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Original Article

Optimizing Municipal Solid Waste (MSW) Collection and Transportation Network Using GIS and Agent-based Modeling Approach: A Case Study in Hung Yen City, Vietnam

Ngo The An[1,*], Tran Nguyen Bang[1], Nguyen Tuyet Lan[1],
Nguyen Quoc Viet[2], Nguyen Duy Trung[3]

[1]*Vietnam National University of Agriculture, Trau Quy, Gia Lam, Hanoi, Vietnam*

[2]*VNU University of Science, 334 Nguyen Trai, Thanh Xuan, Hanoi, Vietnam*

[3]*Hung Yen Urban Environment and Public Works Joint Stock Company, 12 Tay Thanh, Hung Yen, Hung Yen, Vietnam*

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Abstract: This paper presents a method for optimizing the municipal solid waste (MSW) collection system using a simulation model that integrates spatial analysis and an agent-based modeling approach. Parameters for the model, including waste generation loads, collection points, and collection rates, were obtained through field surveys in Hung Yen city. Optimization scenarios were formulated based on the environmental management goals of the local authorities, which include a population growth rate of 1.5%, the expansion of collection routes (adding two new “hand-pulled garbage” routes), additional vehicle investment (two garbage compactors and 40 hand carts), and at-source treatment (more than 25% of households). The scenario analysis shows that all tested factors effectively reduce MSW generation and residue by 59% compared to the “business as usual” scenario. The optimal routing under the formulated scenarios requires establishing 10 additional transfer points and routes through densely populated areas to achieve the local authorities' goal of a collection rate over 80%. Despite these interventions, some households remain outside the collection service. This finding suggests that additional solutions, such as waste recycling for households not covered by the MSW collection service, are necessary to achieve the sustainable development goals for the locality.

Keywords: Solid waste, GIS, network analysis, Agent-based modelling, scenario analysis.

[*] Corresponding author.
Email address: ntan@vnua.edu.vn

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1. Introduction

Waste management has become an increasing environmental concern, constituting a significant issue in modern times [1, 2]. Solid Waste Management (SWM) has played an important part in public health and environmental control [3]. Improper SWM can lead to economic and environmental impacts that place inhabitants at risk [4]. SWM consists of controlling the generation, storage, collection, transport, processing, and disposal of waste [5].

SWM has become more complex in developing countries in term of logistics, fuel and labor costs, and air pollutants emission [6] which represents a challenge for municipalities, particularly at the collection stage. In recent years, municipal solid waste (MSW) management has become an increased concern in emerging countries because of the expansion in waste generation due to economic growth and the acceleration of consumption [7]. In addition, population growth in urban areas and an increase in living standards in developing countries have caused a massive production of MSW as well as alarming issues with environmental, economic, and social impacts [8].

In recent years, the application of geographic information systems (GIS) in MSW management has become quite popular for optimizing solid waste collection network and planning a sustainable waste management [3]. GIS is often used to support environmental management agencies in making decisions on MSW optimally in terms of time and cost by using a multi-criteria decision analysis (MCDA) and overlay analysis through a GIS [9]. Technically, GIS helps control the operation of waste collection and transportation and determine the most suitable landfill locations based on a given dataset of natural and socio-economic conditions [8].

Many research projects applying GIS in MSW management have been implemented in Vietnam. In Ho Chi Minh city, the research on GIS applications to search for the collection and transfer points and monitor the waste transportation process has been carried out since 2005 [10]. In Can Tho city, typical research on applying GIS to monitor and manage the urban solid waste collection and transportation system has been implemented throughout the city by Nguyen et al., [11]. Similar research projects were conducted in Da Nang city [12], Hue city [7], and Quang Binh province [13]. The widespread development of GIS has made this tool more familiar to those working in environmental management. However, the mentioned research was only GIS-based applications, incapable of examinating several scenarios with a set of control parameters. This limitation was considerd as the Multiple Routing Problem (MRP) in the traditional GIS-based route optimization applications [14]. Meanwhile, the potential exploration of spatial analysis based on GIS platforms seems to be unlimited in the new IT era [15], especially when integrating it with agent-based modeling (ABM) approach [16, 17]. This integration improve the searching process for promising solutions in a vast solution space, by running different metaheuristics agents while cooperating by exchanging best moves [18]. Particularly, the ABM desigened in Netlogo software [19] allows scenario analysis to deliver optimal solutions for reliable MSW management with dynamic simulations (i.e. future predictions), making management practice easier. The above potentials are still a big scientific gap that needs research to make GIS applications become more effective.

The aims of this study were firstly to calculate the amount of household waste based on household waste load per capita and the location of residential areas. Then, GIS tools and the Agent-based model (ABM) were combined to predict the waste loads along collection routes, creating a basis to suggest the most optimal collection and transportation options in the future. The research approach was applied in Hung Yen city, a typical city of the Red River Delta for the year 2030. The findings from this study can be used to relocate the waste collection systems in the future to target local environmental sanitation standards.

2. Materials and Methods

2.1. The Study Site

This study was conducted in Hung Yen city, the provincial capital of Hung Yen province, located on the center of the Red River Delta. The city belongs to the economic triangle of Hanoi, Hai Phong, and Quang Ninh (Figure 1). Like other provinces in the Red River Delta, Hung Yen city also has a hot and damp tropical monsoon climate. The terrain is relatively flat, connected by a dense traffic network. The administrative system consists of seven wards and 10 communes.

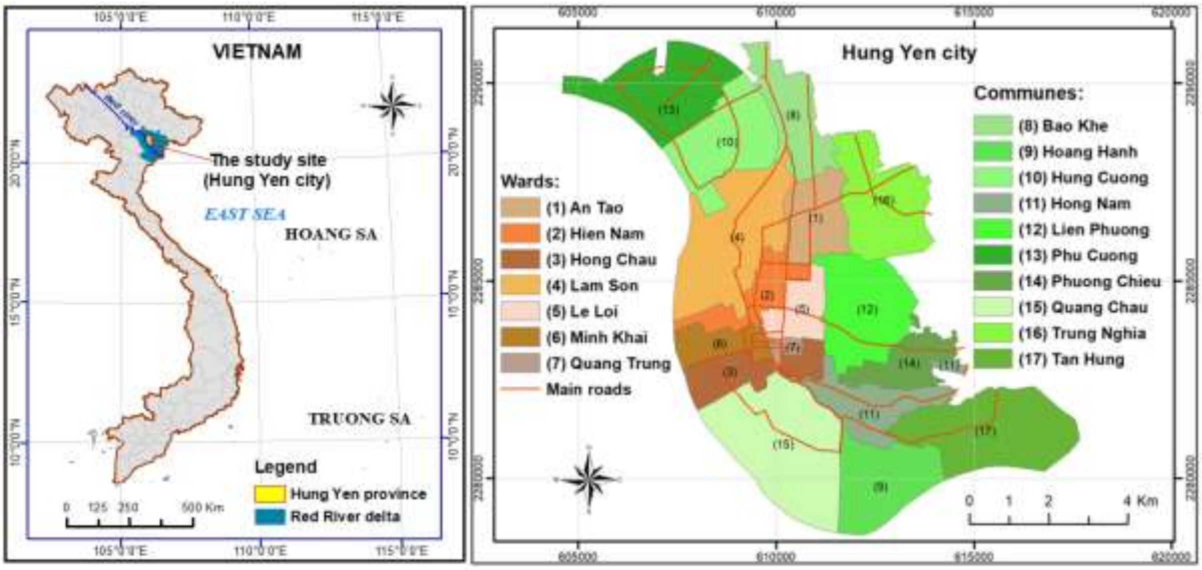


Figure 1. Location of the study site.

2.2. Secondary Data Collection

Secondary data consists of the statistical data on socio-economic, population, environmental management, local waste management system and maps (land use and road). This data was obtained from the Hung Yen Department of Natural Resources and Environment (DONRE), Hung Yen Provincial People Committee, and the Hung Yen Provincial Statistical Office (2021).

