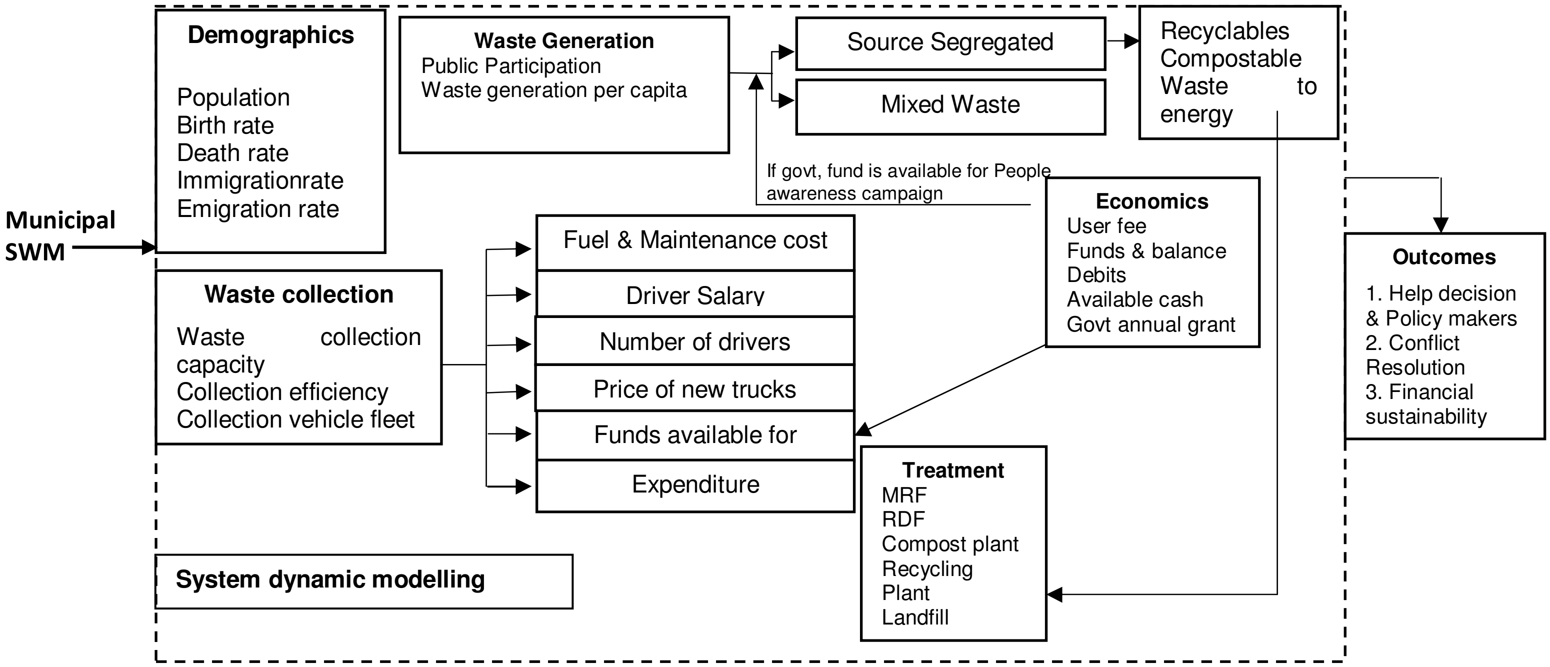

Fig. 1. Conceptual framework of SD model of sustainable SWM.

The progression in the size of the population is assumed to be based on two main factors i.e., birth and immigration of people in the city, which depend on the birth and immigration rates, respectively. While the decline in the population is due to the deaths and emigration of the people from the city. Deaths and emigration depend on the death rate and emigration rate of the people of the city, respectively. A higher birth rate and immigration rate of the population results in larger population size. The population will level off when reaching its maximum possible figure referred to as carrying capacity. The carrying capacity adopted for this research for the city of Lahore is 15 million persons [*The value of maximum carrying capacity (i.e. maximum number of people the city can accommodate or sustain) of the city i.e., 15 million persons is decided based on an expert judgement and from literature survey*].

Sector: GDP. The GDP sector comprises 4 variables viz. GDP, GDP growth rate, GDP per capita, and per capita income (Fig. 1). The GDP per capita and income per capita is the function of GDP and population of the year. The GDP increase per year for Pakistanis 5.79 % [31]. The model assumes that an increase in GDP per year will increase the GDP per capita and income per capita per year.

Sector: PW. The PW sector contains 11 variables. Among others, these variables include the size of household, number of households, unit cost of PW campaign impact, PW buildup, willingness to segregate, literacy growth, literacy level, and PW campaign fraction of required budget. This model represents the effect of the city's literacy rate on PW to segregate waste at the source as shown in Fig. 2b. The availability of funds for the campaign and literacy level, both influence the number of people at the source to segregate the waste. To see the impact of these variables, the sector is divided into two sub-models i.e., (1) literacy level of the city, and (2) funds available for the awareness campaigns. These variables are tracked by using a Stella Architect tool "switch" of the PW campaign as shown in Fig. 2b. One assumption taken for model simplification is that when there is no budget available for the initiative, the willingness of citizens will continue to buildup due to the increase in the city's literacy level.

Sector: WG. The WG sector contains 17 variables viz. municipal SW generation rate, modified SW generation rate, municipal SW generation, collected waste, uncollected waste, collection efficiency, WC capacity, mixed waste (MW), source segregated waste (SSW), among others. Fig. 2c describes the amount of waste generated, waste collected, and waste uncollected. Generally, the amount of waste collected and waste uncollected is variable according to the collection capacity of the WC authority. The collected waste is further divided into two streams i.e., SSW and MW. After the PW campaign, the SSW is a sorted waste at the household into recyclables, compostable, and waste to energy streams [32]. In this model, the impact of the PW campaign on WG per capita per year is also considered. An increase in the number of people separating waste at the source would decrease the WG per capita and the amount of MW which is shown in Fig. 2c. Further, this model is modified by using the switch of SSW, to see the impact of household-level waste segregation on WC.

Sector: WC. The WC sector, as shown in Fig. 3, contains 56 variables required to improve WC efficiency. To name few are: number of drivers, available drivers shift per year, number of available truck shifts per year, number of drivers for trucks, trucks in service, truck shifts per week. This sector will help the authority to improve its collection efficiency of waste, vehicles, and driver fleet. Few assumptions are taken for model simplifications:

1. The truck capacity is 8 tons per truck whereas different capacity vehicles such as 4, 9, 12, and 17 tons are used to collect waste in Lahore.

2. The primary collection of waste from the door-to-door collection is ignored.
3. A separate collection of recyclables is not considered. This sector is further divided into 7 small sub-models such as driver salary, increase in the collection vehicle fleet, number of drivers, increase in truck price cost, etc. These sub-models are discussed further. The collection vehicle fleet sub-model demonstrates the progression of the collection fleet life cycle. As the fuel consumption and maintenance costs are variable over the vehicle's lifecycle (the new vehicle is comparatively fuel-efficient and requires less maintenance), track of each vehicle's life cycle must be kept.

