A GREEDY HEURISTICS MULTIPLE CRITERIA MODEL FOR SOLVING MULTI-LANDFILL SITE SELECTION AND PLANT PROPAGATION ALGORITHM FOR IMPROVING WASTE COLLECTION VEHICLE ROUTING SOLUTIONS

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Abstract

This research focuses on two solid waste management (SWM) problems, particularly the landfill site selection problem (LSSP) and the waste collection vehicle routing problem (WCVRP). Solving LSSP involves the evaluation of multiple criteria to determine the best landfill location. Whereas WCVRP involves, the construction of vehicle routes for collecting waste from customers and discharging their loads at the landfills with the minimum total distance travelled. However, there are two main issues with the existing LSSP and WCVRP models. First, previous models focused only on a single landfill site based on the highest score without considering the operational costs criterion in solving LSSP. Second, the Plant Propagation Algorithm (PPA) has never been considered to solve WCVRP. Thus, this research proposes a greedy heuristics multiple criteria model which includes operational costs for solving multi-LSSP and develops PPA for improving WCVRP solutions. First, the importance levels of LSSP criteria including the operational cost criterion were determined by using a modified analytical hierarchy process. Then, a multiple criteria greedy heuristic model was proposed to construct WCVRP solutions and to find a new landfill site(s) with the minimum total operational costs. Moreover, the WCVRP solutions were improved by using PPA. Both models were tested on a WCVRP benchmark problem and a case-based scenario in Kubang Pasu, Kedah. Five candidate landfill sites were considered. The results revealed that a single landfill site (Candidate 4) was the best solution for the case-based scenario, with a 6.74% reduction in total distance travelled. As for multiple landfills, Candidates 3 and 4 were the best alternative sites. Nonetheless, different study areas generated different outputs based on the area's geographical conditions. The WCVRP solutions using PPA are comparable with other best-known solutions on the benchmark problem in terms of total distance travelled and the number of vehicles used. The proposed models were cost-effective and may facilitate the SWM authorities in identifying suitable locations for new landfill site(s) and waste vehicle routes.

Keywords: Multi-landfill site selection, Waste collection problem, Modified analytical hierarchy process, Greedy heuristics, Plant Propagation Algorithm

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List of Abbreviations

ACO	Ant Colony Optimization
AHP	Analytic Hierarchy Process
ALNS	Adaptive Large Neighborhood Search
ANP	Analytic Network Process
ARP	Arc Routing Problem
BKS	Best Known Solution
DFA	Discrete Firefly Algorithm
GA	Genetic Algorithm
GIS	Geographic Information Systems
F-TOPSIS	Fuzzy Technique For Order Of Preference By Similarity To Ideal Solution
HSA	Harmony Search Algorithm
IoT	Internet of Things
LSSP	Landfill Site Selection Problem
M-AHP	Modified Analytic Hierarchy Process
MCDM	Multi Criteria Decision Making
MHLG	Ministry of Housing and Local Government
MSW	Municipal Solid Waste
NRP	Node Routing Problem
NSWMD	National Solid Waste Management Department
OWA	Ordered Weighted Average
PPA	Plant Propagation Algorithm
PSO	Particle Swarm Optimization
RIC	Random Initial Customer
RS	Remote Sensing
RSW	Ratio Scale Weighting
SA	Simulated Annealing
SAW	Simple Additive Weighting
SRS	Straight Rank Sum
SWCorp	Solid Waste and Public Cleansing Management

SWM	Solid Waste Management
TOPSIS	Technique For Order Of Preference By Similarity To Ideal Solution
TS	Tabu Search
TSP	Traveling salesman problem
VNS	Variable Neighborhood Search
VNTS	Variable Neighborhood Tabu Search
VRP	Vehicle Routing Problem
WCVRP	Waste Collection Vehicle Routing Problem
WCVRPTW	Waste Collection Vehicle Routing Problem with Time Windows
WLC	Weighted Linear Combination

List of Publications

Mat, N. A., Benjamin, A. M., & Abdul-Rahman, S. (2020). A Multi-landfill Site Selection Model for an Effective Solid Waste Management using Greedy Heuristic: A Case Study. *ASM Science Journal, 13,* 1-7.

Mat, N. A., Benjamin, A. M., & Abdul-Rahman, S. (2020). Nearest greedy algorithm for solving a single landfill site selection with resource requirements. *Journal of Sustainability Science and Management, 15*(5), 127-139.

Mat, N. A., Benjamin, A. M., & Abdul-Rahman, S. (2018). Efficiency of heuristic algorithms in solving waste collection vehicle routing problem: a case study. *The Journal of Social Sciences Research,* (SPI6), 695-700.

Mat, N. A., Benjamin, A. M., & Abdul-Rahman, S. (2018). Enhanced heuristic algorithms with a vehicle travel speed model for time-dependent vehicle routing: A waste collection problem. *Journal of Information and Communication Technology, 17*(1), 55-78.

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Mat, N. A., Benjamin, A. M., Abdul-Rahman, S., & Wibowo, A. (2017, November). Nearest greedy for solving the waste collection vehicle routing problem: A case study. In *AIP Conference Proceedings* (Vol. 1905, No. 1, p. 040018). AIP Publishing LLC.