2.3. Field Surveys and Household Interviews

Field surveys were conducted to collect data on the geographical locations of waste collection points, main routes for waste collection, and transport methods. Household interviews were carried out for collecting information on waste generation and disposal at the households. The total number of interviewed households was 170, which was stratified-randomly selected from seven wards and 10 communes in Hung Yen city (10 households per administrative unit were randomly selected out from the household lists provided by wards and communes).

2.4. Waste Load Measurements

We conducted waste weighting measurements at 170 interviewed households once a day at a fixed time. The measurements were repeated three times per month (weighing a duration of three months). The average daily waste per capita was then calculated according to household waste measurements. The amount of waste load collected was determined by counting the number of hand carts and trucks containing garbage in a day, a week, and a month. The waste was weighted for randomly selected hand carts and trucks. The waste load collection was calculated for different administrative units based on their waste collection regulations. The data was summarized as the diary waste load per capita and per administrative unit.

2.5. Mapping, Spatial Analysis and Modeling

2.5.1. Waste Source Distribution Mapping

The MSW in Hung Yen city was generated from households and public sources (e.g., markets and offices). The household locations were mapped based on the 2020 land use map (i.e., residential areas) and the 2022 population statistics. Due to the lack of geographical coordinates associated with all households, a random algorithm was applied to allocate the households into the residential areas (Figure 2). The newly created households were then assigned characteristics randomly based on the descriptive statistics obtained from interviewed data (means and standard deviations).

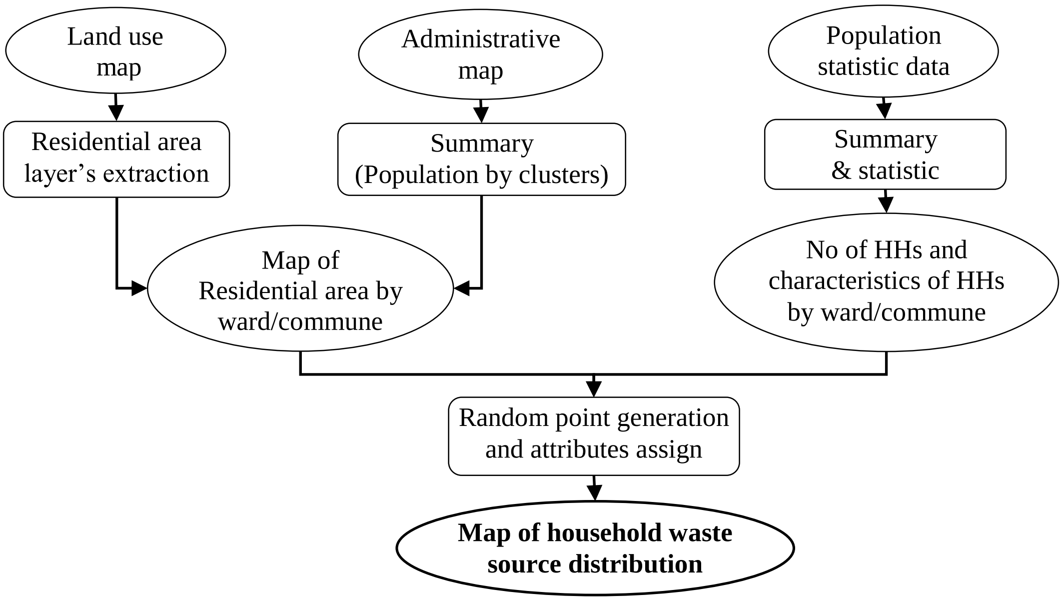


Figure 2. Workflow for mapping distribution of household (HH) waste sources. Maps of public waste sources were simply produced by importing the coordinates obtained from the GPS handheld receiver into ArcGIS software to create point maps.

2.5.2. Waste Collection Mapping

Waste collection maps consist of the transfer points (centralized yards or large trash bins), collection routes, and households located within the collection zones. These maps were created from geographical coordinates measured by the GPS receiver during field surveys and statistical data on collection routes from the Hung Yen Urban Environment and Construction Company Limited. The amount of MSW at each transfer point was determined based on an algorithm that estimates the waste from all sources located within the calculated zones. This mapping method is illustrated in Figure 3. All the maps were produced in ArcGIS 10.8 software. Map units were classified and displayed using the Natural Breaks method.

2.5.3. Agent-based Modeling

In this study, we used ABM approach and perform it in Netlogo [19], a platform designed particularly for ABM which is capable of simulating and representing spatio-temporal data to provide immediate model outcomes as maps.

In the computer model, each waste generation source and vehicle was simulated as an agent capable of operating independently. The waste load of agents depends on the number of people and the waste coefficients associated with them. The discharged/collected location of each agent is defined as the nearest transfer point or trash bin that this agent can find. The route optimization programs were partlty inherited from Dijkstra's algorithm [20] with the combination of optimal functions related to the travel time, cost, collected and residual waste. During the model run, the new agents (new households, transfer points, vehicles) can be created and located automatically depending on the constraints formulated under experimental scenarios.

Firstly, the theoretical model of the MSW management system was simulated for ABM as illustrated in Figure 4. According to this model, the entire waste management system is operated by local authorities i.e. the Hung Yen city People's Committee, local government departments and social organizations at different administrative levels. This component is placed at the top of the diagram, defined as global parameters that control all agents and their behaviors within the simulated system. MSW generators include households, offices, schools, services, and markets. These generators were defined as agents in the simulation model.

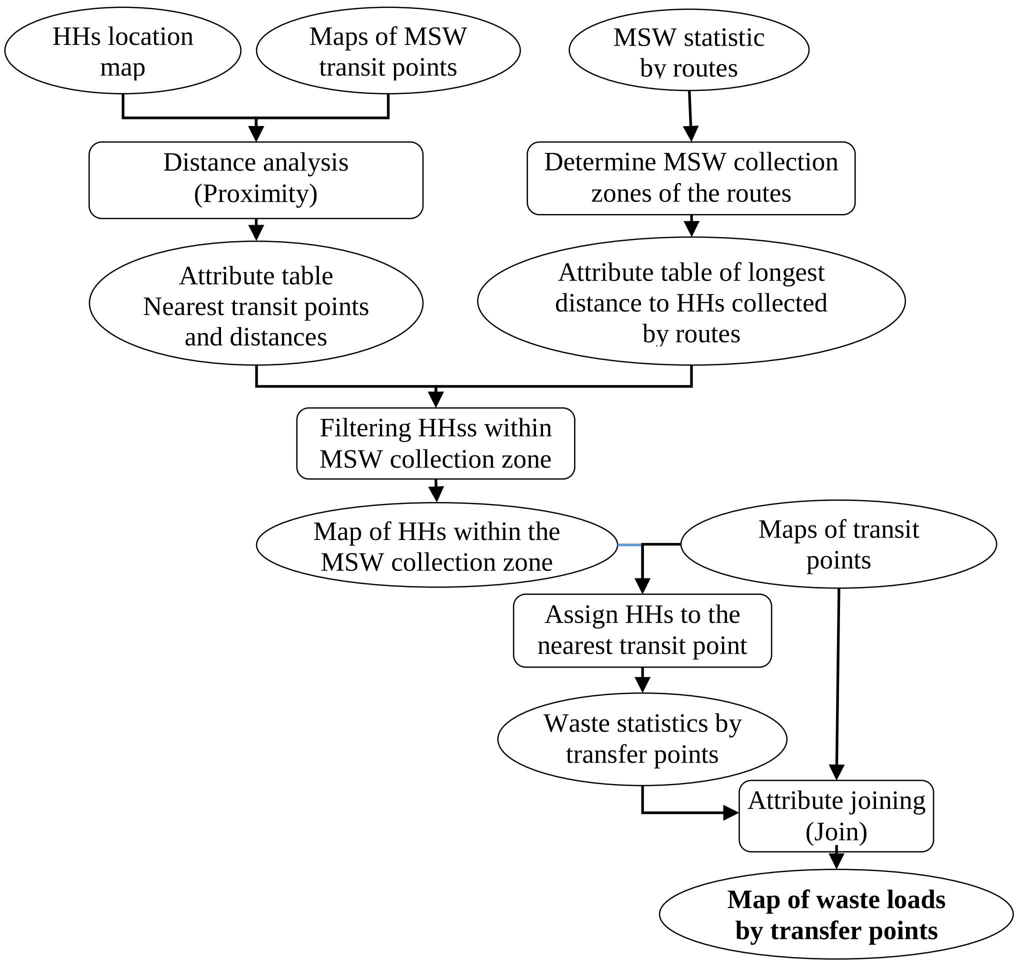


Figure 3. Workflow for mapping of waste load at the transfer points.

