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Planning for hazardous campus waste collection

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ABSTRACT

This study examines a procedure developed for planning a nation-wide hazardous campus waste (HCW) collection system. Alternative HCW plans were designed for different collection frequencies, truckloads, storage limits, and also for establishing an additional transfer station. Two clustering methods were applied to group adjacent campuses into clusters based on their locations, HCW quantities, the type of vehicles used and collection frequencies. Transportation risk, storage risk, and collection cost are the major criteria used to evaluate the feasibility of each alternative. Transportation risk is determined based on the accident rates for each road type and collection distance, while storage risk is calculated by estimating the annual average HCW quantity stored on campus. Alternatives with large trucks can reduce both transportation risk and collection cost, but their storage risks would be significantly increased. Alternatives that collect neighboring campuses simultaneously can effectively reduce storage risks as well as collection cost if the minimum quantity to collect for each group of neighboring campuses can be properly set. The three transfer station alternatives evaluated for northern Taiwan are cost effective and involve significantly lower transportation risk. The procedure proposed is expected to facilitate decision making and to support analyses for formulating a proper nation-wide HCW collection plan.

1. Introduction

In Taiwan, the disposal of hazardous campus waste (HCW) has drawn increased attention in recent years. According to a survey conducted by Li et al. [1], the amount of HCW was about 1656 ton for liquid waste and 271 ton for solid waste, respectively, which are not significantly large, when compared with those of industrial wastes. But the composition of HCW is much more complex; it is thus improper and cost ineffective to treat HCW by a typical industrial hazardous waste treatment center. A special treatment center was thus established in 2005 to take in all HCWs from around the country. Previously, HCWs were collected by private collectors whose technical competence and service quality are unreliable and frequently questioned by the general public. This study was thus initiated to develop an approach for planning an enhanced HCW collection system.

Waste collection is, for the most part, a vehicle routing problem (VRP) (e.g., [2–4]). Since the entire collection area covers the whole country, it is too large to allow for the establishment of a typical optimization VRP model to plan a HCW collection system. Hence, a special heuristic approach was proposed in this study for planning the HCW collection system.

A clustering method, as described by Jain and Fubes [5], was applied to group adjacent campuses into clusters based on their locations, HCW amounts, distances to other campuses, and collection frequencies. This clustering method can significantly reduce the size of an optimization model and make it possible to efficiently analyze problems encountered in planning a large collection system by using the proposed approach.

Various factors should be carefully considered in the planning of a HCW collection system. A collection truck carrying HCW running on the road to a treatment center poses potential risks for the people and the environment along the collection routes. The transportation risk [6,7] involved of a collection system is thus an essential factor that should be evaluated. Historical accident rates for different road types and transportation distances are used to determine the potential transportation risk. Since HCW consists of hazardous materials and potential exposure risk exists during storage, the storage risk is also a major factor to be evaluated [8–12]. Current and Ratick [9] describe the nature of the storage risk and indicate that storage risk exists continuously, unlike transportation risk which is discrete and exists only when the collection truck is on the road. Any accident of a storage facility may cause severe impact on the campus and the surrounding neighborhood and environment. The storage risk is thus considered and, as in other studies (e.g., [9,10]), the HCW quantity stored is used to define the level of storage risk. Furthermore, the collection cost is important and is always a major factor (e.g., [12–14]) to be evaluated. These three factors were used to assess a HCW collection plan in this study.

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With the aforementioned cluster method and three factors, a heuristic model was developed herein to plan a collection system for Taiwan HCWs. Various collection system alternatives, with different types of collection vehicles, collection frequencies, and a transfer station, were generated, compared, and discussed. The proposed model can effectively facilitate the planning for a HCW collection in Taiwan and is expected to be applicable also for similar studies in other parts of the world.

2. Methodology

The proposed procedure for analyzing this HCW collection problem first devises possible alternative collection plans to be simulated. The collection frequency of each alternative is then determined. Two clustering methods are used to group adjacent campuses into clusters, and a heuristic routing approach is applied to determine the collection route in each cluster for estimating the collection cost. This HCW collection clustering analysis is explained as follows.

2.1. Devise alternative collection plans

Various potential alternative collection plans are first devised for (1) different collection frequencies (2) different truckloads, (3) quantity collected based on storage limits, and (4) the providing of an additional transfer station. Two major collection frequencies are considered. The first one assumes that all HCWs are collected by the treatment center and collection trucks are sent out to collect with a pre-specified frequency; the second allows different regions to be collected by different frequencies. Two types of collection trucks with different truckloads of 2 and 3.5 ton are considered. Although trucks with higher capacity are available, they are regarded inefficient because the HCW amount of most campuses is not large. Storage limits are also evaluated. For an alternative that considers storage limits, HCWs are collected whenever a campus reaches its storage limit and its neighbor campuses are collected simultaneously if their HCWs exceed a pre-specified minimum quantity. Finally, since placing an additional transfer station might significantly reduce related risks and cost, alternative plans with adding a transfer station at several possible locations are also formulated.