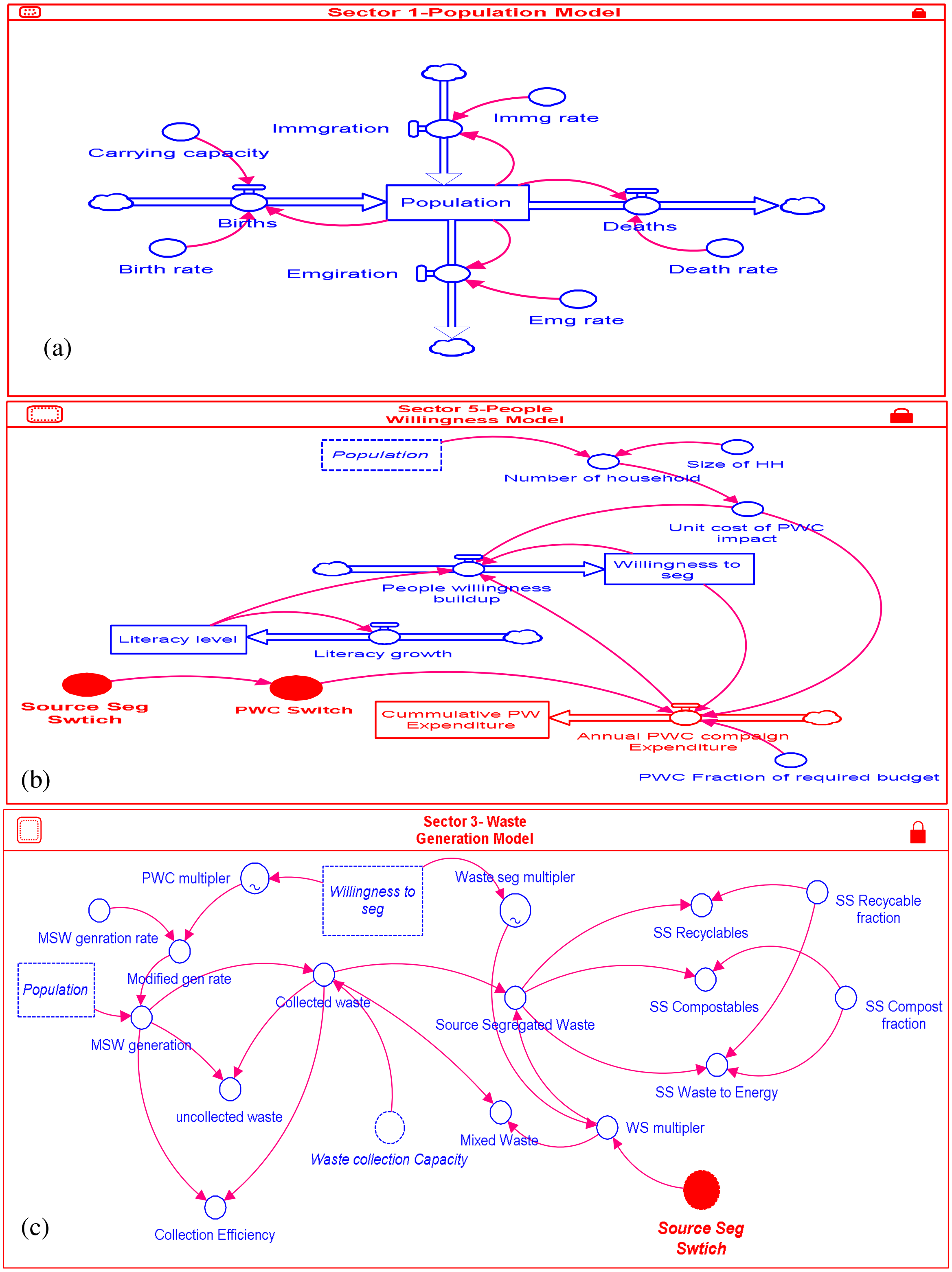

Fig. 2. (a) Population sector, (b) people willingness sector, (c) WG sector.

For simplicity, the life cycle is divided into three major categories: (1) new trucks, (2) midlife trucks, and (3) old trucks and track those using conveyor stocks that progress each truck by 5 *years [Generally, the lifespan of trucks is between 10-15 years. In this research work, it is assumed that after 5 years of truck's life span, the truck will shift to next category of truck].* Further to increase the collection efficiency of waste, the present collection fleet increase will depend on three variables i.e., (1) the number of additional trucks required to collect uncollected waste per year, (2) the number of trucks that can be purchased from the yearly budget, and (3) the number of retiring trucks per year as shown in Fig. 3. Out of the three options mentioned above, the minimum required number of trucks per year will be added to the present collection fleet per year.

The driver's salary sub-model (Fig. 3.) shows the driver's salary growth every year with a gradual rise in driver salary per year. For simplicity, we consider the constant value of the annual growth rate of driver salary, and the salary increase is calculated by multiplying the annual growth rate and current driver salary.

The fuel cost sub-model is structured to measure the vehicle's cumulative fuel cost by multiplying the fuel cost with an average fuel cost growth rate. Since the cost of fuel is variable, track of the increase in fuel costs every year must be kept. For simplicity, the increase in fuel cost per year is considered constant. Similarly, the increase in the number of drivers and the increase in truck price per year is calculated according to the desired collection efficiency of waste and the desired number of trucks.