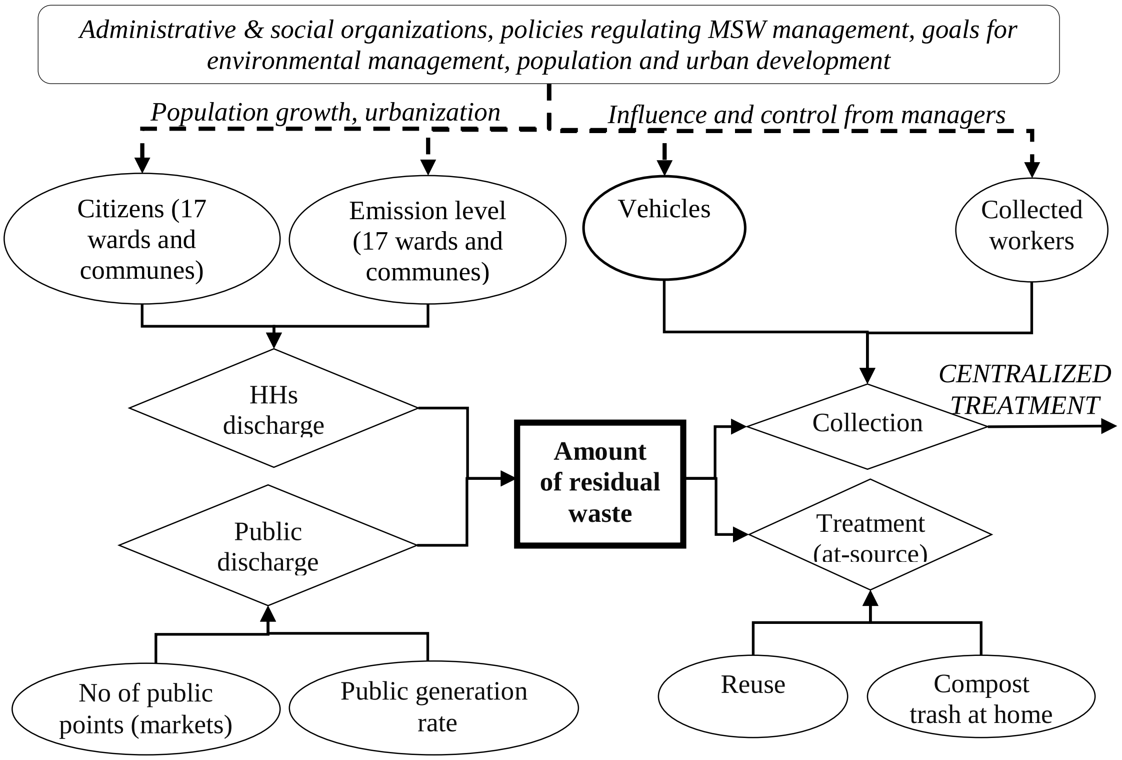


Figure 4. The theoretical model of MSW management system.

The parameters for the mathematical model of the waste management system were determined from the surveyed data, which consist of i) Domestic waste from households; ii) Waste from offices and schools (Table 3); iii) Waste from markets (Table 4); and iv) Collection rates from map attributes (Figure 5).

The computer model was validated for sensitivity and reliability before applying it to evaluate the waste management system for Hung Yen city. Because the model developed in this research is deterministic in nature (i.e., always returns the same results if given the same input values), the validation of the future predictions can be acceptable with the sensitivity analysis [18]. The analysis was conducted through the visual output examination and the sensitivity analysis of input factors, which evaluates the role of controlling (input) variables by checking the variation of model outputs when changing their input values.

2.5.4. Scenario Analysis

The scenarios were designed based on the population development and local MSW management goals. After that, the input parameters were determined according to the defined scenarios (i.e. population growth, number of transporters, area of collected zones etc.). The outputs provided by the validated model ran with different scenarios were comparatively analyzed to propose optimal waste management solutions for the study area.

3. Results and Discussions

3.1. Population, Land use, and Transportation of Hung Yen City

According to the statistical year book [21], in 2021, Hung Yen city has 73.89 km² of land and a population of 118,646 people in 2020. The city's population growth rose by 4.73% during 2018-2020 (Table 1). Hung Yen city's dominant population is the Kinh people; the city's average male-to-female ratio is 47:53.

Table 1. Changes in total population of Hung Yen city 2018-2020

Year	2018	2019	2020
Total population	113,292	114,683	118,646
Pop. growth (%)	0.83	1.23	3.46

Hung Yen city has a delta lowland terrain characteristic with the land uses divided into three main types: i) Agricultural; ii) Non-agricultural; and iii) Unused land. Total agricultural land accounts for a large proportion (53,21) while residential land occupies 14,26% of the total natural land area.

The urban transportation system in Hung Yen city consists of main city roads and internal city roads with some sections of national highways and provincial roads passing through the city (Table 2). Currently, around 85% of city roads are paved with asphalt and cement concrete.

Table 2. Summary of the roads in Hung Yen city

Road type	Length (km)	Road surface structure (km)		
		Concrete cement	Asphalt	Others
Main road	82,227	6,817	62,934	12,476
Internal road	33,041	3,0	25,776	4,265
Total	115,268	9,817	88,71	16,741

Table 3. MSW from households calculated by wards and communes in Hung Yen city

No.	Commune/Ward	No. of people (people)	HHs waste rate (kg/person/day)	No. offices (office)	Office waste rate (kg per day)
1	Tan Hung commune	5,364	0.55	6	317
2	Quang Chau commune	8,313	0.60	10	529
3	Hong Nam commune	4,192	0.60	6	370
4	Hoang Hanh commune	3,474	0.55	7	370
5	Quang Trung ward	9,669	0.70	18	1,110
6	Hong Chau ward	5,259	0.75	7	476
7	Phuong Chieu commune	5,306	0.65	11	581
8	Minh Khai ward	6,248	0.70	22	1,216
9	Le Loi ward	7,486	0.70	19	1,004
10	Lien Phuong commune	8,070	0.60	9	529
11	Hien Nam ward	8,984	0.80	29	1,585
12	An Tao ward	10,681	0.75	29	2,061
13	Lam Son ward	8,166	0.80	35	2,114
14	Trung Nghia commune	8,906	0.55	7	370
15	Hung Cuong commune	4,650	0.50	10	529
16	Bao Khe commune	7,178	0.55	8	423
17	Phu Cuong commune	6,700	0.55	13	687

3.2. Sources of Municipal Solid Waste

MSW from the residential area: Surveyed data found that households in Hung Yen city were the main sources of MSW generations. The loading rates by administrative units are very different, ranging from 0.5 to 0.8 kg per person per day (Table 3). The average MSW load of the city is 0.64 kg per person per day, higher than the 2019 generation load of Hung Yen province (0.52 kg per person per day) and lower than that of national average load (0.80 kg per person per day) [21]. However, this loading rate is reasonable for Hung Yen province as it is constituted by many rural communes. Generally, the generation load in urban wards is higher than that of the rural communes, at 0.7 and 0.6 kg per person per day, respectively. These findings are quite similar to the studies conducted in Hue [7], Dong Hoi [14], and Can Tho [11].