For convenience of discussion, each alternative in the following is referred to by a code name. For example, FF stands for those with a fixed collection frequency for all regions, VF stands for those with various collection frequencies for different regions, 2 T stands for using 2-ton collection trucks, and 3.5 T stands for using 3.5-ton collection trucks. FF-2 T refers to the alternative with a fixed collection frequency and using 2-ton truck to collect HCW. Alternatives that take storage limits into consideration are referred to by SLq. For example, SL0.1 refers to the alternative with the minimum quantity set to be 0.1 ton and so forth.

2.2. Determine collection frequency for each region

For each alternative, the collection frequency for each region must be determined first. In this study, the collection frequency for a region is determined by the following equation:

$$N = \frac{AW}{TL} \times CN \tag{1}$$

where AW is the average annual HCW quantity of a campus in a region; N is the collection frequency to be determined; CN is the number of campuses to be collected per trip; and TL is the loading capacity of a collection truck. If the determined N is not an integer, it is set to be the ceiling integer. CN is determined by the average distance among campuses in a collection region, the distance from the region to the treatment center, and a typical collection speed. For regions close to the treatment center, more campuses can be collected in one collection trip, and for regions far away from the center, less campuses can be collected per trip. Besides, the longer the average distance is among campuses in a region, the fewer the campuses that can be collected in one trip, and vice versa. FF alternatives treat the entire nation as one region to determine their collection frequency, while VF alternatives determine the frequency for each region individually.

2.3. Campus clustering

Since campuses are distributed all over the country, it is difficult to implement an optimum comprehensive collection routing for the entire HCW collection system. Clustering methods, thus, are applied. The methods group adjacent campuses into clusters, and then determine the collection route in each cluster by a heuristic approach in order to estimate the collection cost. The methods can generate a collection plan that is reasonably efficient within an acceptable computational time. The methods for alternatives with and without considering storage limits are explained in detail as follows.

2.3.1. Clustering without considering storage limits

The first step for the campus clustering procedure is to determine the desired number of clusters to be grouped in each collection region. The desired number of clusters in each region is estimated by the following equation.

$$K = \frac{y}{N \cdot m} \tag{2}$$

where K is the desired number of clusters in a region; y is the total annual HCW amount in the region; m is the HCW amount collected by one collection truck; and N is the number of times HCW is collected annually, as determined by Eq. (1).

The HCW collection frequency, t, in each region is assumed to be fixed. Once the collection frequency is pre-specified, the amount of HCW generated during each collection period can be estimated. Clusters of adjacent campuses can be formed when the total HCW amount of each cluster is close to what a collection truck can transport. The K-mean clustering method [5] was then applied to pre-cluster all campuses according to their distances between one another. For any cluster whose total HCW amount exceeds the limit of a collection truck, the cluster is pruned by spinning off some of its constituent campuses to join adjacent clusters. This clustering approach is detailed as follows.

(a) K-mean clustering: According to the number of desired clusters, K, determined by Eq. (1), each campus is assigned to a cluster through the following steps.
   - Step 1: K campuses are randomly chosen as the centers of the desired K clusters;
   - Step 2: For all campuses, each of them is assigned to the closest cluster, based on its distances to all cluster centers;
   - Step 3: The new center of each cluster is recalculated. It is the centroid of all campuses in each cluster;
   - Step 4: Repeat Steps 2 and 3 until the location of each cluster center is no longer changed.

(b) Cluster alteration: Any cluster with total HCW amount exceeding the collection limit of a truckload is altered by spinning off some of its constituent campuses to adjacent clusters. This cluster alteration procedure follows the steps described below.
   - Step 1: A cluster that is overloading is marked as an overloading cluster. Select in the currently overloading cluster the campus that is geographically closest to any adjacent non-overloading cluster.

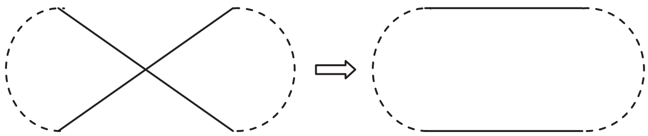

Fig. 1. The 2-opt method.

Step 2: Split the selected campus off its current cluster and add it to its closest adjacent non-overloading cluster.
Step 3: Repeat Steps 1 and 2 until all the clusters have their HCW amount below the one-truckload limit.