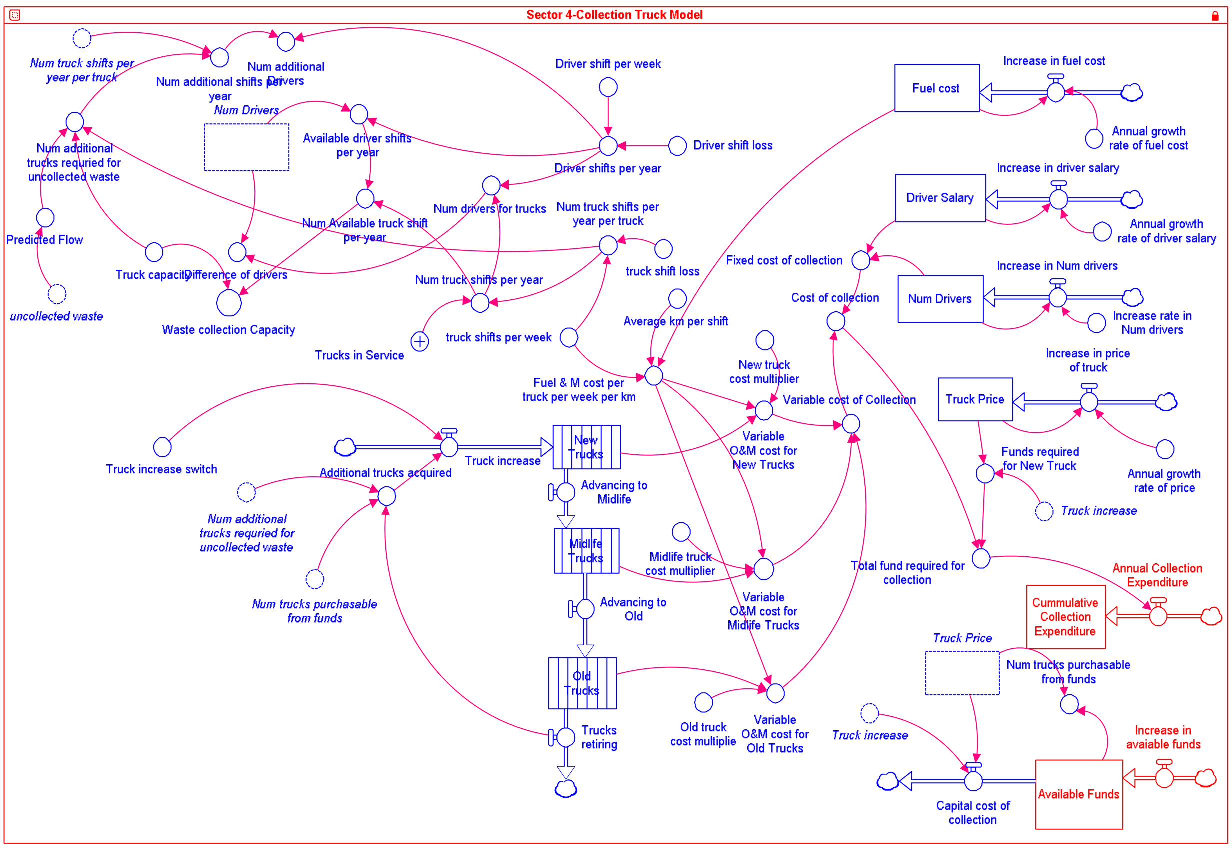

Fig. 3. Waste collection sector.

Sector: MRF. The MRF sector contains 67 variables. To name a few are: MW, MRF stock input, MRF stock, the variable cost for MRF, MRF waste to landfill, fixed cost for MRF, the fixed unit cost of MRF, and others (Fig. 4). The sector is built to deal with MW, which is divided into (1) recyclables (11% recyclable fraction), (2) compostable (75% compostable fraction), (3) waste to energy (14% waste to energy fraction), and (4) landfill waste [32]. According to its design capacity of 91,250 tons per year (250 tons per day), MRF extracts usable material, and the useless part of the waste ends up in landfills. This sector is further divided into three sub-models: (1) new facility development, (2) variable cost, and (3) RDF (Fig. 4). Development of new MRF sub-model encompasses the on/off switch of the new MRF, the capacity ratio trigger for the development of a new facility, the time required for setting up a new facility, and the capacity of the new facility. The purpose of the new MRF development switch is to provide an option to the respective authority to build a new facility or not. The capacity ratio trigger is a variable that will trigger the development of a new facility at desired existing plant capacity. For example, if the authority wants to build the new plant when existing plant capacity exceeds 50, 70, or 90 percent.

This variable would therefore start the development of new facilities when the current capacity of the plant exceeds the specified percentage of plant capacity. The advantage of the capacity ratio trigger is to forecast the budget requirement for the new facility.

The variable cost sub-model includes all the variable and fixed costs. The MRF's operational and maintenance costs are variable costs (the new plant has less operational and maintenance cost as compared to the old plant). Whereas the cost of land, MRF installation, and MRF equipment cost is the fixed cost of MRF.

The RDF sub-model (Fig. 4). is intended to manage waste, capable of producing energy. This waste is segregated at the source level and sorted at MRF. It goes to the RDF plant where it is processed and converted to small pellets, which are then burnt to produce energy. This sub-model is similarly divided into 4 categories such as new facility development model, the variable cost model, etc. These small subs-models follow the same components and functionality as discussed above.

Sector: Recycling plant. This sector contains 29 variables, to name a few: source segregated recyclables, MRF recyclables, recyclables input, recyclable output, recyclable waste to landfill, and others. The recyclables have been processed according to the recycling plant capacity and excess waste ends up in landfills. The sector is further divided into 4 sub-models such as the development of the new facility, recycling plant capacity, annual revenue generated from recyclables, and annual recycling plant expenditure. Sub-models have the same components as discussed.

Sector: Compost plant. The compost plant sector is designed similarly to other treatment/reuse sectors. It contains 4 sub-models and 33 variables such as MRF compostables, source segregated compostables, compost input, compost waste, composting residue, composting residue factor including others. The compost plant treats waste with a design capacity of 273,750 tons per year (750 tons per day) and the remaining untreated waste is disposed of in the landfill. The annual expenditure, annual revenue generated, new facility development, and compost plant capacity sub-models are designed as mentioned above.

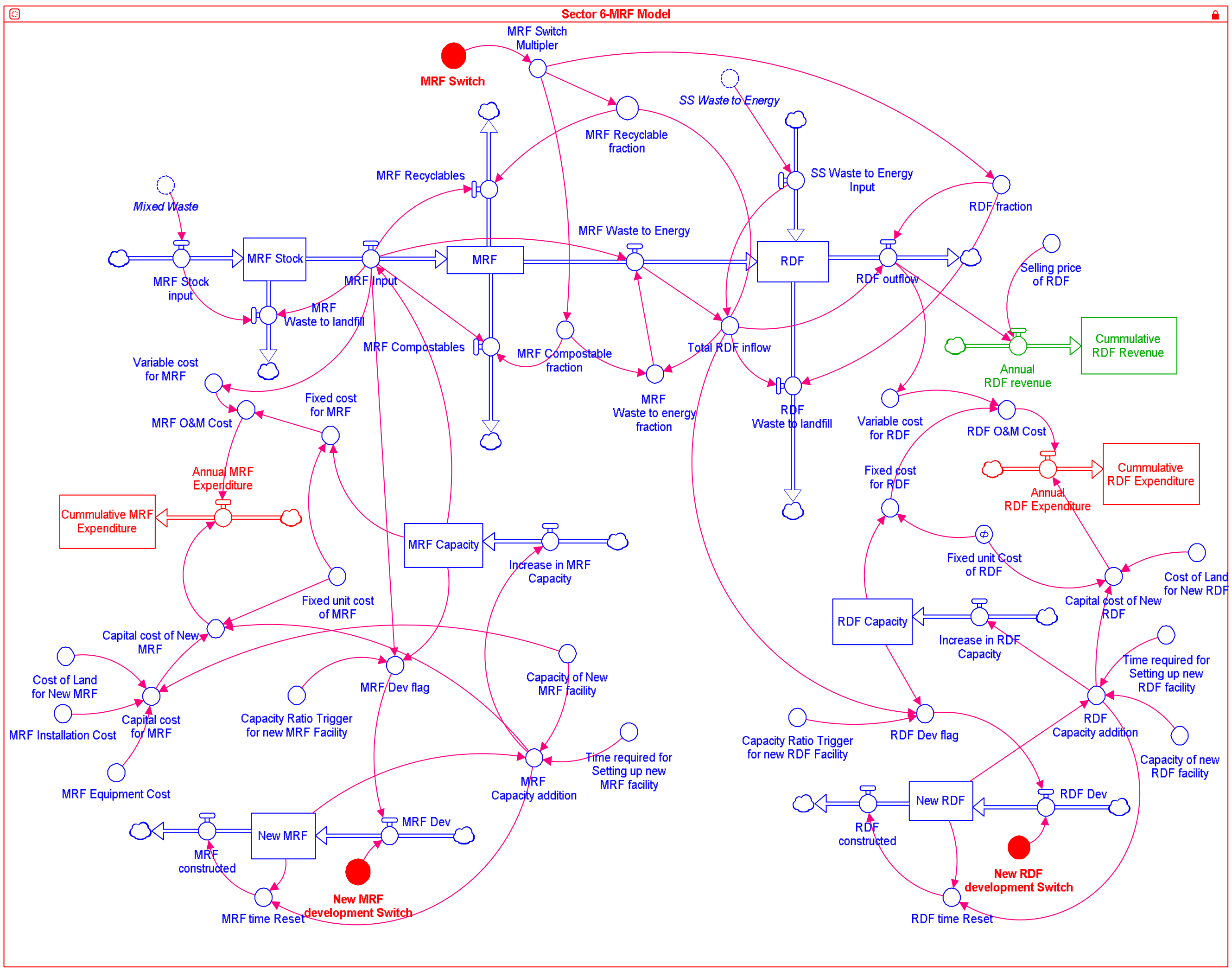

Fig. 4. MRF sector.