MSW from offices and schools: The city has two headquarter complexes (province and the city agencies); commune/ward head offices, schools, and other agencies. Waste from these sources is mainly packaging, newspapers, tea residue, cans, school supplies, etc. According to the surveyed data, the average generation rates were quite varied across administration units, ranging from 317 to 2,114 kg per day per office (Table 3).

MSW from markets and other types of services: This is a relatively large source of waste generated with very different rates, ranging from 500 to 3,900 kg per day (Table 4).

Table 4. Volume of waste generated from markets in Hung Yen city

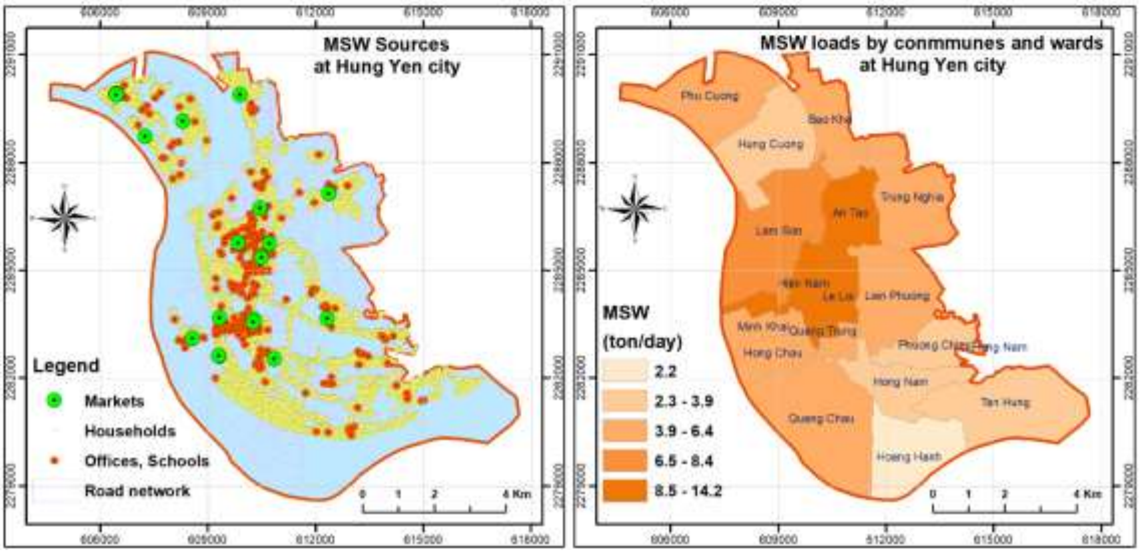
Market name	Location (number of markets)	Waste rate (kg per day)
Hang Dau market	Quang Chau commune	1,500
Chieu market	Quang Trung ward	1,000
Nam Tien market	Hong Chau ward	800
Doc Vi market	Phuong Chieu commune	1,000
Pho Hien market	Le Loi ward	2,500
Thai Khang market	Lien Phương commune	1,000
Gao market	An Tao ward	3,000
Dau market	Trung Nghia commune	1,800
Hien Nam market	Hien Nam ward	1,000
Coi market	Phu Cuong commune	500
Other markets	Hong Chau ward (1); Minh Khai (2); Hien Nam (1); An Tao (2); Trung Nghia (1); Hung Cuong (1); Bao Khe (1); Phu Cuong (4)	3,900
Total waste amount		18,000

Table 5. MSW generated by collection zones in Hung Yen city

No	Collection zone	Units for estimation	Generated waste (tons per day)
1	Roads, sidewalks, and residential houses in inner-city wards of the city	29,711 households	55.1
2	The area of waste collection points in suburb wards and communes belong to Hung Yen City which has established a socialized waste collection team and has a collection point for placing 10 m^3 containers to store the waste.	25 points	28.7
3	Local agencies and organizations in Hung Yen City	61 units	8.5
4	Restaurants and hotels for catering services	55 units	6.2

Currently, the amount of waste generated as reported by the Urban Environment and Construction Company Limited (the company responsible for collecting MSW in Hung Yen city) is about 70 to 80 tons per day. This total MSW is from four main groups (collection zones) with the amount generated as shown in Table 5.

The locations of MSW sources are illustrated as a map in Figure 5a. Based on this map, the MSW loads were calculated by administrative units and presented as a map in Figure 5b. As can be seen from Figure 4b, the largest MSW loads concentrate in central wards due to their high population, high rate of generation, and many public areas.



(a) (b)

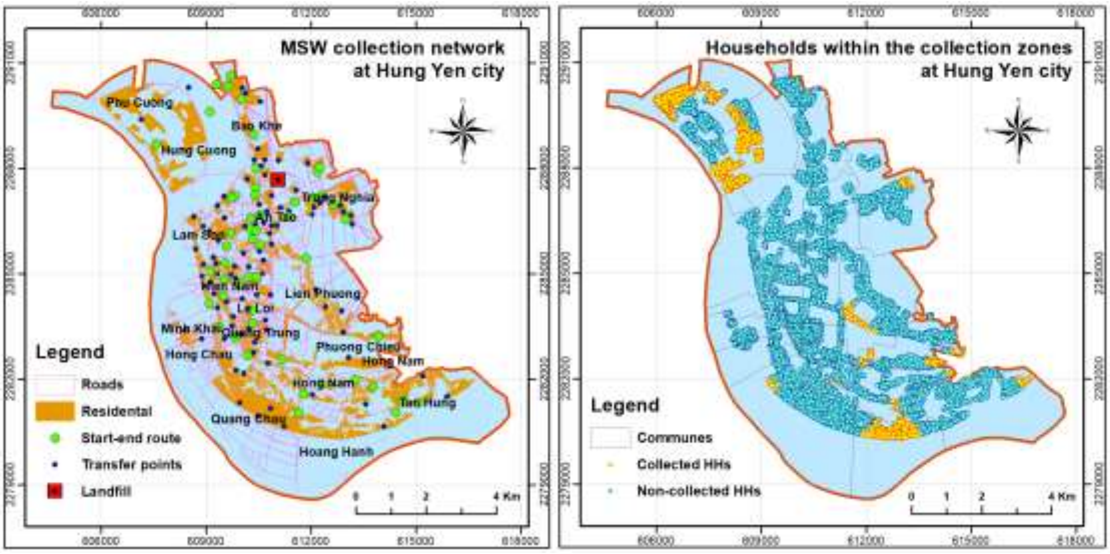
Figure 5. (a) Map simulating the locations of households, offices and schools, and (b) Map of MSW generations calculated by wards and communes.

The MSW load reaches over 8.5 tons per day in Quang Trung, Le Loi, An Thao and Hien Nam wards, followed by the densely populated communes, including Trung Nghia (6.4 tons per day), Phu Cuong (6.1 tons per day), Lien Phuong (5.7 tons per day). These figures indicate that the average amount of waste generated for each person living in the city has to bear over 0.7 kg of waste per day if not collected. Meanwhile, the ability to treat at home (at-source treatment) only occurs in rural areas at a relatively low rate, about 5% (surveys, 2020). Therefore, MSW collection is crucial to ensure environmental hygiene, especially in urban areas like Hung Yen city.

3.3. Curent Municipal Solid Waste Collection

The MSW collection and transportation in Hung Yen city is carried out by the Urban Environment and Construction Limited Company. Currently, waste is collected from 140 inner city streets with a length of over 60 km. The waste from households, offices, schools, restaurants, businesses, and hotels is also collected at the same time. In suburb communes, MSW is firstly collected by the hand-pulled garbage and then moved to the 10 m^3 containers located in eight locations in three central communes.

The MSW collection network represented by the start-end and transfer points is shown in Figure 6a. Based on the surveyed data on the collection distance limits and the population distribution map (Figure 5a), the locations of households whose waste is and is not collected were produced accordingly as Figure 6b.



(a) (b)

Figure 6. (a) Map of MSW collection network, (b) Map of households within the collection zones.