2.3.2. Clustering considering storage limits

For alternatives that consider storage limits, the clustering method is different. The average weekly HCW amount generated by each campus is first determined. Then, the storages of all campuses are increased weekly until any one campus reaches the specified storage limit that must be collected. After that, use the campus as the center of a cluster and then apply the aforementioned nearest neighbor method again to find neighboring campuses with HCW exceeding a pre-specified quantity and have them collected simultaneously until the collection truck is fully loaded. Repeat this procedure until all campuses are clustered.

2.4. Collection routing for each cluster

A heuristic approach is applied to generate the collection route of each cluster and to determine the total collection distance of the cluster so as to make estimation of the entire collection cost. The collection route generated by the approach for each cluster is divided into three major sections, as explained below:

1. Highway to the treatment center: The HCW from each region is transported via the national highway network to the treatment center. The route on the highway network between each region and the treatment center is determined by the shortest path method [15].
2. Highway to a cluster: the route from the highway network to the boundary of a cluster is also determined by the shortest path method.
3. Collection route in a cluster: The inner-cluster collection route is determined by using the nearest neighbor method [16] and the 2-opt move method [17]. The distance between two campuses is determined by the Euclidean distance instead of the street distance. The nearest neighbor method is a path searching method. The method searches, from a starting node, the nearest node from the previously selected node in each step to determine a path. The searching process continues until the path can reach all nodes in the entire network without forming any cycle. However, the path determined by this method may not be the optimal one, although it selects the nearest node in each step. The 2-opt method [17] was thus applied to shorten the path further. It modifies the path with inappropriate crossing links by reorganizing the links into a more efficient route, as shown in Fig. 1.

This routing method, although not true optimization, can generate a HCW collection plan that is reasonably efficient within an acceptable computational time.

2.5. Assessing a HCW collection alternative by three factors

Three major factors: transportation risk, storage risk, and collection cost are evaluated to assess a HCW collection alternative. They are described below, respectively.

2.5.1. Transportation risk

A hazardous waste collection plan may have substantial risk if collection trucks pass routes that are accident prone [11]. In estimating the transportation risk, the probabilities of accident [18] obtained from historical accident data for three types of roads, national highways, inter-city highways, and local roads, are used. The transportation risk is computed by the probability of accident and the collection traveling distance, as determined by the following equation:

$$TR = pd \tag{3}$$

where TR is the transportation risk (unit: accident frequency per million truck trips); p is the probability of accident per million truck-kilometers; and d is the distance of a collection travel (unit: kilometer).

2.5.2. Storage risk

Although HCW is stored on each campus temporarily, potential risk for accidental hazards exists, making the storage risk an essential factor to be considered, and efforts must be made to minimize its possible impact on the campus and the surrounding community and environment. The storage risk of an alternative HCW collection plan is determined by the following equation.

$$SR = \frac{\sum_{j}\sum_{i} C_{ij} Pr_j}{TC} \tag{4}$$

where SR is the annual average storage risk of an alternative collection plan; C_{ij} is the average storage of campus i during period j before next collection trip; Pr_j is the ratio of period j to the entire year; and TC is the number of all campuses.

2.5.3. Collection cost

In addition to minimizing related transportation and storage risks, a good HCW collection plan should be cost effective too. Since the entire collection region is partitioned into numerous clusters based on the collection capability of one truckload, i.e. each cluster is collected by one truck trip, the cost is thus primarily estimated to be the cost of one truck trip, as formulated below.

$$C_k = UTL + \sum sd_k \times UD + P \times t \tag{5}$$

where C_k is the collection cost for cluster k; UTL is the cost per trip; sd_k is the total collection traveling distance within cluster k; UD is the cost per unit collection traveling distance; P is the personnel cost per unit collection time; and t is the collection time.

The total collection distance is computed from three parts: (1) the internal traveling distance within a cluster; (2) the distance between the cluster and the closest highway entrance; and (3) the distance between the highway entrance and the treatment center. The internal traveling distance within a cluster is the length of the path determined by the aforementioned clustering and routing methods. The coefficients of UTL, UD, and P were collected from the data reported by Institute of Transportation in Taiwan.

3. Case study

The national HCW collection system in this study covers all middle schools, high schools, colleges and universities in Taiwan. In total, there are 1323 campuses. The entire country was divided into 16 regions according to their administrative boundaries. The HCW quantities, as listed in Table 1, were estimated based on national surveys [1,19]. Digit maps for road networks are obtained from the Institute of Transportation in Taiwan. Transportation cost information is obtained from a local report [20]. Table 2 lists the cost information, including the collection cost, hourly wage, and cost

Table 1
The HCW quantities generated in campuses of Taiwan.