Sector: Landfill. The landfill sector contains 4 sub-models and 26 variables. Among others, these variables include waste from compost plant, MRF, recycling plant, and RDF.

Sector: Financial. The financial sector Fig. 5 comprises 37 variables such as total revenue, own source revenue, funds balance, own source expenditure, total expenditure, specified fee growth rate, specified fee increase including others. The sector is further divided into 3 sub-models i.e. SW user fee, funds balance, and government grants. The amount and increase in SW user fees per year are decided by the management, if management wants to get back 25, 50, or 70 % of system operating charges. The SW user fee model will analyze the sustainable and implementable amount of SW fees on the consumer. Fund's balance contains the input of own-source revenue generated and output of own source utilization of revenue generated from own source treatment options used in the sustainable SWM model.

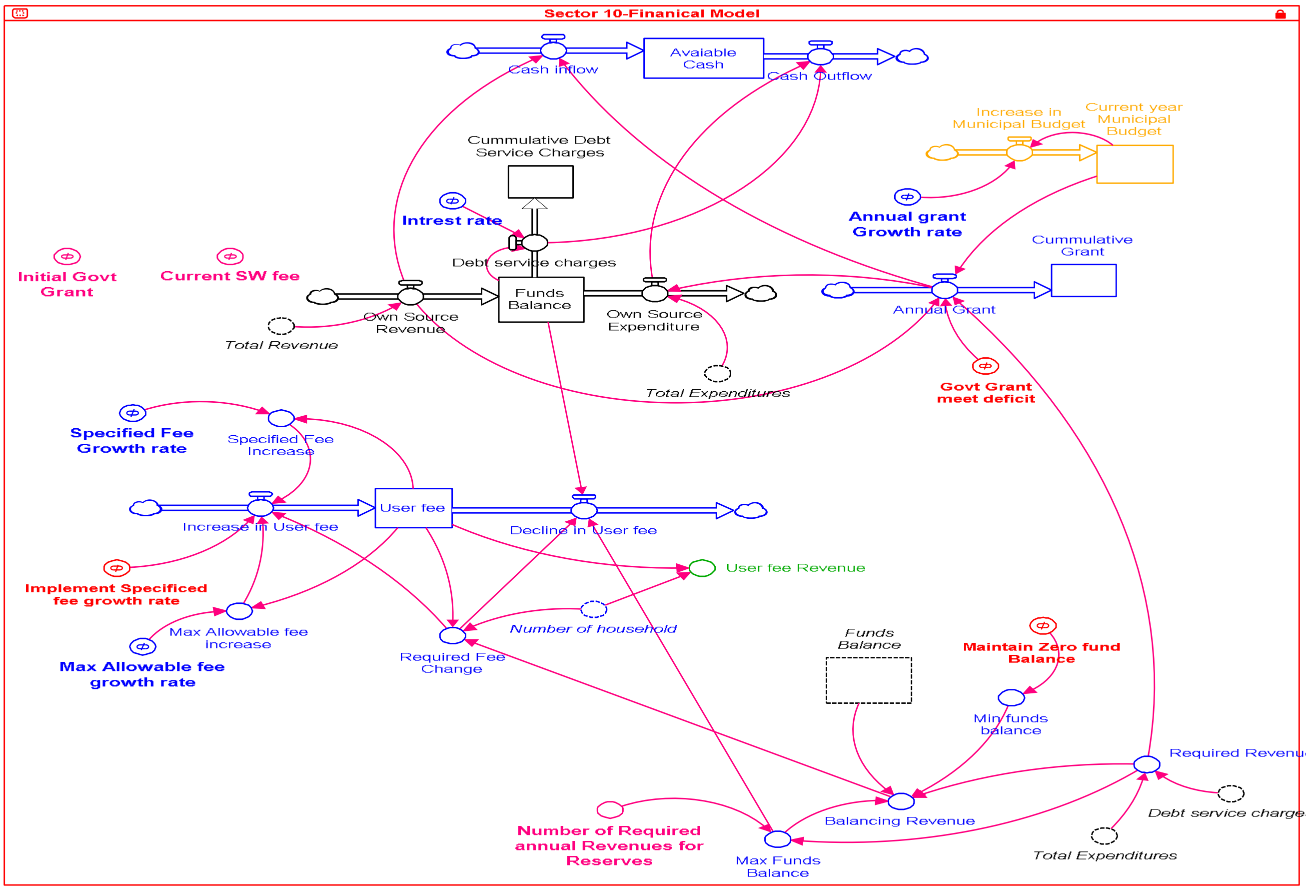

Fig. 5. Financial sector.

B. Model Validation

Model development is not adequate. Its validation is of utmost importance. It improves trust and safe use of the developed model. Forrester, 1979 describes that confidence in SD modeling can be increased by the wide range of validation tests. These include the (1) model structure, (2) model behavior, and (3) its policy implications. However, the validity of this confidence is not directly related to the model construction. The objective of validation is only to transfer confidence into the model's soundness and usefulness as a policy tool [10]. The usefulness of SD modeling is based on the credibility of the validation procedure. No model is often accepted unless it passes the aforesaid validation tests [33]–[37]. Validation tests are further elaborated below.

Model structural validity test. Model structural validity test is considered at the core of the validation process [38]. However, the participation of stakeholders in the modeling process results in increased model credibility [39]. It increases the probability of adoption of the model-based recommendations [40]. The structural validity test includes extreme condition test, dimension consistency test, and boundary adequacy test. In this study first, two aforementioned tests were performed. These ensure the validity of the specific tests performed in the situation being examined in the study [10], [41], [42].

Behavior validity test. Behavior validity test is used to compare the model-generated behavior with the real world. It is essential as it gives to which extent the model results conform to real-life system behaviour. It also helps in evaluating the sufficiency of associated data used for the model and whether the model is fit for intended use [10], [33], [38], [43], [44]. An example of the dynamic model of municipal SW for the city of Bangkok is quite relevant here. It was developed to deal with the problem of space shortage for landfills. Model results indicated that that model can be used to test environmental policies, related to the recycling program. Moreover, the author validated this model by using extreme condition test, dimensional consistency, and behavior sensitivity test. Similarly, face validity test along with these tests were applied to the SD energy policy model [45].

III. RESULTS

A. Dimension consistency test

The dimension consistency test was conducted to check the internal validity of the model. It checks the dimension of units of all the variables that are equal on both sides of the equation. It was conducted by using the built-in function in the SD software i.e., Stella Architect. The results showed that all units in the 10 sectors (population, GDP, WG, WC, PW, MRF, compost plant, recycling plant, landfill, and financial) were dimensionally consistent and corresponded to the units in the real world.

B. Extreme conditions tests

In the population sector, the extreme conditions test was applied, and the model provided correct results. These extreme conditions are briefly discussed as under.