Mat, N. A., Benjamin, A. M., Abdul-Rahman, S., & Wibowo, A. (2016, October). A framework for landfill site selection using geographic information systems and multi criteria decision making technique. In *AIP conference proceedings* (Vol. 1782, No. 1, p. 040011). AIP Publishing LLC.

CHAPTER ONE
INTRODUCTION

1.1 Research Background

Solid waste refers to a range of terms, including refuse, rubbish, litter, and street sweeping. It is generated by living organisms' activities which are often solid and discarded as worthless or undesirable by the individual or organization that generates the waste (The Open University, 2022). Solid waste may be divided into several types based on its origin, hazardous, agricultural, industrial, and industrial waste (Aziz & Amr, 2016). This research looked into municipal solid waste (MSW).

MSW is comprised of wastes gathered from residences, offices, small-scale institutions, and commercial organizations. The composition and classification of MSW vary greatly between localities all across the world. Kitchen waste, yard waste, paper and cardboard, plastic and rubber, metal, glass, electronic waste, and inert materials are the most common types of MSW (Nanda & Berruti, 2021).

In Malaysia, an enormous amount of MSW has been reported in around 33,000 tons per day, which corresponds to 1.17 kg/person per day (Lacovidou & Ng, 2020). To mitigate the harmful effects of MSW on both humans and the environment, the government and emerging research activities have taken the initiative to devise strategic and effective solutions (Soltani et al., 2015).

This is the reason why solid waste management (SWM) has become a major concern in most countries at this present time. The SWM refers to a service offered by the government to residents of a country to handle generated residual waste. As each country races towards becoming a developed country in the future, the growing amount of solid waste released into the environment has turned into one of the most pressing concerns that the government must handle. This rise is the result of the rapid population, expanding urbanization, and rapid economic progress, thus resulting in changes in the living standards or lifestyles of most citizens. Therefore, SWM requires extra care to yield a healthy atmosphere.

According to Lacovidou and Ng (2020), data on the SWM process are in scarcity, inclusive of all forms of waste generation and collection, as well as waste transportation, treatment, and disposal. These shortcomings are a huge concern amidst the growing community. Therefore, an efficient SWM must be prioritized. This emphasizes the need for developing effective SWM strategies that create a healthy atmosphere.

The SWM encompasses all activities connected to the management of waste disposed of by society, from generation to final disposal. In fact, SWM activities are divided into six operational components: (1) waste generation, (2) waste handling, separation, storage, and processing at the source, (3) waste collection, (4) waste transfer and transport, (5) waste separation, processing, and transformation, as well as (6) disposal (Tchobanoglous et al., 1993). The interdependence of the components is demonstrated in Figure 1.1.