	Junior high schools	Senior high schools	Vocational high schools	Colleges	Total
CHW quantity (ton)	620	262	119	497	1498
Percentage	41	17	8	33	100

Sources: [1,19]

Table 2
Cost items for truck collection.

Cost item	2-ton truck	3.5-ton truck
Collection cost per unit distance (NTD/km)	3.6	3.7
Hourly wage of collectors (NTD)	651	704
Cost per truck trip (NTD/trip)	1149	1248

per truck trip of 2 and 3.5 ton trucks, respectively. Table 3 lists the maximum storage limits pre-specified for campuses with different annual HCW quantity ranges, for use in SLq alternatives. The cost for establishing and operating a transfer station is primarily collected from Taiwan EPA [21]. The proposed method is applied to this Taiwan HCW collection problem. The results and comparison are discussed in detail in the next section.

4. Results and discussion

Several different HCW collection alternatives are evaluated for different collection frequencies, truckloads, and storage limits. Results obtained for different alternatives are compared based on three essential factors: transportation risk, storage risk, and collection cost.

Moreover, the alternatives for establishing a transfer station at three different locations are also assessed.

4.1. Alternatives with different collection frequencies

To evaluate and compare the results obtained for different alternatives, we must make estimations on the distance between the treatment center and each collection region, the average speed of a collection vehicle on different roads in each collection region, and the collection time for each campus. Fig. 2(a) and (b) shows the clustering results for alternatives FF-2 T and VF-2 T, respectively. Alternative FF-2 T collects four times per year for all regions, and the numbers of collection times for VF-2 T range from 1–7 times per year for different regions. The results are compared based on the three essential factors, as listed in Table 4. Alternative VF-2 T reduces the transportation risk by 23.9% when compared with that for alternative FF-2 T. For regions with low HCW quantities, e.g., Yilan, Taitung, and Hualien, alternative VF-2 T requires fewer trips than that for alternative FF-2 T and thus subsequently reduces the transportation risk. The storage risk for alternative VF-2 T is 17.8% less than that for alternative FF-2 T. For regions with high HCW quantities, e.g. Taipei, Taoyuan, Taichung, Chianhua, Yunlin, Tainan, Kaohsiung, and Pingtung, the collection frequency of alternative FF-2 T is not high enough as to collect all of their HCWs and a significant amount of HCWs must be stored on campus, which subsequently causes high storage risk. The total collection cost of alternative FF-2 T is 8.1% higher than that for VF-2 T because such collection frequencies are inappropriate for regions with low HCW quantities and far from the treatment center, e.g., Yilan, Taitung, and Hualien. The collection costs for these regions can be reduced if it can increase the average truckload of each collection trip and thereby avoid needing additional trips.

Based on the results listed in Table 5, alternative VF-3.5 T reduces the transportation risk by 31.1% compared with alternative FF-3.5 T. The collection frequency of alternative FF-3.5 T is set to be three times per year. As listed in Table 5, for regions with low HCW quantities, e.g. Yilan, Taitung, and Hualien, excessive trips are required causing more transportation risk for alternative FF-3.5 T than for alternative VF-3.5 T, as is also the case with FF-2 T vs. VF-2 T. The storage risks for regions with low quantities, e.g. Taoyuan, Taichung, Chianhua, Tainan, and Kaoshiung, are about 1.5% slightly higher than those for VF-3.5 T. For alternatives FF-2 T and FF-3.5 T, the regions with high HCW quantities have high storage risks because collection frequencies are not high enough to collect all their HCWs. The collection cost of VF-2 T is 15.4% less than that for FF-2 T. For the regions with low HCW quantities, alternatives FF-2 T and FF-3.5 T collect HCW too often, so the truckload per trip is not fully utilized and the collection cost is thus too high. Alternatives VF-2 T and VF-3.5 T are superior to alternatives FF-2 T and FF-3.5 T.

4.2. Alternatives with different truckloads

Based on the maximum number of campuses a truck/trip can collect in each region, as listed in both Tables 4 and 5, the collection frequency for 2-ton and 3.5-ton collection trucks are determined. The clustering results for alternatives VF-2 T and VF-3.5 T are illustrated in Fig. 2(b) and (c), respectively. Tables 4 and 5 compare the results of alternatives VF-2 T and VF-3.5 T. Lower collection frequency is required for trucks that can carry much more load, especially for regions with low HCW, e.g. Taitung, as it needs only one trip to collect all HCW each year. In average, the associated transportation risk decreases about 42%, but its associated storage risk is significantly increased by about 62% because the storage risks become much higher for these regions if they are collected only once or twice per year. The total collection cost for alternative VF-3.5 T is about 43% less than that for alternative VF-2 T. However, the treatment center requires continuous daily processing of HCWs, and thus collection with a 3.5-ton truck may be inappropriate because its collection frequency is low and insufficient to provide daily input to the treatment center.