At first, the model was run with a carrying capacity adopted for the city i.e., 15 million persons. This resulted in the goal-seeking behavior of the population; in the start, the population increased exponentially then the growth in the population remained constant, after achieving the target population of 15 million persons (Fig. 6a). In a base run simulation(without carrying capacity) the population curve showed an exponential increase in population growth. The population reached 3.84 billion persons in 100 years (Fig. 6a) testifying to the correctness of the model.

Secondly, the test made run by giving the birth and immigration rate equal to zero. This resulted in an exponential decay curve of the population (Fig. 6b) which was divergent from actual behaviour testifying model correctness.

Thirdly, the model was tested by giving the death and emigration rate of the city equal to zero. It exhibited an exponential increase in the population (Fig. 6c).testifying to the model correctness in case of extreme behaviour. Whereas the real-world situation is to follow an S-shaped curve which was obtained in this study when actual conditions were applied (Fig. 6c).

In the GDP sector, the extreme conditions test was also successful. The first was that there is zero increase in GDP per year. This resulted in a constant value of GDP per year i.e., 270 billion USD per year (2020) throughout the simulation (Fig.7a) which was in contrast to the GDP behavior in the base run i.e., the increase in GDP is 5.79 % per year. The extreme condition resulted in an exponential increase in GDP value per year, it reached 71 trillion USD in 100 years. A similar trend was followed by GDP per capita and per capita income (Fig. 7a).

In the PW sector, the extreme conditions test also gave correct results. The model was run with the assumption that 1 percentage budget would be spent on the PW campaign. The PW to segregate waste at source increased with the increase in literacy level of the city and PW campaign Fig. 7b). There was a sharp increase in PW in the first five years of the simulation period and later reached its saturation level of 100 persons and became constant.

This resulted in a slight increase in the number of PW to separate waste at the source due to an increase in the literacy level of the city. It linearly increased with the literacy level of the city Fig. 7b), thus testifying to the model correctness. In the WG sector, the extreme conditions test was carried out with the assumption that the waste segregation into compostable, recyclables and waste to energy took place at the source. This resulted in the SSW amount of 70 thousand tons per year (Fig. 7c), which was in contrast to the SSW amount achieved in the base run simulation (zero percentage source segregation) (Fig. 7c). This behavior was consistent with the real situation when the household does not implement the source segregation program, and the SSW from the household is not achieved.

In the WC sector, the extreme conditions test was carried out with several assumptions that gave correct results, thereby validating the model. The first assumption was to increase the number of trucks in service that would take place according to the minimum value of 3 variables viz. (1) the number of trucks required for the collection of uncollected waste, (2) the number of trucks that can be purchased from funds, and (3) number of trucks retiring per year. The results showed that the number of trucks in service became constant after achieving the desired requirement of trucks i.e., 225 trucks for the remaining period of simulation (Fig. 8a). The same trend was shown by WC capacity, which reached upto 65% in 25 years and then became constant for the remaining period of simulation. This was in contrast with the baseline data where authority was not purchasing new trucks. This resulted in a decline in WC capacity throughout the simulation as the trucks were retiring every year. Thus, the extreme condition test validated the WC sector.

The second assumption was the hiring of new drivers by the authority with a hiring rate of 5 percent of the total number of drivers in-service per year. The increase in number of trucks in service took place as mentioned above. When the authority decided to hire more drivers, the WC capacity increased due to an increase in the number of drivers and trucks (Fig. 8b). This was again, in contrast with the baseline simulations where authority was not hiring new drivers but number of trucks in service increases every year. This resulted in a constant value of WC capacity, and number of drivers per year as shown in (Fig. 8b).

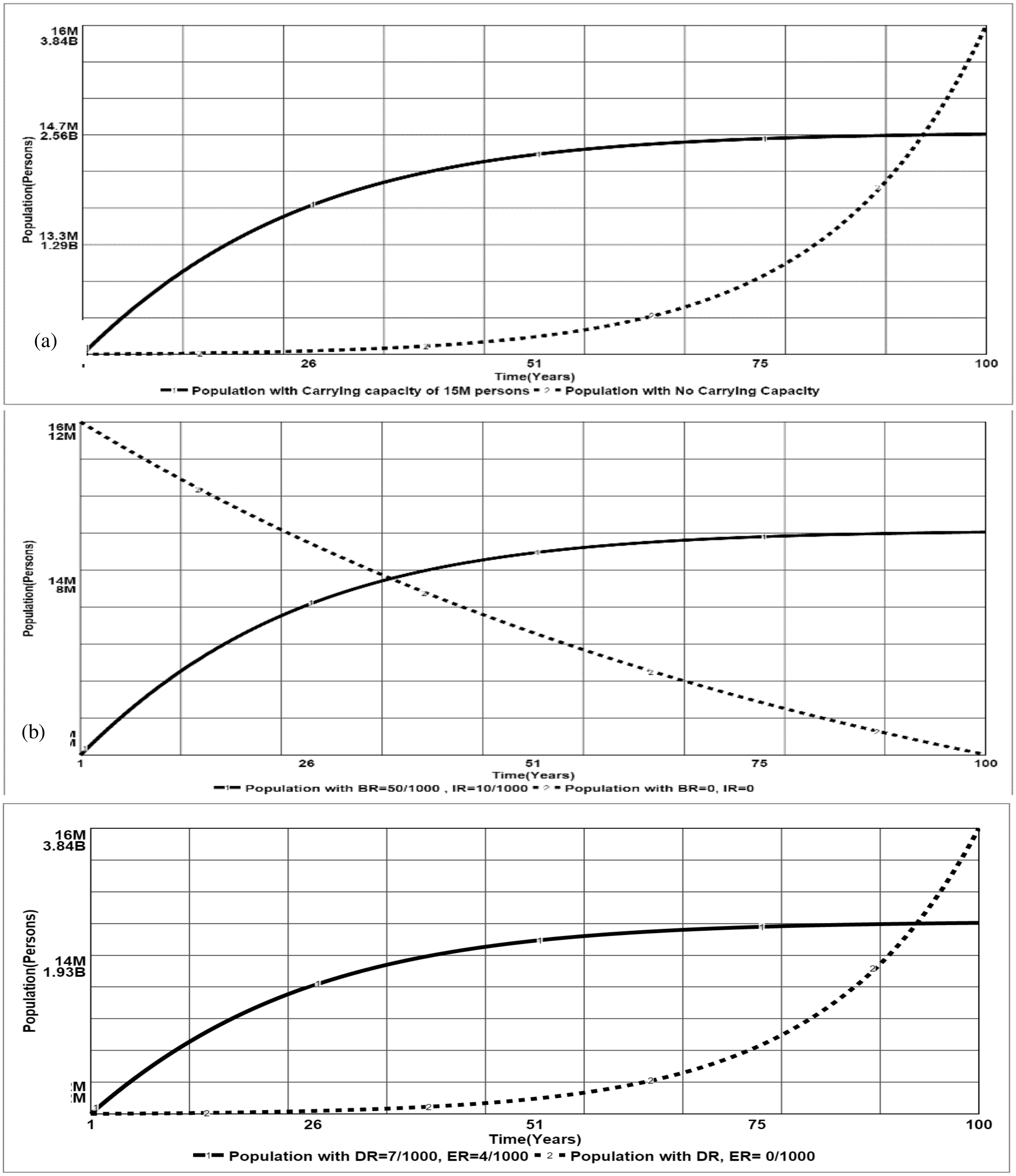

Fig. 6. (a) Population curve with and without carrying capacity of 15 million persons, (b) Population growth curve with death rate and emigration rate equal to zero people per year & 0.007&0.004 people per year, respectively, (c) Population growth curve with birth rate and immigration rate equal to zero people per year & 0.05 &0.010 people per year, respectively.