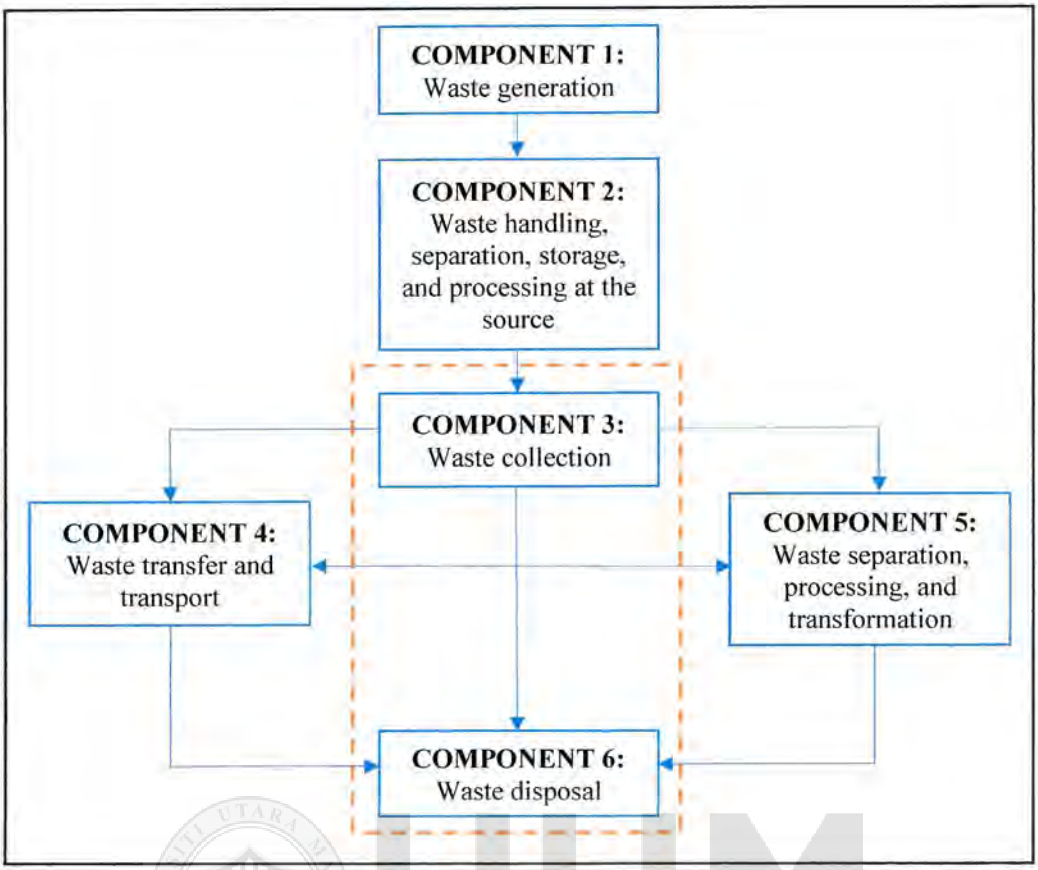

Figure 1.1. The functional components of SWM

Referring to Figure 1.1, any procedure involving the discovery of items that is not usable or gathered for systematic disposal is called waste generation (Component 1). Waste handling, separation, storage, and processing at the source (Component 2) refers to procedures that take place at the point of waste generation to enable the collection process. For example, trash bins are placed in areas where a considerable volume of waste accumulates.

Waste collection (Component 3) requires important tasks, including installing waste bins, accumulating waste out of those bins, and disposing of the collected waste at landfill sites. The collection vehicle needs to be emptied before returning to the depot after completing the collection task. Waste transfer and transport (Component 4) denotes the processes involved in transporting waste from local waste collection points to provincial waste disposal facilities in large waste transport vehicles.

Waste separation, processing, and transformation (Component 5) refer to the facilities, instruments, and processes used to recover recyclable or reusable materials from solid wastes to improves the performance of other SWM functional aspects. The final stage of waste management is waste disposal (Component 6). Here, waste is disposed of using appropriate methods, such as landfills or energy waste plants.

This research focused on components 3 and 6, which are waste collection and disposal, respectively. As for Component 6, this research omitted the methods to dispose of waste. Instead, it looked into landfills, particularly finding the best location to open new landfills. Both components are discussed in the following two sub-sections.

1.1.1 Waste Collection Vehicle Routing Problem (WCVRP)

Waste collection refers to the collection and transportation of waste by municipal services or similar institutions, public or private corporations, specialized enterprises, or the general government. MSW collection can be selective, that is, for a specific type of product, or undifferentiated, that is, for all types of waste at the same time (Glossary of Environment Statistics, 2001).

The primary goal of waste collection is to collect waste from the right source as much as possible, timely, and economically. This is to facilitate the subsequent level of decomposition or treatment of waste with the aim of maximizing reuse and recycling.

Waste management authorities develop and implement waste collection plans based on collecting zone characteristics (such as population density and building types) and public acceptance of various collection methods. They must also assess the appropriate number of separately collected waste fractions for their situation, the goals set in the local waste management strategy and by national legislation, the environmental attitudes and perceptions of the residents, and, where applicable, seasonal changes (European Commission, 2021).

The problem of solid waste collection is addressed by private companies appointed by the government to manage and dispose of solid waste in a specific region. Solid waste collection is a collection activity that must be completed on time from various collection points to landfill facilities. This problem is described as a waste collection vehicle routing problem (WCVRP) (Beliën et al., 2014; Molina et al., 2019).

Previously, solid waste was collected without weighing in any demand or route planning, but it was simply turned over to drivers. Due to the expanding population and urbanization, a cost-effective waste collection system is in need. Therefore, many researchers are currently finding a solution to this issue (Molina et al., 2019).

The WCVRP involves routing vehicles that start from a depot, which later collects waste from customers, and the vehicles must discharge their loads at the target landfill sites. Upon returning to the depot, these vehicles must be empty. Vehicles are permitted to make multiple trips to landfill sites. Figure 1.2 presents the situation for the WCVRP involving multiple vehicles and landfill sites.

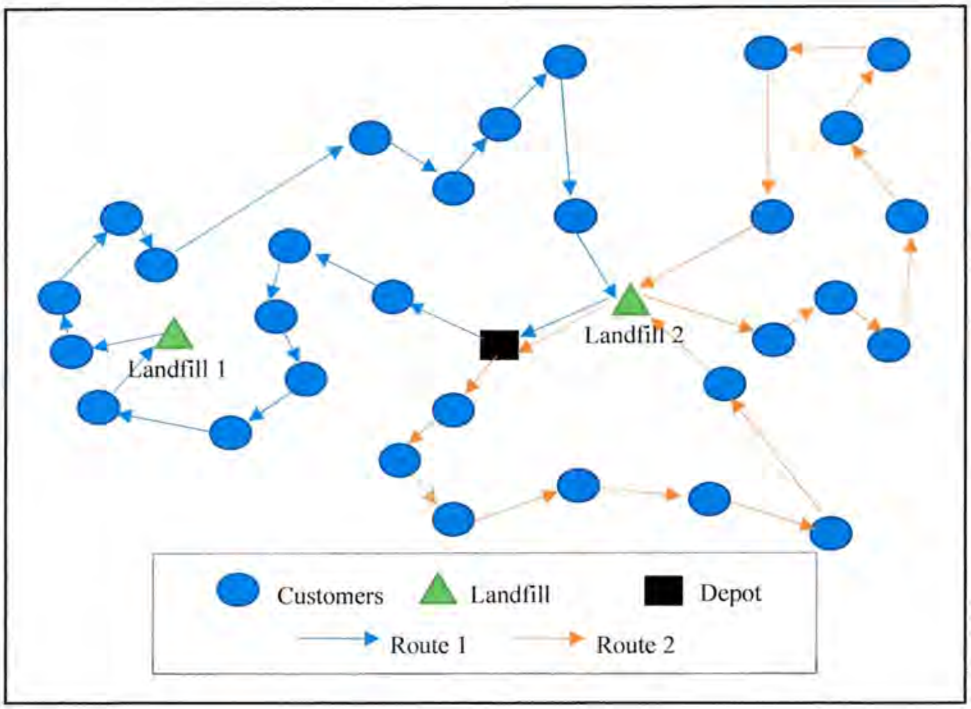

Figure 1.2. A route sequence of multiple vehicles with multiple trips to landfill sites