Table 3
Maximum storage limits for campuses with different annual HCW quantities for both 2-ton and 3.5-ton alternatives.

(a) 2 ton								
Annual CHW range (ton)	0–0.5	0.5–1	1–1.5	1.5–2	2–2.5	2.5–3	3–3.5	3.5–30
Number of campuses	445	326	230	124	55	24	22	56
Maximal storage (ton)	0.25	0.5	0.75	1	1.25	1.5	1.75	2
(b) 3.5 ton								
Annual CHW range (ton)	0–1	1–2	2–3	3–4	4–6	6–30		
Number of campuses	771	354	79	26	10	42		
Maximum storage (ton)	0.5	1	1.5	2	3	3.5		

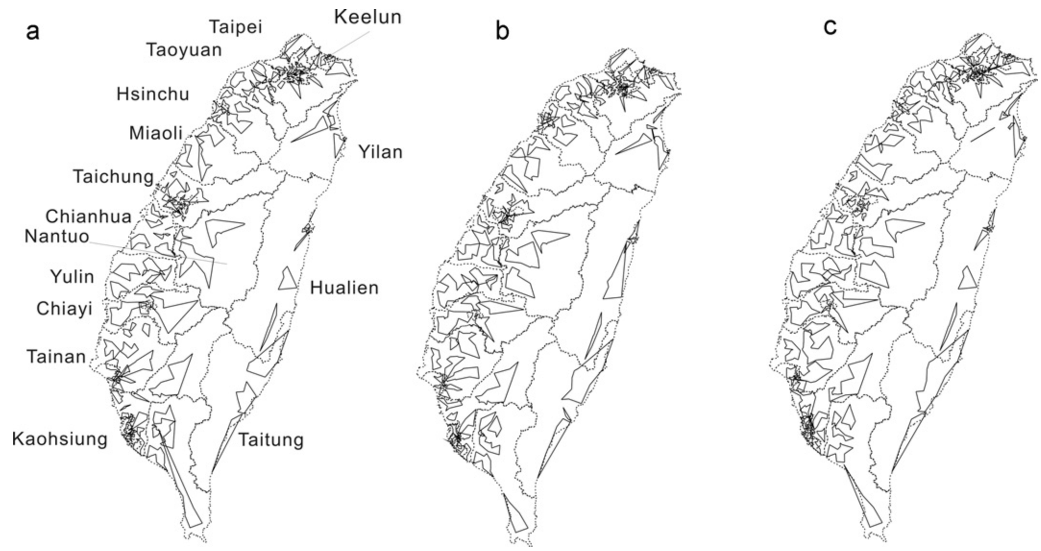

Fig. 2. Clustering results for alternatives (a) FF-2 T; (b) VF-2 T; and (c) VF-3.5 T.

4.3. Alternatives with different storage limits

For these alternatives, whenever the HCW storage of a campus reaches its limit, the HCW must be collected, and neighboring campuses whose HCW exceeding a specified minimum quantity are also collected, if possible. Table 6 compares the results for alternatives SL0.1–2 T to SL0.4–2 T vs. VF-2 T and SL0.1–3.5 T to SL0.6–3.5 T vs. VF-3.5 T. Among SL alternatives, the transportation risks for alternatives SL0.2–2 T and SL0.3–3.5 T, as illustrated in Fig. 3(a) and (b), are 10% and 34% less than those for SL0.4–2 T and SL0.6–3.5 T,

Table 4
Comparison between the results for FF-2 T and VF-2 T.