The extreme conditions test was also applied to the treatment sector; the model gave correct results. The assumption was that the authority implements SSW policy at the household level. The model simulation exhibited that if implemented, it would reduce the load on landfills. It would improve the throughput of MRF, RDF, and compost plants. Due to waste load reduction on the landfill, it would accommodate waste even after 100-years.

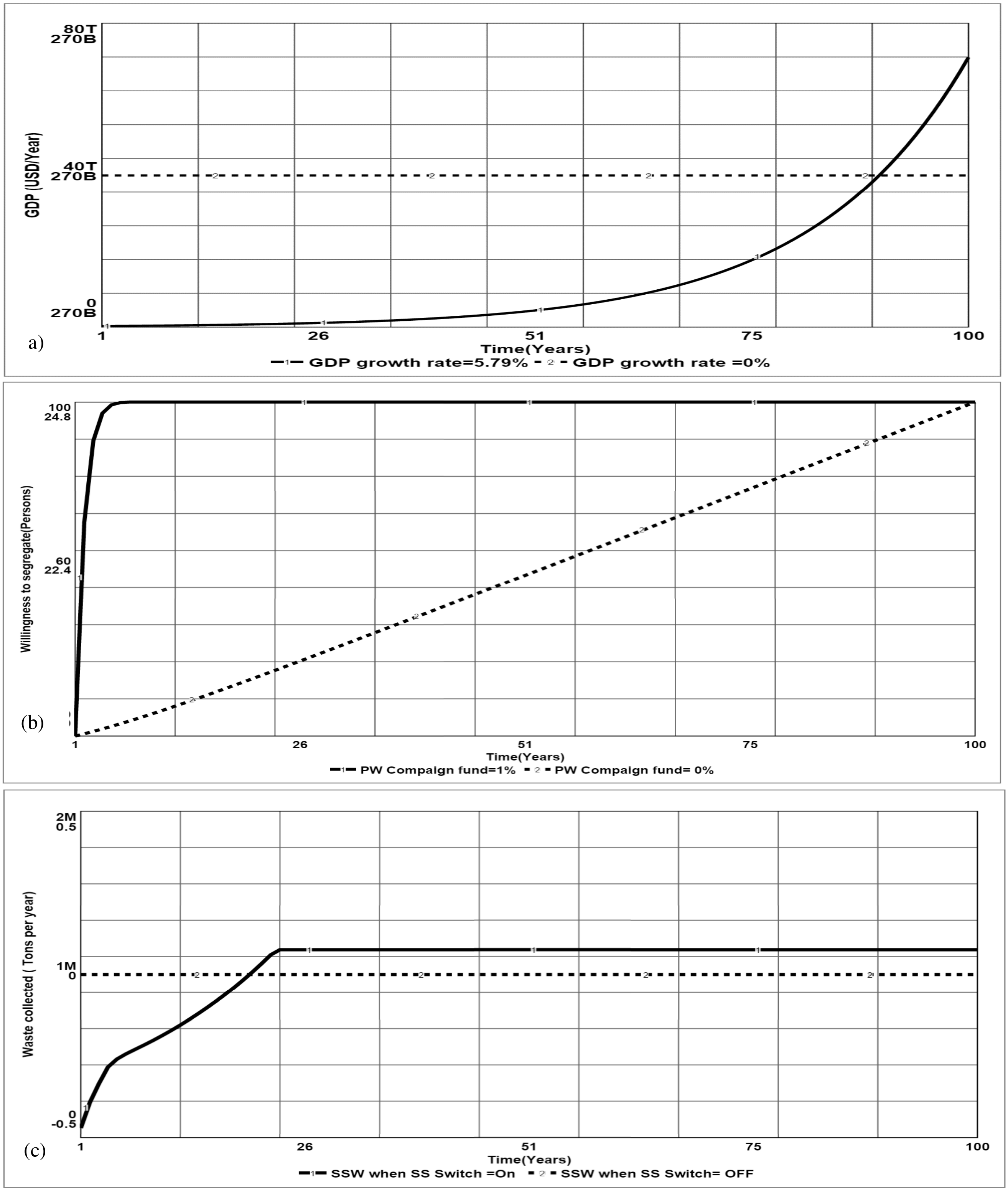

Fig. 7. (a) GDP per year with GDP growth rate equal to zero percent and 5.79 percent, (b) -People willingness to segregate waste at source when 1 and 0 percent of the budget is available for campaign, (c) Waste generation when Source Segregation is on, & off.

This was different from results obtained using baseline condition i.e., no SSW policy. This resulted in increased waste load on MRF and landfill. One million two hundred thousand tons of waste would reach MRF and 45 million tons at the landfill during the simulation period i.e., 100 years (Fig. 8c). This would necessitate a new MRF and landfill facility for baseline condition.