Figure 1.2 depicts a WCVRP flow that includes a single depot, thirty customers, and two landfill sites. All vehicle leaves the depot with an empty load. Customers' waste must be collected. When the vehicles are full during collection, they must be emptied at one of the landfills before being used to accumulate waste from other remaining customers. Multiple visits to landfills may be required to complete collection before returning empty vehicles to depot.

Most of the studies on WCVRP have attempted to tackle real-life problems across various countries, including China (Zhang et al., 2020), the Czech Republic (Achamu & Berhan, 2021), Ethiopia (Achamu & Berhan, 2021), Indonesia (Nurprihatin & Lestari, 2020; Yuliza et al., 2021), Iran (Babaee Tirkolaee et al., 2019), Malaysia (Mat et al., 2018), Serbia (Stanković et al., 2020), and Spain (Molina et al., 2019; Rodriguez et al., 2021).

Heuristic techniques have been widely used in WCVRP research. The two types of heuristic techniques are constructive heuristics and iterative improvement heuristics. Constructive heuristics is a step-by-step process used to develop initial solutions to a problem until a complete result is achieved. Instances of constructive heuristic algorithms often used to solve WCVRP are clustering algorithm (Hurkmans et al., 2021; Liu & Liao, 2021; Sackmann et al., 2017), savings algorithm (Achamu & Berhan, 2021; Liu & Liao, 2021; Marković et al., 2019; Sackmann et al., 2017), parallel algorithms (Molina et al., 2019), nearest neighbor algorithm (Nurprihatin & Lestari, 2020; Yuliza et al., 2021), cheapest insertion algorithm (Yuliza et al., 2021), and greedy algorithm (Benjamin & Beasley, 2010; Buhrkal et al., 2012; Campos & Arroyo, 2017).

Meanwhile, an iterative improvement heuristic algorithm is a strategy to improve the initial solution. Metaheuristics are another name for the iterative improvement heuristic. Examples of metaheuristic algorithms often used to solve WCVRP are local search (Nevrlý et al., 2019), simulated annealing (SA) (Babaee Tirkolaee et al., 2019; Stanković et al., 2020; Wu et al., 2020; Zhang et al., 2020), variable neighborhood tabu search (VNTS) (Molina et al., 2019), harmony search algorithm (HSA) (Marković et al., 2019), genetic algorithm (GA) (Aliahmadi et al., 2020; Stanković et al., 2020; Yuliza et al., 2021), particle swarm optimization (PSO) (Qiao et al., 2020; Stanković et al., 2020; Wu et al., 2020), ant colony optimization (ACO) (Stanković et al., 2020), tabu search (TS) (Qiao et al., 2020), and adaptive large neighbourhood search (ALNS) (Hurkmans et al., 2021; Liu & Liao, 2021).

1.1.2 Landfill Site Selection Problem

In many municipalities worldwide, landfilling is the most preferred method for solid waste disposal (Nanda & Berruti, 2021). The selection of suitable landfill sites is one of the most critical issues in SWM. (Ali & Ahmad, 2020). The landfill site selection problem (LSSP) is a time-consuming and complex task that requires the evaluation of many elements with numerous features (Nazari et al., 2012).

The best disposal location must be chosen carefully when establishing a landfill that fulfills regulations while minimizing costs to the economy, the environment, human health, and society (Siddiqui et al., 1996). The most efficient way to reduce waste is to implement a recycling program and build a new landfill due to the growing amount of waste that cannot be treated, the limited amount of landfill space, and the impossibility of expanding the current landfill (Chang et al., 2008).

Although there are areas suitable or environment-friendly that can be proposed as landfill sites, it is impossible to be built if there is resistance from the public around that area. In other words, this is known as public opposition issue. Among those issues are: Not In My Backyard (Al-Anbari et al., 2018; Aragonés-Beltrán et al., 2010; Bahrani et al., 2016; Chang et al., 2008; Colebrook & Sicilia, 2007; Nas et al., 2010; Vasiljević et al., 2012), Not In Anyone's Backyard (Aragonés-Beltrán et al., 2010; Bahrani et al., 2016; Chang et al., 2008; Colebrook & Sicilia, 2007; Nas et al., 2010;

Vasiljević et al., 2012), Not In My Neighbor's Backyard (Aragonés-Beltrán et al., 2010; Colebrook & Sicilia, 2007), Built Absolutely Nothing Anywhere Near Anyone (Al-Anbari et al., 2018; Aragonés-Beltrán et al., 2010; Colebrook & Sicilia, 2007), Not On Planet Earth (Al-Anbari et al., 2018; Colebrook & Sicilia, 2007), and Locally Unwanted Land Use (Colebrook & Sicilia, 2007). All these issues have pressured decision-makers to make critical decisions for the LSSP process.