Region	Maximal number of campuses per collection trip	Annual collection frequency	Collection cost (NT$)	Transportation risk (number of incidents/million trucks-year)	Average storage risk (kg/campus)	Number of collection trips	Average truckload (ton)
FF-2 T							
Taipei	7	4	1,657,614	920	306	216	1.847
Yilan	5	4	270,451	261	171	28	855
Taoyuan	8	4	501,539	270	300	72	1.752
Hsinchu	9	4	344,881	181	198	56	1.687
Miaoli	10	4	88,829	48	163	16	1.900
Taichung	10	4	488,328	255	293	104	1.834
Chianhua	11	4	143,392	65	271	36	1.835
Nantou	11	4	56,054	36	131	12	1.964
Yunlin	12	4	79,538	32	203	24	1.658
Chiayi	12	4	80,979	30	167	28	1.741
Tainan	13	4	140,015	53	227	76	1.850
Kaohsiung	12	4	271,229	158	256	96	1.784
Pingtong	11	4	90,941	54	212	28	1.814
Taitung	6	4	133,971	234	86	20	531
Hualien	3	4	440,562	875	106	44	550
Keelun	7	4	194,514	105	230	24	1.688
Total			4,982,837	3575	241	880	1.683
VF-2 T							
Taipei	7	5	1,697,178	941	252	220	1.855
Yilan	5	3	144,942	140	342	15	1.996
Taoyuan	8	6	622,874	330	222	90	1.752
Hsinchu	9	4	344,788	181	198	56	1.687
Miaoli	10	4	88,096	47	218	16	1.836
Taichung	10	7	489,200	257	195	105	1.819
Chianhua	11	6	142,491	64	180	36	1.835
Nantou	11	3	54,181	32	174	12	1.875
Yunlin	12	5	66,364	26	162	20	1.989
Chiayi	12	5	73,818	28	164	25	1.950
Tainan	13	6	139,850	52	151	78	1.802
Kaohsiung	12	7	245,889	109	167	91	1.863
Pingtong	11	5	103,684	92	170	30	1.674
Taitung	6	2	35,325	56	343	6	1.771
Hualien	3	3	137,052	258	426	15	1.861
Keelun	7	4	194,514	105	230	24	1.676
Total			4,580,248	2719	225	839	1.828

Table 5
Comparison between the results for FF-3.5 T and VF-3.5 T.

Region	Maximal number of campuses per collection trip	Annual collection frequency	Total cost (NT$)	Transportation risk (number of incidents/million trucks-year)	Average storage risk (kg/campus)	Number of collection trips	Average truckload (ton)
FF-3.5 T							
Taipei	7	3	949,807	526	420	123	3.243
Yilan	5	3	152,957	148	228	15	1.597
Taoyuan	8	3	338,772	182	400	48	2.629
Hsinchu	9	3	185,859	98	264	30	3.148
Miaoli	10	3	74,352	42	218	12	2.447
Taichung	10	3	298,051	157	390	63	3.028
Chianhua	11	3	87,054	44	361	21	3.145
Nantou	11	3	41,244	28	174	9	2.618
Yunlin	12	3	39,565	16	271	12	3.344
Chiayi	12	3	43,101	16	273	15	3.250
Tainan	13	3	79,477	30	303	42	3.294
Kaohsiung	12	3	151,973	83	363	54	3.131
Pingtong	11	3	52,439	48	283	15	3.341
Taitung	6	3	101,209	178	114	12	857
Hualien	3	3	315,704	620	142	30	792
Keelun	7	3	168,212	90	218	21	1.915
Total			3,079,776	2305	326	522	2.909
VF-3.5 T							
Taipei	7	3	949,807	526	420	123	3.243
Yilan	5	2	97,301	94	342	10	2.395
Taoyuan	8	4	313,458	169	333	44	2.868
Hsinchu	9	3	185,859	98	264	30	3.148
Miaoli	10	2	56,203	30	326	10	3.039
Taichung	10	4	286,741	153	342	60	3.183
Chianhua	11	4	80,311	37	271	20	3.346
Nantou	11	2	36,146	21	262	8	2.945
Yunlin	12	3	39,565	16	271	12	3.344
Chiayi	12	3	43,101	16	273	15	3.250
Tainan	13	4	80,119	30	227	44	3.195
Kaohsiung	12	4	149,202	82	291	52	3.251
Pingtong	11	3	52,439	48	283	15	3.341
Taitung	6	1	21,928	41	343	3	3.429
Hualien	3	2	85,339	157	297	10	2.419
Keelun	7	2	129,163	69	327	16	2.517
Total			2,606,682	1587	321	472	3.139

respectively. When the minimum quantity is set too high, neighboring campuses not reaching the quantity will not be collected, wasting the load capacity of some collection trips and requiring additional trips that increase the transportation risk subsequently.

As listed in Table 6, no significant difference for transportation risk is observed among alternatives SL0.1–2 T, SL0.2–2 T, and VF-2 T, although those of SL0.3–2 T and SL0.4–2 T are slightly higher. The transportation risks of all SLq-3.5 T alternatives are higher than that of VF-3.5 T. Other than SL0.5–3.5 T and SL0.6–3.5 T, the total collection distances of most SLq-2 T and SLq-3.5 T alternatives are shorter than those for VF-2 T and VF-3.5 T, respectively. However, the transportation risks of most SL alternatives are still higher than those for VF alternatives because they pass roads of higher transportation risks.