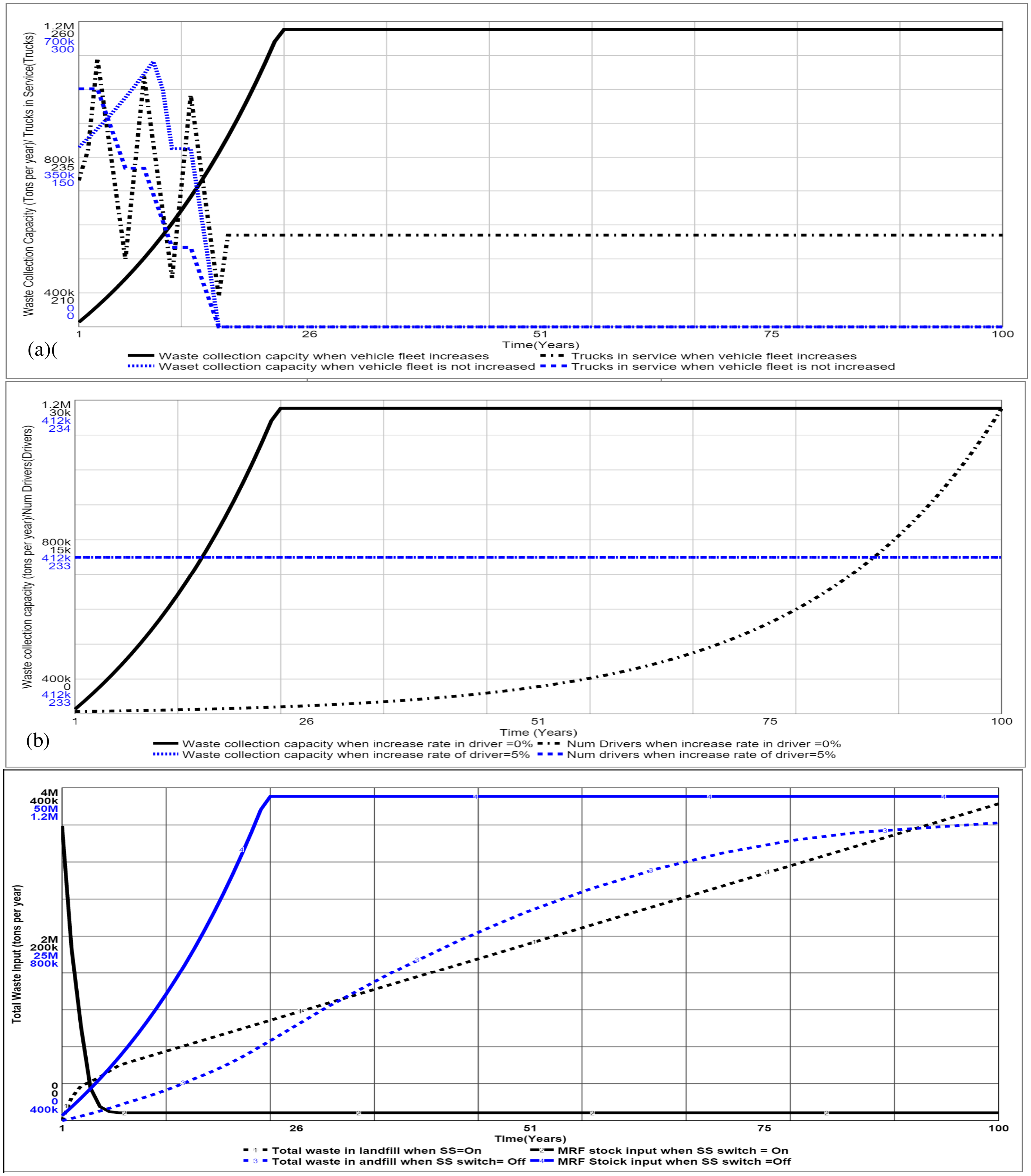

Fig. 8. (a) Increase in num trucks and waste collection capacity by increasing/not increasing in the collection vehicle fleet,(b) Waste collection capacity and number of drivers when an increase in the number of drivers = 0% & 5 %, (c) Effect of waste source segregation on the total amount of waste in landfill.

In the financial sector, the extreme condition test gave correct results. The assumption was the implementation of an SW user fee of 100 PKR per household. The results showed the variation in funds balance due to expenditure of funds and the own source generation of revenue. The total revenue generated up to 25.6 trillion PKR for 100 years due to a 10% raised in SW user fee every year. This trend was in contrast with the baseline situation, in which no SW user fee was implemented (Fig. 9a). This resulted in the generation of the total revenue of 0.3406 trillion PKR in 100 years, which was less than the total revenue generated with SW user fee i.e., 25.6 trillion PKR in 100 years, thus testifying to the model correctness (Fig. 9a).

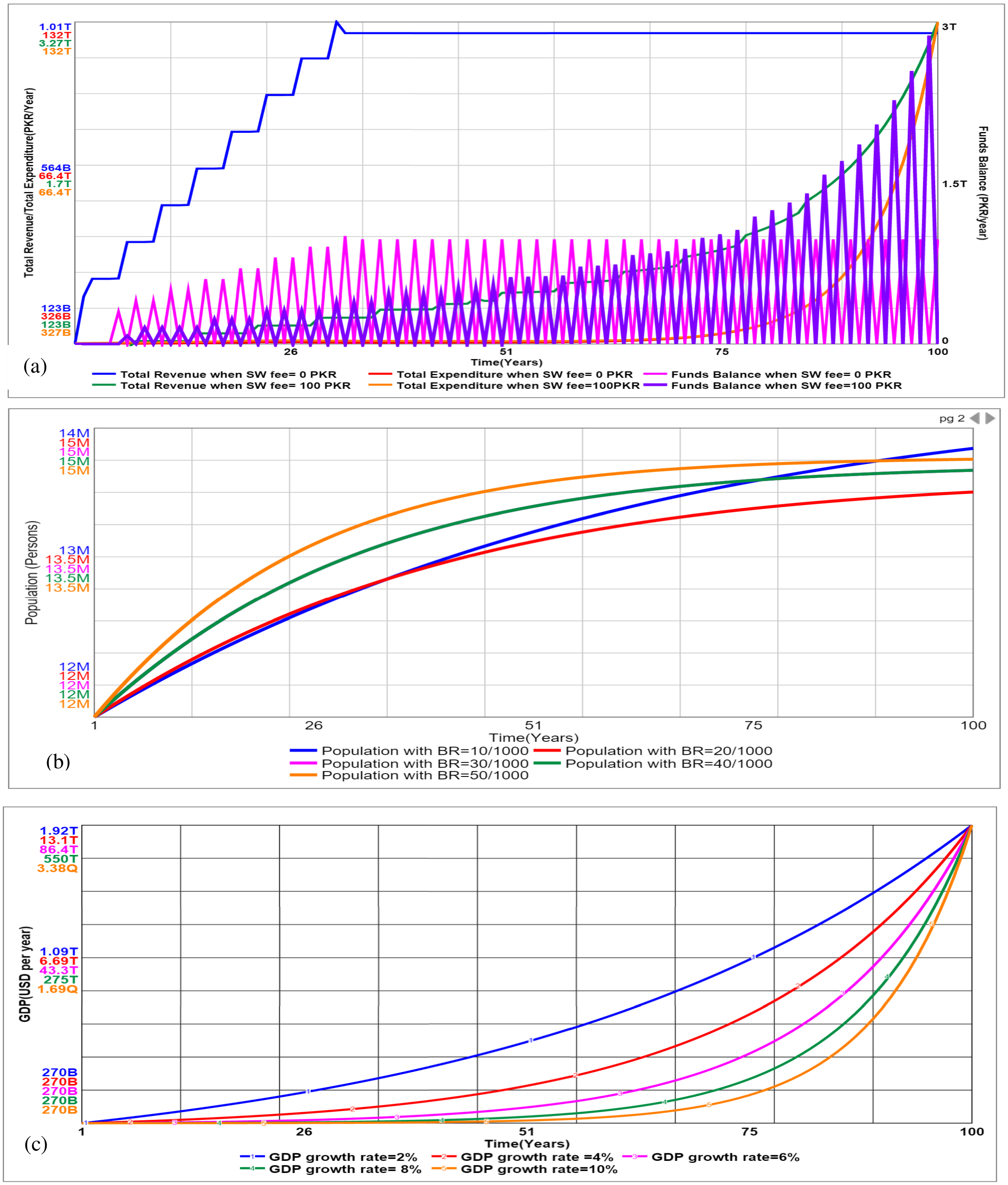

Fig. 9. (a) Effect on Funds Balance by the implementation of the solid waste user fee, (b) Population cure at a varying birth rate from 0.1 to 0.5 persons per year, (c) GDP per annum at varying GDP growth rate from 1-10%.

C. Behavioral sensitivity test

The behavioral sensitivity test was performed on the population sector by varying birth rates in a range of 0.01 to 0.05 births per year. Color coding is used to show each. The blue color shows the scale for a lower birth rate i.e., 0.01, and on the other extreme orange color shows the scale for a higher birth rate i.e., 0.05 births per year. The same color coding is adopted in all upcoming behavioral sensitivity graphs. The X-axis shows the time in years in all the graphs.

The simulations showed that with a higher birth rate (0.05 births per year), the population reached its target population of 15 million persons in a short period i.e., 31 years, for the lower birth rate (0.01. births per year), the target population would not be reached throughout simulation period (Fig. 9b).