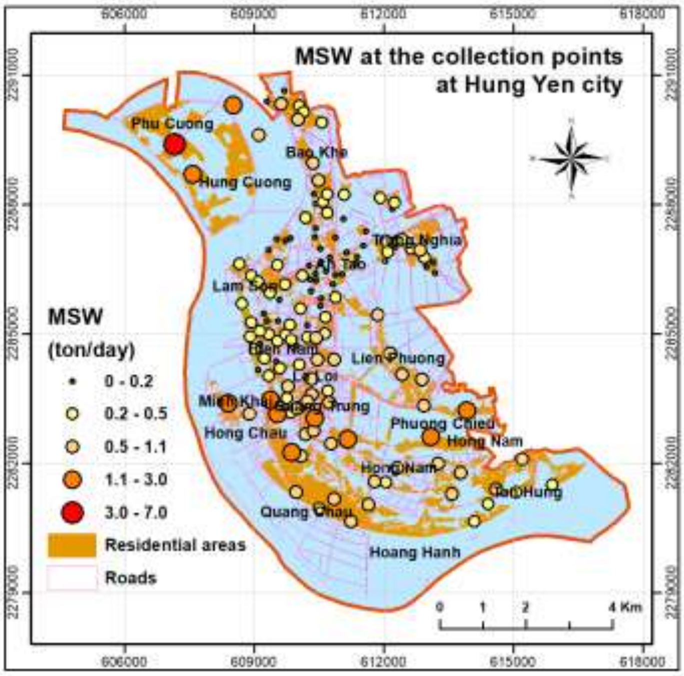


Figure 7. Map of amount of MSW concentrated at collection points.

MSW collection rates were estimated from the attributes associated with waste sources (i.e., administration, collection zone, and household size) on map 6b. The results show that the rates of MSW collection in the urban areas were over 95% of the total amount of MSW generated, much higher than that of rural areas (66%). In the two communes of Phu Cuong and Hung Cuong (on the northwest corner), the collection rates accounted for only 40-50% because these communes have a large amount of waste generated while the roads are small, which prevented the accessibility of collection vehicles. Therefore, in those communes, the collection was carried out along a fixed route once a day, and the amount of trash left during the day was very high. In brief, the collection rate in Hung Yen city is lower than the national collection rate (91%) and also the Red River Delta rate (96.8%) [21].

The current status of MSW loads from all sources within the collection zone limit accumulated at the collection points was determined as in Figure 7. These findings are an important suggestion for designing vehicles and their collection routines to ensure minimal residual waste.

In brief, the MSW collection work is currently concentrated in urban areas of Hung Yen city. In the inner city area, the waste from streets and local households is often collected twice a day. Transit stations with high concentrations of waste are also mainly located in densely populated areas or near local markets.

The waste transport vehicles in use in Hung Yen city include three garbage compactor trucks (one 2.5 ton vehicle; one 5 ton vehicle; and one 7 ton vehicle); one hookup garbage transport car carries a closed container; one road cleaning truck; and one sweeper truck (Table 6). The average transportation distance from gathering points to the waste treatment area is around 18 to 23 km.

Table 6. Current status of the city's MSW transportation vehicles

No.	Vehicles for collection and transportation	Quantity
1	400-liter manual waste collection truck	91
2	Transporting trucks (2.5 tons vehicle: 01 5 tons vehicle: 01 7 tons vehicle: 01)	03
3	Hooklip garbage compactors carries a closed containers with a capacity of 10 m^3	01

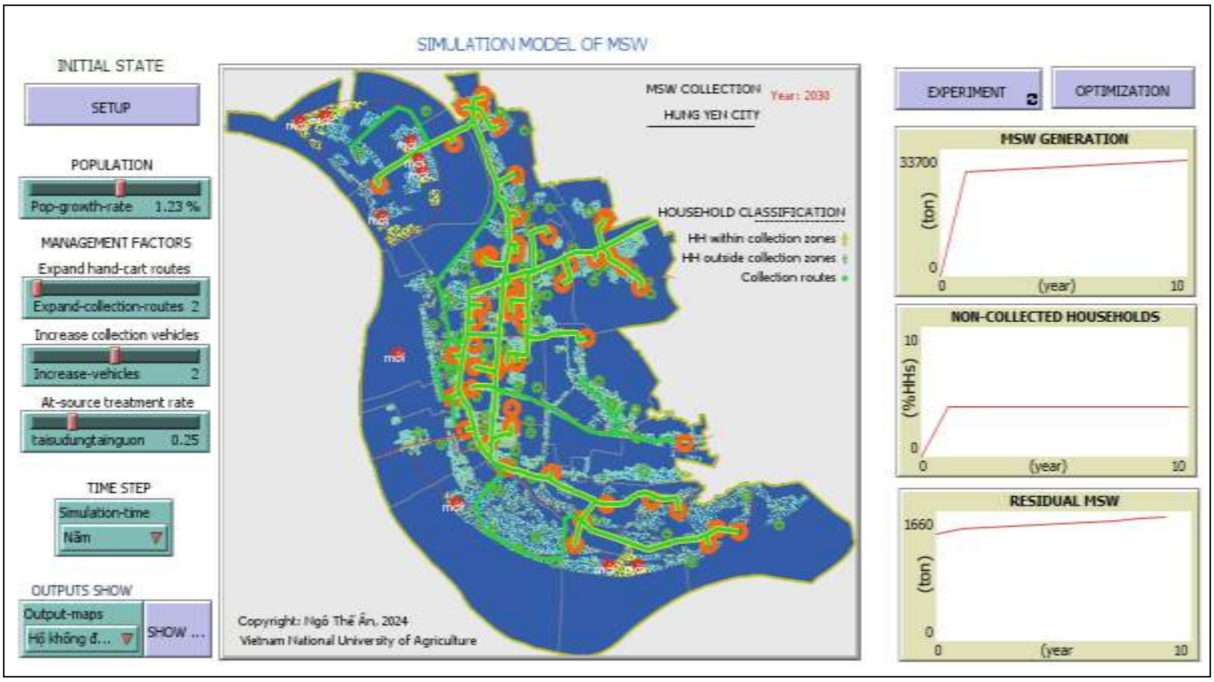


Figure 9. The MSW model interface.

3.4. Simulation of the Waste Management System

Based on the theoretical model (Figure 4), the computer model was elaborated in NetLogo software [19]. In which, the model interface (Figure 9) was designed with sliders to control input experimental factors (i.e. population growth, number of additional collection routes, vehicles, reuse/treatment at-source). The computer model consists of four operational programs, namely "Population growth" for predicting population growth; "MSW generation" for estimating MSW generated by households, markets and offices; "MSW collection"; "MSW reuse"; "MSW decoposition"; and "Update presentation" for updating status of all agents in the model after each model run.

The route optimization programs was formulated as a special module embeded in the model with the optimal functions related to the travel time, cost, collected and residual waste as explained in the methods section.

The model outputs can be viewed through a map with detailed MSW sources, administrative boundaries, roads and collection routes. In addition, there are also graphs summarizing the amount of waste generated, collected and left over in the study area.

3.5. Model Validation

Model validation was done by moving sliders that represent controlling variables in the model's interface when running the model. The results of the sensitivity analysis are presented in Figure 8.