The storage risks of alternatives SL0.2–2 T and SL0.3–3.5 T are about 0.8% and 23% less than those of alternatives VF-2 T and VF-3.5 T, respectively. Since VF alternatives collect HCW under a fixed frequency without considering the amount of HCW being stored, their storage risks are thus higher than those for SL alternatives.

Table 6
Comparison of SL and VF alternatives.

Scenario	Collection cost (NTD/year)	Transportation risk (number of incidents/million truck-years)	Average storage risk (kg/campus)	Total collection distance (km/year)	Number of collection trips (trip/year)	Average collection distance per trip (km/truck)	Average truck load (ton/truck)
SL0.1–2 T	4,223,061	2750	306	301,528	760	397	1.941
SL0.2–2 T	4,211,208	2708	223	300,207	757	397	1.901
SL0.3–2 T	4,509,096	3058	262	318,100	800	398	1.838
SL0.4–2 T	4,546,809	3097	283	320,144	804	398	1.829
VF-2 T	4,580,248	2719	225	343,215	880	390	1.828
SL0.1–3.5 T	2,566,599	1734	268	182,060	452	403	3.301
SL0.2–3.5 T	2,492,793	1651	249	176,952	442	400	3.365
SL0.3–3.5 T	2,462,818	1606	245	174,643	438	399	3.389
SL0.4–3.5 T	2,501,513	1632	247	176,742	442	400	3.337
SL0.5–3.5 T	3,465,705	2433	280	237,352	629	377	2.405
SL0.6–3.5 T	3,471,159	2437	274	237,434	632	376	2.389
VF–3.5 T	2,606,682	1587	321	192,275	484	397	3.146

Table 7
Comparison of transportation and storage risks for establishing a transfer station at one of three different locations.

	Taoyuan		Miaoli		Taichuang	
	(1)	(2)	(1)	(2)	(1)	(2)
Transportation risk (number of incidents/million truck-years)	1516	867	1744	994	2001	1123
Average storage risk (kg/campus)	1046	1046	1462	1462	1657	1657

(1): Before establishing a transfer station. (2): After establishing a transfer station.

Table 8
Comparison of costs for establishing a transfer station at three different locations.

Location of the transfer station (regions to collect)	Annual cost (unit: NT$)		
	(1)	(2)	(3)
Taoyuan (Taipei, Yilan, Taoyuan, Keelun)	2,491,182	1,442,635	657,832
Miaoli (Taipei, Yilan, Taoyuan, Hsinchu, Miaoli, Keelun)	2,926,035	2,070,875	464,445
Taichung (Taipei, Yilan, Taoyuan, Hsinchu, Miaoli, Keelun)	3,420,911	2,908,135	122,061

(1): The annual collection cost before a transfer station is established for the collected regions. (2): The annual collection cost after a transfer station is established for the collected regions. (3) = (1) – (2) – OC – AC, where OC (=NT$ 308,600) is the annual cost for operating a transfer station, and AC (=NT$ 82,115) is the annual cost, in 20 years and 5% discount rate, of the initial fixed cost for establishing a transfer station.

Between SLq-2 T and SLq-3.5 T alternatives, the collection costs of SL0.2–2 T and SL0.3–3.5 T are the lowest because the specified minimum quantities are appropriate and can effectively reduce the number of collection trips. By comparing the obtained results, the collection costs of SL0.2–2 T and SL0.3–3.5 T are 8.1% and 5.5% lower than VF-2 T and VF-3.5 T, respectively. With a pre-specified minimum quantity for collecting neighboring campuses, the campuses with low HCW quantities are collected not so often as for alternatives with a fixed collection frequency. For alternatives with a fixed collection frequency, all campuses must be collected at the fixed frequency regardless of their amounts, and subsequently some inefficient collection clusters with campuses having low HCW amounts might be formed. An appropriate pre-specified minimum quantity can avoid this problem and reduce the associated cost.

4.4. *Evaluating establishing a transfer station*

Three alternatives, based on alternative VF-2 T, for establishing an additional transfer station are also evaluated. In these alternatives, 2-ton trucks are used to collect HCWs and 10-tons trucks are used to transfer HCWs to the treatment center. The efficiency of each transfer-station alternative is evaluated based on the risk involved and cost reduced. Since the treatment center is located in the south of Taiwan, there is no cost incentive for the authorities concerned to build a transfer station in the south regions. Therefore, each of the three possible places located in the north regions of Taoyuan, Miaoli, and Taichung, is assessed for the feasibility to build a transfer station therein.

As listed in Table 7 and compared with the result for alternative VF-2 T, the transportation risk for a transfer station being installed at each of the three locations is reduced by 57%, 57%, and 56%, respectively. The transportation risk is significantly reduced because a 10-ton truck can load five times quantity than that for a 2-ton truck and thus the number of collection trips to the treatment center is significantly reduced. The storage risk is almost the same as that for alternative VF-2 T because the HCW average storage quantity remains the same for the transfer-station alternatives.