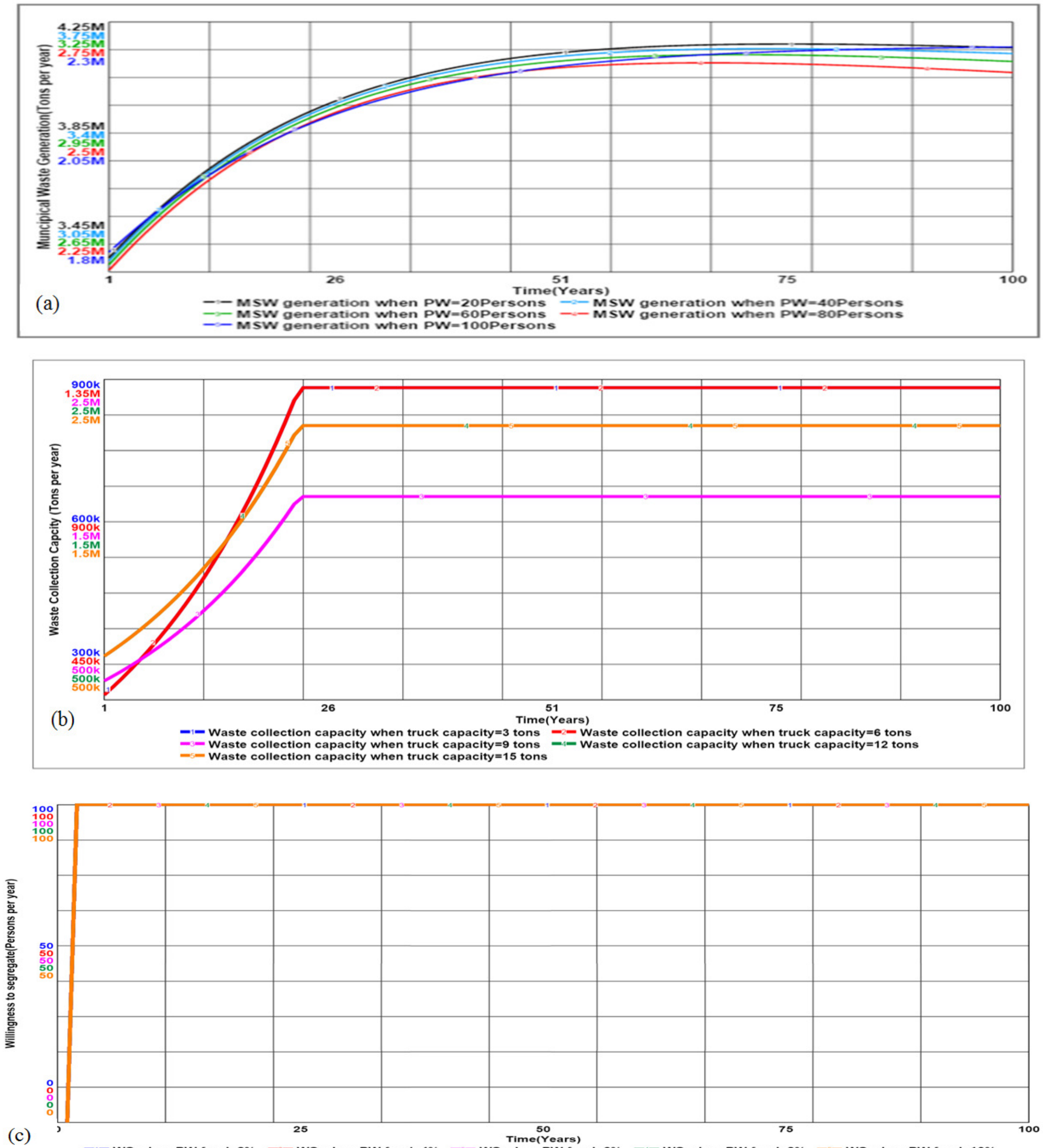

Fig. 10. (a) Municipal Waste generation tons per year by varying the number of people willing to segregated waste at source, (b) Waste collection capacity having a different truck capacity from 3 to 15 tons,(c) People willingness to segregate waste at source at varying budget from 0 to 10 percent of the budget.

In the GDP sector, the behavioral sensitivity test validated the model. The GDP per year was calculated by varying the percentage of GDP growth rate per year from a maximum increase of 10% to the lowest increase of 1%. The results showed (Fig. 9c), that the higher percentage resulted in a higher value of GDP per year i.e.,3380 trillion USD in 100 years, and a lower percentage showed a lower value of GDP per year i.e., 1.92 trillion USD in 100 years.

The behavioral sensitivity test was conducted on the WG sector by changing the number of PW to segregate waste at the source. This test also validated the model. The test was performed by varying the number of PW to segregate waste at the source from 20 persons to 100 persons. The simulation results showed that, lower the number of PW (i.e., 20 persons), the more the generation of waste such as 3.45 million tons in 100 years. This was in contrast with a higher number of people segregate waste at the source (i.e., 100 persons), which resulted in less generation of waste (i.e., 1.8 million tons) in 100 years (Fig. 10a).

The validation test was also successful in the WC sector. It was carried out by varying the truck capacity from 3 tons of waste per truck to 15 tons of waste per truck. The WC capacity of trucks in service was increased upto 0.22 million tons when a higher capacity i.e., 15 tons of trucks were used to collect waste. This would also result in a lower amount of uncollected waste (Fig. 10b). The result was vice versa with the low capacity of a truck.

Validation test on PW sector also gave correct results. In the PW sector, the test was performed by varying the fraction of the budget allocated for the PW campaign. This resulted in an increase in the rate of PW to segregate waste at source at a higher budget fraction (10%)and low at a lower fraction of the budget (2%) (Fig. 10c).

The behavioral sensitivity test was applied to the MRF sector. The model gave correct results. This test was performed by varying MRF capacity from 150 to 500 tons per day. The results showed that at low capacity (i.e., 150 tons per day), MRF sorted less waste into recyclables, compostables, and waste to energy, and more waste was directed to landfills. This was vice versa with high capacity MRF (i.e., 500 tons per day). The more recyclables, compostables, and waste to energy were sorted from the waste and less amount was disposed of off to landfill.

IV. CONCLUSIONS

In this paper, a holistic municipal SWM SD model was developed including all possible components and feedback effects of variables forming the basis of sustainable SWM. This includes (1) revenues from all the proposed treatments and processes that economize the expenditure costs required for operating and maintaining these systems. (2) the PW campaign fund, which in turn economizes the waste segregation burden. Similarly, the model creditability and confidence are increased by performing structural and behavioral validation tests such as; (1) the dimensional consistency test that confirms the units of all 10 sectors and 40 sub-models, (2) the extreme condition test shows that the 10 sectors mirror the real situations, and (3) the behavioral sensitivity test results the non-sensitive models. This model helps in analyzing the real-time data and identification of sustainability variables for measuring the SWM system sustainability.

V. FUTURE SCOPE

This study will contribute to the body of knowledge by developing a new SD based model covering all the dimensions of a sustainable SWM system, provide unique insights into the highly complex and dynamic behavior of the SWM system, help managers and decision makers to explore various policy options, carry out 'what-if' analysis under different possible scenario. In addition, it will help them to prepare short- and long-term management plans that conform to regulatory requirements in terms of sustainability while meeting social expectations of service performance.

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Conflict of Interest. The authors of this paper certify that they have NO affiliations with or involvement in any organization or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this paper.

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