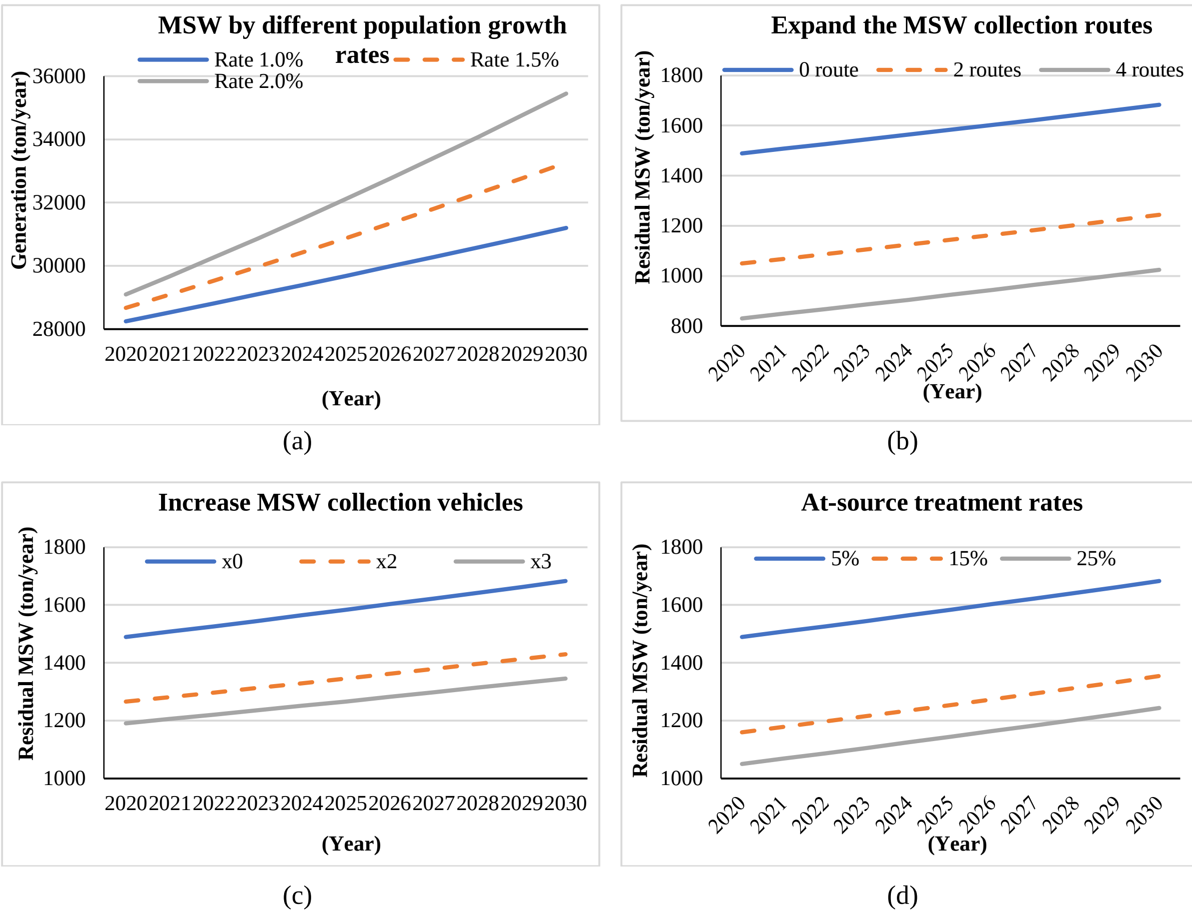


Figure 8. Results of sensitivity analysis for some model input parameters.

Analyzed results show that all parameters are sensitive in the model (significant differences in model outputs). With three different population growth rates (1.0, 1.5, and 2.0%), the amounts of waste generated shown on the three corresponding graphs are very different from each other (Figure 8a). These results are similarly found when expanding routes for the "hand-pulled garbage" (Figure 8b), increasing the number of waste transport vehicles (Figure 8c), and increasing the "at-source treatment rates" (Figure 8d). For the model in this study, we do not need a systematic output validation because the amount of MSW is calculated deterministically based on the coefficients measured from field surveys. As long as the input parameters are accurate and sensitive, the model will be acceptable for calculating results according to the formulated algorithms [18].

3.6. Optimizing the MSW Collection Network for Hung Yen City

3.6.1. Setting up Scenarios for Evaluating the Effects of Interventions on MSW Collection

According to the findings from previous sections, four interventions were identified to improve waste collection rates, thereby to improve residual waste and minimize environmental impacts for Hung Yen city. The first intervention factor is to expand collection routes using handcarts for rural communes. As mentioned (in Section 3.3), MSW at the current wards was collected relatively stable, at over 95%. Meanwhile, there is still a great residual MSW at the communes far from the center due to narrow roads and no collection station nearby. Therefore, prioritizing the expansion of the collection routes to rural areas is a necessary and suitable solution for the current context of rapid urbanization.

Residual waste is also significantly high in wards and communes near the center (Figure 6). Therefore, the second immediate intervention is to increase the transfer stations to avoid the overload of MSW in the living areas. The "at-source treatment" is also considered a practical solution in waste management. This solution is the third intervention factor to reduce pressure on waste collection. In addition, the population is also a factor that needs to be formulated in the experimenting scenario. Although population growth is not the target of intervention in environmental management, this factor directly affects the amount of waste generated, so we include it along with the three interventions above to predict the future MSW when population changes are significant.

The hypothetical scenario to examine the interventions for improving MSW management according to the four interventions mentioned above was quantitatively formulated as follows:

- Remain annual population growth rate at 1.50% (according to the Master Plan for the socio-economic development of Hung Yen province until 2030);
- Expand the MSW collection to rural areas: open 2 new "hand-pulled garbage" routes (according to the planning of the DONRE, 2020).
- Increase the collection vehicles: increase 2 garbage compactors and 40 hand carts in the densely populated area (according to the planning of the DONRE, 2020).
- Facilitate the "at-source treatment" for organic waste at households up to 25%.

The above experimental scenario is analyzed and compared with the control scenario (BAU) when the above factors (interventions) only remain as the current situation (i.e. population growth rate is 3.46%, at-source treatment in rural areas is 5%, no changes in collection routes and vehicles as in Table 5).

3.6.2. Results of Scenario Analysis

The model is operated with the above two scenarios to produce results for the evaluation of the waste management system. In each scenario, the model was run independently 30 times. Average results in the year 2030 are presented in Table 7.

As mentioned in the previous sections, the waste generated depends mainly on population and markets. Therefore, under Scenario 2, when population growth is controlled, the total waste generated is predicted to decrease significantly compared to the BAU scenario. Under Scenario 2, MSW generation and residual reduce by 17% and 59%, respectively (Table 7). However, in scenario 2, it is assumed that there are collection interventions (by expanding collection routes and increasing vehicles) and the "at-source treatment" facilitation so the amount of residual waste is significantly reduced compared to the BAU scenario, with a residual rate reduced at nearly 30 ton/day.

Table 7. Results of running the model for different scenarios until 2030 (N = 30)

Scenarios	Σ waste generation (tons)		Σ residual waste (tons)	
	Days	Year	Days	Year
The BAU (scenario 1)	128.1	46,762	51.2	18,704
The experiment (scenario 2)	105.9	38,659	21.2	7,732
Differences		-8,103(17%)		-10,972 (59%)

Table 8. Effective reduction of MSW from Scenario 2 in 2030 compared to BAU

The interventions	Generated MSW reduction (%)	Residual MSW reduction (%)
Population control (remain rate)	7,2	-
Expand collection routes	-	26.0
Increase collection vehicles	-	20.1
Facilitate the “at-source treatment”	-	10.7