The collection costs of the transfer-station alternatives, as listed in Table 8, are reduced by NT$ 657,832 (26%), NT$ 464,445 (16%), and NT$ 122,061 (4%), respectively. The cost reduction achieved by installing a transfer station in Taoyuan exceeds those of the other two places, because the HCW quantity of Taipei and other north regions is substantially high. Establishing a transfer station in Taoyuan is, therefore, a worthy alternative to consider.

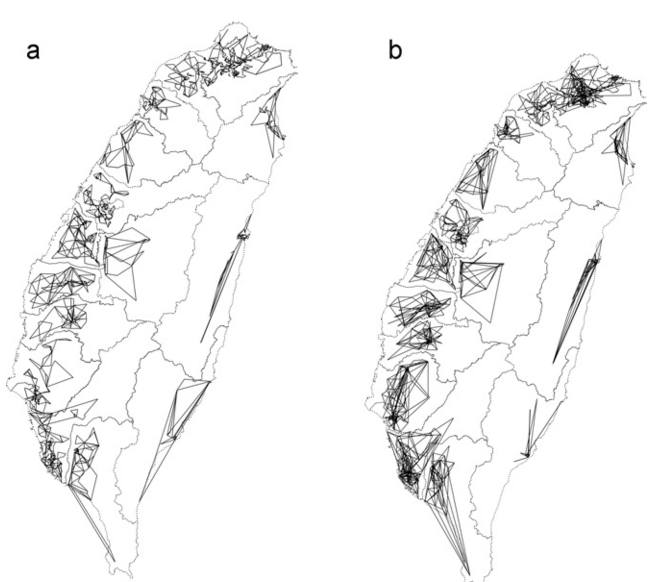

Fig. 3. Clustering results for alternatives (a) SL0.2–2 T and (b) SL0.3–3.5 T.

5. Conclusion

A procedure is proposed in this work for developing a HCW collection plan in Taiwan. The procedure utilizes clustering methods to simulate FF, VF, and SL alternatives and assess the alternatives based on three essential factors: transportation risk, storage risk, and collection cost.

The transportation risks for FF alternatives are about 23–31% higher than those for VF alternatives because the collection frequency is set too high for regions that have low HCW quantities and are far from the treatment center. On the other hand, for high quantity regions, the fixed collection frequency of a FF alternative is insufficient to collect all of their HCWs, and a significant amount of HCW will still be stored on their sites which subsequently causes high storage risk. The total collection costs for FF alternatives are higher than those for VF alternatives because the total collection distance for regions with low HCW quantities is long.

Different truckloads are also analyzed for this HCW collection problem. When compared to alternative VF-2 T, the result of alternative VF-3.5 T shows the transportation risk is reduced by 42%, the total collection cost by 43%, while the storage risk is increased by

62.1%. The alternative using large trucks can significantly reduce the number of trips and thus lower the transportation risk and collection cost, but it causes the accumulation of HCW that worsens the storage risk. By contrast, using small trucks may be in a better position to assure campus safety if the storage risk, increased by using large trucks, is unacceptable.

For alternatives with different minimum quantities to allow neighboring campuses to be collected simultaneously, an appropriate quantity should be pre-determined. If the quantity is set too low, low quantity neighboring campuses will be collected too often as to become cost inefficient. If it is set too high, neighboring campuses without reaching the quantity will not be collected, cause some collection trips not as fully loaded as possible, which is cost inefficient, too. For the case studied, the quantity set to be 0.2 ton for SLq-2 T or 0.3 ton for SLq-3.5 T is appropriate. The collection costs decrease because the numbers of collection trips are significantly reduced for regions with small HCW quantities. SL0.2–2 T is a good alternative to consider since its collection cost is lower than that for VF-2 T and has slightly smaller transportation and storage risks. The SL0.3–3.5 T alternative is also worthy of consideration because its storage risk and collection cost are both lower than VF-3.5 T, although its transportation risk is slightly higher.

Moreover, adding a transfer station may improve the HCW collection plan. This work thus evaluates three transfer station alternatives based on their risks and cost reductions, while comparing them with the VF-2 T alternative. The alternatives reduce more than half of the transportation risks for the regions collected by the transfer station, because the alternatives significantly reduce the number of collection trips to the treatment center. Due to the large HCW quantity in Taipei and other north regions, the alternative of having a transfer station in Taoyuan achieves highest cost reduction by 26% and is regarded as a worthy alternative to consider.

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