In Malaysia, the National Solid Waste Management Department (NSWMD) is responsible for selecting landfill sites. The Solid Waste and Public Cleansing Management Corporation (SWCorp) completes the project after selecting a location. The NSWMD is responsible for planning the locating process, which must be in compliance with the requirements.

In Malaysia, landfill candidate locations are assessed using Geographic Information Systems (GIS). It is a technique for accelerating the site selection process by eliminating undesirable locations according to a set of criteria. To minimize environmental hazards, a guideline entitled "Technical Guidelines for Sanitary Landfill, Design, and Operation" was created to select a landfill site. Resource planning is a useful tool for landfill management because it can help decision-makers weigh the possibility of reducing resource utilization when choosing new landfills for lengthy usage periods.

In LSSP, the selection criteria for each investigation tend to differ, which is based on the physical condition of the research area (Bahrani et al., 2016). It is possible to think of choosing a new landfill location as a Multiple Criteria Decision Making (MCDM) process. There are many factors to take into account and evaluate in order to choose a suitable location from among several potential candidate sites (Melo et al., 2006). The selection criteria can be found in the form of quantitative or qualitative based on the structure of the data obtained.

The LSSP has extensively studied in the literature and taken into account a variety of criteria, including road accessibility, slope, land use, protected areas, groundwater, geology, surface water, airport, railways, residential areas, land cost, landfill lifespan, and public acceptance should also be considered in the landfill siting. Most previous studies have classified these selection criteria into several groups based on their perspectives. For example, Karimi et al. (2019) categorized the criteria as environmental, technical, and economical. They applied the analytical hierarchy process (AHP)-based pairwise comparison to calculate the importance weights of the criteria. Meanwhile, Mora and Peláez (2020) grouped the criteria as technical, environmental, social, and economic. They also applied the AHP to rank the criteria based on the importance weight. However, most of the previous studies have categorized these selection criteria into three groups, which are environmental, economical, and social criteria (Kahraman et al., 2018; Rahimi et al., 2020; Rahmat et al., 2017), as proposed in this research as well. Other MCDM methods such as Fuzzy MULTIMOORA was used to rank the LSSP criteria (Rahimi et al., 2020). The criteria listed in the literature are discussed in the next chapter.

Generally, there are some thoughts from prior studies regarding the site selection process of a new landfill, and one of them claimed that the LSSP is composed of a two-stage process: (1) discovery of potential candidate sites via an initial screening procedure and (2) detailed inspection of landfill suitability in relation to the criteria (Chang et al., 2008; Charnpratheep et al., 1997). Meanwhile, Nazari et al. (2012) presented the LSSP process in four stages: (1) determination of potential candidate locations through preliminary screening based on exclusionary criteria, (2) additional evaluation of potential locations in accordance with evaluation criteria, the candidate sites ranked, and suitable sites are selected based on the final score, (3) site investigation based on environmental impact assessment, subsurface exploration, and cost/benefit analysis, and lastly, (4) the final decision.

The GIS is suitable for preliminary site screening studies because it can effectively retrieve, analyze, and display information as well as manage and store large amounts of spatially distributed data from a variety of sources (Asefa & Mindahun, 2019; Rahman et al., 2008). In the literature, GIS has been widely utilized for various applications, including LSSP. Numerous studies have used GIS either as a standalone tool (Adeli & Khorshiddoust, 2011; Arkoc, 2014; Delgado et al., 2008; Hafezi Moghaddas & Hajizadeh Namaghi, 2011; Yildirim, 2012) or in collaboration with other approaches such as remote sensing (RS) (Abd-El Monsef & Smith, 2019; Alexakis & Sarris, 2014; Mallick, 2021; Paul et al., 2014; Şener et al., 2011) to solve LSSP.

In conjunction with the evolution of GIS technology, which began in the 1950s, MCDM emerged as a decision-making tool that aids in the analysis and resolution of decision problems involving many varieties of conflict criteria. The MCDM approaches may also help decision-makers rank a group of alternatives or make a choice among those alternatives (Sumathi et al., 2008).

Among the MCDM methods that have been widely used in solving LSSP are AHP (Ali et al., 2021; Alkaradaghi et al., 2019; Barzehkar et al., 2019; Sisay et al., 2021; Zarin et al., 2021), Fuzzy AHP (Ali & Ahmad, 2020; Karasan et al., 2018; Karimi et al., 2019; Mallick, 2021; Pasalari et al., 2019), Fuzzy Technique For Order Of Preference By Similarity To Ideal Solution (F-TOPSIS) (Ali et al., 2021), weighted linear combination (WLC) (Karimi et al., 2019), Fuzzy WLC (Barzehkar et al., 2019; Zarin et al., 2021), Fuzzy MULTIMOORA (Rahimi et al., 2020), and simple additive weighting (SAW) (Alkaradaghi et al., 2019). These past studies used MCDM methods to analyse the importance of each criterion considered in the problem and finally ranked the alternatives to choose the best solution for the LSSP. Thus, in this research, the widely used approach, the AHP, is utilized to determine the level of importance of the LSSP criteria in Malaysia.