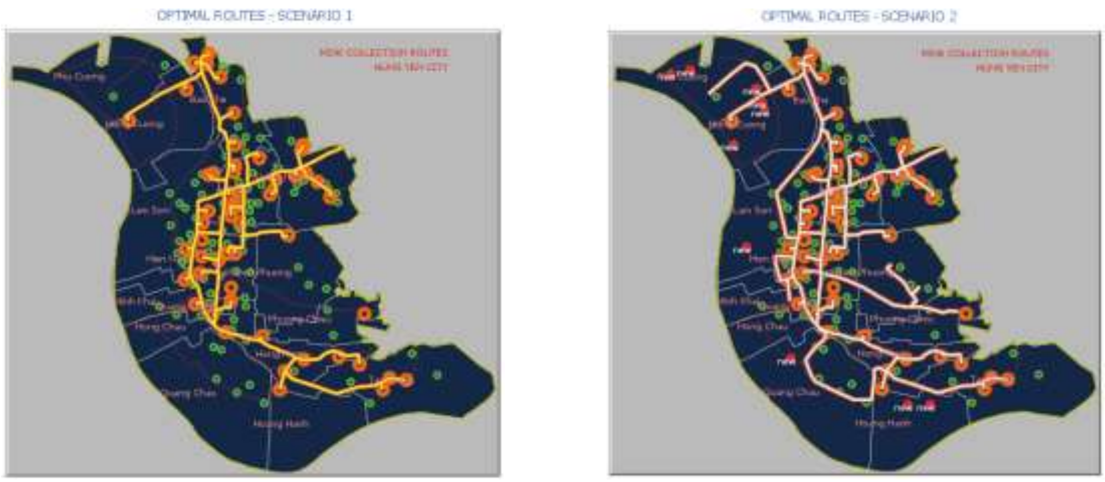
Detailed analysis of scenario 2 also shows that two suburban communes will be invested in additional waste transfer stations to collect waste from the communes to the landfill. Based on the spatial analysis algorithm with the collection zone set-up for the routes, the amount of residual waste (not collected) decreases by 26.0% compared to the BAU Scenario. Similarly, the increase in collection vehicles contributes up to 20.1% of residual MSW reduction while the promotion of “at-source treatment” results in a 10.7% reduction (Table 8). This result proves that expanding routes and investing vehicles is immediately effective for MSW collection, but capital to invest in this intervention is also needed to ensure the feasibility of the solution.

Currently, the MSW management pressure is very high, existing in all stages, from collection, transportation, and treatment. The at-source treatment is considered very effective for reducing management pressure. Outputs of the model run with Scenario 2 reveal that if the at-source treatment of organic waste is widely applied at 25% for rural areas, the discharged waste will be reduced significantly, at over 9.6 tons/day, equivalent to 10.7% of the waste generated from households (Table 10). The at-source treatment does not bring a strong impact on residual SMW as the other interventions but it requires less financial investment. Therefore, next to the benefit of decreasing environmental pressure, the at-source treatment can save costs for MSW management. Of course, to implement this solution, it is necessary to combine environmental communications, which include training on household waste treatments with the participation of socio-political bodies at the village level.

3.6.3. Optimizing the Municipal Solid Waste Collection Network

The current collection routes have been operated for more than 10 years in the study area. However, the collection efficiency is not as good because the rates of collected MSW still vary widely between the communes; particularly, the collection rate is relatively low in rural areas (Figure 5b). Therefore, the collection route optimization is still necessary for all scenarios to supplement experimented interventions. Route optimization combined with dynamic MSW predictions over time requires complex techniques. In addition to the combination of the optimal functions (i.e. maximal collection and minimal distance), as often found in current GIS software, the model in Netlogo also needs to formulate the constraints (i.e. number of collection vehicles, number of routes) and the dynamic of those constraints over the model run. The model built in Netlogo was run for route optimization with the general target of a maximum collection rate of 80% (according to the plan of DONRE). The model results according to the two experimental scenarios are presented in Figure 9.

According to Figure 9, the optimal routes for Scenario 1 (BAU) are more focused in the center and shorter than that of Scenario 2. As scenario 2 has two additional garbage compactors and 40 hand carts and the expansion of some collection routes in the rural areas, so the distance traveled also increases significantly. In addition, to ensure the collection target reaches 80% as mentioned above, the optimization algorithm proposed 10 transit points (labeled "new") to be located in densely populated areas in the northwest of the map (Hung Cuong and Phu Cuong communes). The compensation for the long-wide route network of Scenario 2 is the significant improvement of collection efficiency, reducing 43% of residual MSW.



(a) (b)

Figure 9. Optimal collection routes for (a) Scenario 1, and (b) Scenario 2.

More importantly, route optimization is a technical assistance necessary for realizing the interventions examined by the scenario analysis. However, even with the best scenario (scenario 2), when optimizing the collection routes, there are still some households scattered outside the collection service area (bright yellow points in Figure 10).

The existence of some households whose waste is not collected along optimal routes could be found similarly in many studies in the field of route optimization [4, 5, 12]. This technical problem cannot be resolved solely by the computer models due to practical constraints related to the equipment and infrastructure existing in the study area. However, the optimal route findings are meaningful in orienting investment positions for other interventions, for example, waste recycling according to the circular economy mechanism applied specifically to households outside the collection attempt by the local government departments.

Currently, the Ministry of Natural Resources and Environment (MONRE) gives a high priority to enhance the MSW sorting at source, and the collection system that is specifically designed for the already sorted MSW [22]. However, the prerequisites to establish such a collection system are very difficult for the localities which includes Hung Yen city [23].

Therefore, Hung Yen city creatively proposed an at-source treatment practice as an alternative solution for the at-source sorting, and to reduce the landfill treatment pressure, simultaneously. The at-source treatment scenario was predicted by the computer model to be effective in reducing up to 10.7% of total residual MSW compared to the BAU scenario. Therefore, the at-source treatment solution is particularly suitable to the "National strategy on integrated solid waste management to 2025, with a vision to 2050" of Vietnam which aims to minimize the amount of waste in landfills and reduce environmental pollution sustainably [24]. The at-source treatment also supports the Decree No. 08/2022/ND-CP by the National Assembly of Vietnam on elaboration of several articles of the Law on Environmental protection and the Circular 02/2022/TT-BTNMT by MONRE which detailed a number of articles of the Law on Environmental protection [25, 26].

Figure 10. Households are and are not collected by the optimal option of Scenario 2.

The simulation model suggested the optimal routing that requires 10 transfer points and routes to be additionally established through densely populated areas is perfectly aligned with the Vietnam 2020 Law on Environmental Protection [27] regarding to Waste management and control of other pollutants (Chapter VI). This legal chapter stated clearly that "Facilities collecting and transporting domestic solid waste shall cooperate with communal People's Committees, residential communities and representatives of residential areas in determining time, places, frequency and routes for collecting domestic solid waste, and make them publicly available" (Article 77, Clause 3 and 4). These Clauses are a foundation to allow Hung Yen city to mobilize resources to establish the infrastructure needed for the optimal routing. The expanding collection routes solution has been evaluated above as being very effective in reducing residual MSW (up to 26%) and it's very feasible when the local collection target was only setup at 80% of MSW load, which matches the lowest level within the targets (from 80–95%) of the "Solid waste development strategy in urban areas and industrial zones in Vietnam to 2020" [28]. Thus, the solutions proposed by Hung Yen city are consistent with the MSW management orientation mentioned in the central legal documents and can be effective as Vietnam's expected goals.

4. Conclusions

In 2020, the total MSW load in Hung Yen city was about 80 tons per day. Waste generation fluctuates widely between administrative units, ranging from 0.5 to 8.0 kg per person per day, with high loads concentrated in wards and communes near the city center. Currently, the MSW collection system is primarily located in densely populated clusters. The collection rate for urban areas is about 95%, while the rate for rural areas is only 66%, leaving many households outside the collection zones. The simulation model of the MSW collection system was built based on spatial analysis results performed using GIS software. The model was validated for scenario analysis and route optimization for Hung Yen city. Based on the environmental management goals of local governments, scenarios to reduce MSW collection pressure were formulated with four interventions: (i) maintaining a population growth rate of 1.5%, (ii) expanding collection routes for rural areas, (iii) increasing the number of collection vehicles, and (iv) facilitating at-source treatment of organic waste. Scenario analysis results show that expanding routes and investing in vehicles are the most effective measures for MSW collection, reducing residual waste by 26.0% and 20.1%, respectively, compared to the BAU scenario. However, these interventions require substantial investments for purchasing vehicles and equipment, as well as operational costs. At-source treatment reduces residual waste by 10.7% but does not require high investment. Route optimization results indicate the necessity of establishing 10 additional transfer points within the current collection system, combined with the four intervention factors, to achieve the local authorities' collection target of over 80%. Despite these interventions, some households remain outside the collection service. This result suggests the need for additional solutions, such as waste recycling practices for households beyond the collection capacity of the local environmental management system.