1.1.3 Resources related to SWM

To effectively manage solid waste, using available resources is essential and should not be neglected. Efficient planning to utilize resources may reduce the total operational costs involved in providing SWM services. These resources include the number of vehicles or drivers (Stanković et al., 2020; Zhang et al., 2020), total travel distance (Nurprihatin & Lestari, 2020; Yuliza et al., 2021), total travel time (Aliahmadi et al., 2020; Hurkmans et al., 2021), fuel consumption (Hashim et al., 2019; Qiao et al., 2020), and total working hours (Marković et al., 2019).

In the perspective of waste collection routing, vehicles utilized during the collection process are viewed as resources. Using a single vehicle to collect waste across the research area, for example, is insufficient. Using multiple vehicles is a reasonable solution that can lighten an employee's load. Depending on the number of vehicles assigned to the collection process, a reasonable choice might be reached by developing a vehicle routing schedule. (Beliën et al., 2014).

Next, travel distance reduction does offer numerous benefits, including reduced collection time, cost, and air pollution emission (Malakahmad et al., 2014). Sulemana et al. (2018) discovered that route optimization might minimize operating costs in terms of travel distance, travel time, and fuel consumption.

As a result, it is crucial to finalize the resources that are available within a construction project because demands frequently exceed initial estimates, and it can be difficult to secure resource commitments, which could hinder project efforts (Reel, 1999; Somers & Nelson, 2001). At the beginning of the LSSP and WCVRP, the resources needed (such as vehicles, drivers, and fuel) to facilitate the transport of customers' solid waste to landfills should be described and allocated equitably among the most appropriate landfills. As a result, customers can be served efficiently while incurring minimal operating costs. This should improve the current SWM system's effectiveness.

1.2 Problem Statement

Over the past century, solid waste disposal has increased primarily as a result of population growth and lifestyle changes (Rezaeisabzevar et al., 2020). Therefore, a holistic strategy is needed for coping with solid waste issues. SWM activities involve waste generation, waste processing and storage, waste collection, waste transfer and transportation, waste separation and transformation, and waste disposal (Tchobanoglous et al., 1993). Among these activities, the collection and disposal of solid waste are the most serious urban environmental issues in most countries. Therefore, SWM capabilities must be environmentally friendly, technically feasible, socially and legally acceptable, and financially viable (Abdel-Shafy et al., 2018).

Among the methods for managing and disposing of solid waste are open burning, sea dumping, incineration, and sanitary landfills. Landfill is ranked lowest when comparing waste management strategies based on waste reduction, land requirement, recycling, and reuse (Bosompem et al., 2016; Motlagh & Sayadi, 2015). However, landfill management is crucial because it is less expensive and simpler to operate than other methods (Osra & Kajjumba, 2020). This is also supported by Nanda and Berruti (2021) who stated that in many municipalities worldwide, landfilling is the most preferred technique for getting rid of solid waste.

The most crucial step in LSSP is the accurate detection of the priority and importance of each criterion as this is an extremely tough process (Sener & Sener, 2020). An integration of GIS and MCDM techniques has indeed been widely used to solve LSSP. However, this particular combined technique has two drawbacks.

The first issue is that, according to previous studies, there are three clusters of LSSP criteria (i.e., environmental, economical, & social). Among several criteria that are usually considered under economical clusters are landfill lifespan, land cost, job opportunity, construction costs, and building materials. This research proposes a new criterion in the economical cluster that has yet to be explored in previous studies, namely the operational cost associated with the resources used during waste collection services. Previous research has shown that resources such as (1) the total distance traveled to transport the collected waste to the landfill, (2) the number of vehicles/drivers needed for collection, (3) the total number of hours worked by drivers and (4) total fuel consumption can significantly affect total operating costs. For example, multiple-trip to landfill sites for unloading waste may affect the travel distance of the vehicles. Rationally, landfill sites that are far from residential areas or covered areas may contribute more travel distance when compared to the nearest landfill sites. However, how far the drivers need to travel to serve all customers, along with other required resources, is not provided to the management team. Therefore, this research believes that this criterion should be considered when selecting a new landfill site. The information on the required resources of each candidate landfill site may assist the management team in planning their resources effectively. Indirectly, the total operating costs of each candidate can be estimated.

As for the second issue, previous studies have mostly proposed a single landfill site based on the highest score (ranking). However, no study has considered the selection of multiple landfill sites. As such, this present study proposes a new approach to address multiple LSSP, which also benefits the authorities. If the current techniques, which are based on the scoring approach, are used to select multiple landfill sites, the selected sites could be a bad decision due to the overlap of covered areas (see Figure 1.3).

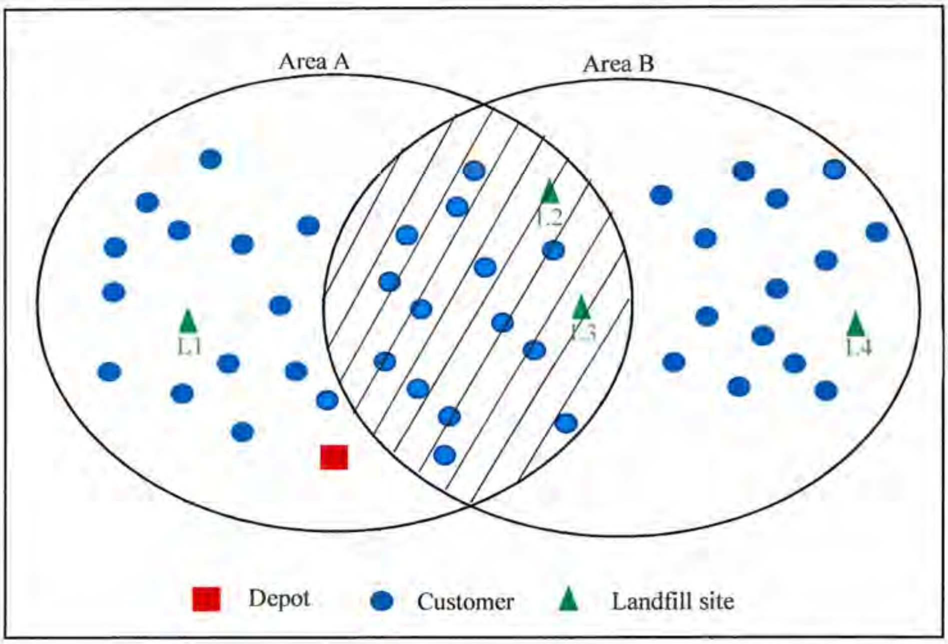

Figure 1.3. An example of overlapping covered areas

Figure 1.3 illustrates an example of the overlapping areas between areas A and B. In this example, if landfill sites L2 and L3 gain the highest ranking score, both landfills will cover customers in the same area. Based on the customers' locations and landfill sites shown in Figure 1.3, landfill sites L1 and L4 may produce the desired solution for multiple LSSP. In this research, a new strategy is used to address the issues raised.

The potential technique to tackle both issues is by applying the heuristic approach, such as the greedy heuristic algorithm, in the LSSP process. This algorithm can provide information on resource requirements for each candidate landfill site. This approach, however, has never been considered in previous studies (Donevska, Jovanovski, & Gligorova, 2021). The use of resources in selecting a new landfill is critical, particularly during the implementation process of a large project, when the organization can begin planning, arrange strategies, and make decisions to improve the existing systems.

In fact, there are many good algorithms and heuristics for optimization problems, such as WCVRP. The increasing complexity of these issues in practice demands newer and better algorithms. It should be noted that regularly occurring issues may justify the introduction of new algorithms with minor improvements. As it happens, many attempts at developing new algorithms draw inspiration from nature. The plant propagation algorithm (PPA) is an optimization problem inspired by nature. It mimics how plants, namely the strawberry plant, reproduce. Its popularity stems from its ease of use and the few parameters requiring unrestricted configuration (Sulaiman, Salhi, & Fraga, 2014).

The research focuses on evaluating PPA performance on larger and higher-dimension problems when solving WCVRP. This algorithm has been used successfully to solve a variety of optimization problems, including complex process and design issues (Salhi & Fraga, 2011), nonlinear and non-convex high dimensional optimization problems (Sulaiman et al., 2014), constrained engineering optimization problems (Sulaiman et al., 2014), unconstrained and constrained optimization problems (Sulaiman & Salhi, 2015), spring design optimization problems (Sulaiman et al., 2018), and traveling salesman problem (TSP) (Selamoğlu & Salhi, 2016).

Since PPA had been successfully solved routing problems such as TSP, it motivates this research to apply PPA in solving more complicated routing problems such as WCVRP (that has never been solved before by using PPA). In this research, the data size of the WCVRP involves up to 2100 nodes and the constraints of the depot, customers, vehicles, and landfills need to be satisfied in order to propose good feasible solutions.

In addition, the PPA is used in this research because of the unique development strategies called short and long runners. The short runner is applied to search for the best area by exploiting the local area if conditions are favorable. Whereas, the long runner is applied for exploring new and more remote areas if preferable. Both strategies are explained in detail in Chapter 3. Therefore, in this research, the quality of PPA with both strategies is evaluated in solving the WCVRP. The quality of PPA in terms of waste collection resource requirements is discussed in terms of total distance travelled, total fuel consumption, total travel time, number of vehicles needed and average working time per driver needed to complete the collection process. In conclusion, the greedy heuristic and the PPA algorithm developed in this research should aid the waste management team, SWCorp, NSWMD, and the Ministry of Housing and Local Government (MHLG) in achieving their sole mission of providing a cost-effective SWM system.

1.3 Research Questions

Based on the given problem statement, several disputes have arisen and are summarized as follows:

1. What are the criteria that must be considered in selecting new landfill sites in Malaysia?

2. How important is the total operational costs in the process of selecting new landfill sites?

3. How to propose multiple landfill sites for the waste management team?

4. Is PPA a suitable algorithm for solving WCVRP?

5. How efficient is PPA in solving WCVRP?

1.4 Research Objectives

The main objective of this research is to develop a greedy heuristic for multiple landfill site selection and to improve waste collection vehicle routing solutions by using PPA. To achieve the main objective, the following specific objectives must be fulfilled:

1. To identify the criteria that must be considered in selecting new landfill sites in Malaysia.

2. To determine the level of importance of landfill site selection criteria including the new criterion, operational cost by using Modified-AHP.