References

[1] M. G. Jurczak, M. Tarabuła, A. D. Read, Increasing Participation in Rational Municipal Waste Management: A Case Study Analysis in Jaslo City (Poland), Resources, Conservation and Recycling, Vol. 38, No. 1, 2003, pp. 67-88, https://doi.org/10.1016/S0921-3449(02)00124-6.

[2] T. Wagner, P. Arnold, A New Model for Solid Waste Management: An Analysis of the Nova Scotia MSW Strategy, Journal of Cleaner Production, Vol. 16, No. 4, 2008, pp. 410-421, https://doi.org/10.1016/j.jclepro.2006.08.016.

[3] M. E. Asefa, B. K. Barasa, M. D. Adare, Application of Geographic Information System in Solid Waste Management, Z. Yuanzhi, C. Qiuming, C. (eds.), Geographic Information Systems and Applications in Coastal Studies, Rijeka: IntechOpen, 2022, pp. 1-21, https://doi.org/10.5772/intechopen.103773.

[4] R. Sallem, M. J. Rouis, Optimization of Household Waste Collection Routes Using GIS: Case Study of El Bousten District, Commune of Sfax, Tunisia, Current World Environment, Vol. 12, No. 1, 2017, pp. 53-60, https://doi.org/10.12944/CWE.12.1.07.

[5] M. A. E. Hallaq, R. Mosabeh, Optimization of Municipal Solid Waste Management of Bins Using GIS: A Case Study, Nuseirat City, Journal of Geographic Information System, Vol. 11, No. 1, 2019, pp. 32-43, https://doi.org/10.4236/jgis.2019.111003.

[6] A. Malakahmad, P. M. Bakri, M. R. M. Mokhtar, N. Khalil, Solid Waste Collection Routes Optimization Via GIS Techniques in Ipoh City, Malaysia, Procedia Engineering, Vol. 77, 2014, pp. 20-27, https://doi.org/10.1016/j.proeng.2014.07.023.

[7] V. C. Mai, S. H. Nguyen, C. D. Dao, T. V. Le, H. A. Phan, A GIS Application in Optimizing the Collection and Transportation Route of Domestic Solid Waste in Hue City, Vietnam, A.T. Nguyen, L. Hens (eds), Global Changes and Sustainable Development in Asian Emerging Market Economies, Springer, Cham, Vol. 2, 2022, pp. 599-610, https://doi.org/10.1007/978-3-030-81443-4_38.

[8] S. M. H. Erfani, S. Danesh, S. M. Karrabi, R. Shad, A Novel Approach to Find and Optimize Bin Locations and Collection Routes Using a Geographic Information System, Waste Management & Research, Vol. 35, No. 7, 2017, pp. 776-785, https://doi.org/10.1177/0734242X17706753.

[9] V. R. Sumathi, U. Natesan, C. Sarkar, GIS-based Approach for Optimized Siting of Municipal Solid Waste Landfill, Waste Management, Vol. 28, No. 11, 2008, pp. 2146-2160, https://doi.org/10.1016/j.wasman.2007.09.032.

[10] L. T. Quynh, N. X. Hoa, D. T. Trung, GIS in Domestic Solid Waste Management: Applicability and Practice Experience, Journal of Human Geography Research, Vol. 3, No. 34, 2021, pp. 31-38 (in Vietnamese).

[11] N. T. Lanh, Y. Matsui, N .H. Trung, N. P. Thanh, GIS and GPS Application Support Monitoring and Management of Municipal Solid Waste Collection - Transfer System in Can Tho city, CTU Journal of Science-CTUJoS, Vol. 20b, 2011, pp. 1-11 (in Vietnamese).

[12] L. T. Tuan, Geographic Information System (GIS) Application in Household Solid Waste Management in Cam Le District, Da Nang City, Graduation Thesis, University of Education, University of Da Nang, 2015, (in Vietnamese).

[13] N. D. Truong, GIS Application for Solid Waste Management in Dong Hoi City, Quang Binh Province. Master's Thesis in Urban and

Construction Management, Hanoi University of Architecture, 2014 (in Vietnamese).

[14] J. F. Cordeau, G. Laporte, A. Mercier, A Unified Tabu Search Heuristic for Vehicle Routing Problems with Time Windows, Journal of the Operational Research Society, Vol. 52, No. 8, 2001, pp. 928-936, http://www.jstor.org/stable/822953 (accessed on October 10th, 2023).

[15] W. Song, C. Wu, Introduction to Advancements of GIS in The New IT Era, Annals of GIS, Vol. 27, No. 1, 2021, pp. 1-4, https://doi.org/10.1080/19475683.2021.1890920.

[16] E. Bonabeau, Agent-based Modeling: Methods and Techniques for Simulating Human Systems, Proceedings of the National Academy of Sciences of The United States of America, Vol. 99, 2002, pp. 7280-7287, https://doi.org/10.1073/pnas.082080899.

[17] A. A. Monshar, A. A. Bazu, V. Palade, An Agent-based Optimisation Approach for Vehicle Routing Problem with Unique Vehicle Location and Depot, Expert Systems with Applications, Vol. 192, 2022, https://doi.org/10.1016/j.eswa.2021.116370.

[18] T. A. Ngo, L. See, Calibration and Validation of Agent-Based Models of Land Cover Change, Heppenstall, A. J. Crooks, A. T. See, L. M. & Batty, M. (eds.), Agent-Based Models of Geographical Systems, Springer, 2012, pp. 181-197, https://doi.org/10.1007/978-90-481-8927-4_10.

[19] U. Wilensky, NetLogo [Online], Center for Connected Learning and Computer−Based Modeling (1999). Northwestern University, Evanston, Illinois, USA, Available: http://ccl.northwestern.edu/netlogo/ (accessed on October 10th, 2023).

[20] P. Frana, An Interview with Edsger W. Dijkstra, Communications of the ACM, Vol. 53, No. 8, 2010, pp. 41-47, https://doi.org 10.1145/1787234.1787249.

[21] GSO, Statistical Yearbook of Vietnam 2021, Statistical Publishing House, 2021 (in Vietnamese).

[22] MONRE, The National Environmental Status Report in 2019: Domestic Solid Waste Management, Ministry of Natural Resources and Environment, 2020 (in Vietnamese).

[23] T. T. K. Lien, A. H. Hu, P. P. S. Toan, Situation, Challenges, and Solutions of Policy Implementation on Municipal Waste Management in Vietnam Toward Sustainability, Sustainability Vol. 13, No. 6, 2021, pp.1-16, https://doi.org/10.3390/su13063517.

[24] Prime Minister of Vietnam, Approval to Adjust the National Strategy on Integrated Solid Waste Management by 2025, with a Vision to 2050. Available Online: https://thuvienphapluat.vn/van-ban/tai-nguyen-moi-truong/Quyet-dinh-491-QD-TTg-2018-dieu-chinh-Chien-luoc-quoc-gia-quan-ly-tong-hop-chat-thai-ran-381368.aspx (accessed on October 16th, 2023) (in Vietnamese).

[25] The National Assembly, Decree No. 08/2022/ND-CP January 10, 2022 of Government Elaboration of Several Articles of The Law on Environmental Protection, Law No. 72/2020/QH14, Hanoi, Vietnam (in Vietnamese).

[26] MONRE, Circular No. 02/2022/TT-BTNMT dated January 10, 2022 on Detailing A Number of Articles of Law on Environmental Protection, No. 02/2022/TT-BTNMT, Hanoi, Vietnam (in Vietnamese).

[27] The National Assembly, Law on Environmental Protection. Law No. 72/2020/QH14, 2020, Hanoi, Vietnam (in Vietnamese).

[28] Prime Minister of Vietnam, Solid Waste Development Strategy in Urban Areas and Industrial Zones in Vietnam to 2020, Available online: https://thuvienphapluat.vn/van-ban/tai-nguyen-moi-truong/Quyet-dinh-152-1999-QD-TTg-phe-duyet-chien-luoc-phat-trien-chat-thai-ran-do-thi-va-khu-cong-nghiep-Viet-Nam-den-2020-45446.aspx (accessed on October 16th, 2023) (in Vietnamese).