3. To propose multiple landfill sites with the minimum total operational costs by using a greedy heuristic.

4. To develop PPA for improving WCVRP solutions.

5. To evaluate the quality of WCVRP solutions by using the developed PPA in terms of total travel distance, number of vehicles/drivers required, total working hours

of drivers, and total fuel consumption using a case-based scenario and benchmark problem set by Kim et al. (2006).

1.5 Research Significances

The models proposed in this research should offer significance in the areas of decision science/operation research and the waste management industry.

1.5.1 Decision Science / Operation Research

1. A new model with resource-based analysis for the LSSP of an effective SWM system.

2. A new criterion for LSSP, which is a resource-based operational cost under economical cluster, is proposed. The analysis of four resources presented in this research are (1) the total travel distance to transport collected waste to the landfill, (2) the total number of vehicles or drivers needed for the collection, (3) the total working hours of each driver, and (4) total fuel consumption to serve all customers.

3. A new approach to propose multiple landfill sites for solving LSSP by using a greedy heuristic algorithm.

4. A metaheuristic algorithm, namely PPA, is developed and proposed to solve WCVRP. The discussion on the quality of solutions obtained from PPA may give some insights to other researchers within this research area.

1.5.2 Waste Management Industry

Three significances for the waste management industry are listed as follows:

1. The new model proposed in this research may help the waste management team, SWCorp, NSWMD, and MHLG to realize their vision, which is to provide an efficient and cost-effective SWM system.

2. The new criterion considered in the process of LSSP may help the management team to estimate the total operational costs so that available resources can be utilized effectively.

3. The new approach that can be used to propose multiple landfill sites may give alternative solutions to the management team if more than one landfill site is needed.

1.6 Research Scope

Three research scopes are listed as follows:

1. This research focused on Component 3 (waste collection) and Component 6 (waste disposal) of SWM activities. This is because; both components could consume 70-80% of operational costs (Achamu & Berhan, 2021). Hence, even a minor enhancement in these components can greatly reduce operational costs.

2. The greedy heuristic and PPA employed in this research were applied in C++ on an Intel® Core ™ i7-8550U CPU @ 1.99 GHz with 8.00 GB memory. However,

different languages used will have different solutions in terms of total computational time.

3. Both algorithms were tested using Kim et al. (2006) WCVRP benchmark problem and a case-based scenario in the Kubang Pasu district. Kubang Pasu is one of the districts located in the northern part of the state of Kedah. The data for this case-based scenario was gathered in 2015.

1.7 Research Organization

Chapter One starts with an overview of SWM, the two components of SWM highlighted in this research (i.e., WCVRP and LSSP), followed by resources related to SWM. Next, the problem statement, research questions, objectives, research contributions in terms of decision science and waste management industry perspectives, as well as the scope of this research are presented.

Chapter Two provides a review of the LSSP and WCVRP. As for LSSP, the criteria and solutions used in the literature to solve LSSP are reviewed. There is also a description and justification for using Modified AHP to weigh in the LSSP criteria. Meanwhile, for WCVRP, the mathematical model, objectives, constraints, techniques, and applications of PPA in previous studies are reviewed. Finally, the description and justification for using the PPA to address the WCVRP are provided.

Chapter Three describes the methodology used to achieve the objectives related to the LSSP. This research is composed of four phases of research flow; problem identification, data collection, model development, and implementation, as well as data analysis. Two sets of data are used to test the algorithm, referring to the WCVRP benchmark problem proposed by Kim et al. (2006) and case-based scenario in Kubang Pasu, Kedah. The AHP was applied to weigh and rank the selection criteria. Next, the greedy heuristic algorithm was used to evaluate the potential landfill sites based on resource requirements.

Chapter Four illustrates the methodology used to achieve the objectives related to the WCVRP. Again, four phases of the research flow had been deployed; problem identification, data collection, model development, and implementation, as well as data analysis. The constructive heuristic algorithm, namely the random initial customer (RIC) based greedy algorithm, was used to generate several initial solutions. The initial solution was then improved by using PPA. Both algorithms were tested using the WCVRP benchmark problems introduced by Kim et al. (2006).

Chapter Five presents an overview of respondents' profiles, analysis of the identification criteria, ranking of the criteria using the Modified AHP technique, computational results for the LSSP model for the case-based scenario in Kubang Pasu, Kedah, and WCVRP benchmark problems, as well as computational results for WCVRP model for the WCVRP benchmark problems. Finally, this chapter compares the solutions to the WCVRP benchmark problems offered by Kim et al. (2006).

Chapter Six summarizes this research in general and examines some of the research limitations, assumptions, and contributions to the body of knowledge, practitioners, as well as policymakers. It also outlines some recommendations for future research endeavors.

CHAPTER TWO
LITERATURE REVIEW

2.1 Introduction

This chapter is broken down into three sections. The first section goes over the landfill site selection criteria and the techniques used to determine their importance. The second section discusses WCVRP as an arc routing and node routing problem, its objectives and constraints, and the techniques used for WCVRP. The third section goes over previous studies that used PPA to solve problems in other fields. This chapter concludes with a summary of research gaps identified through reviews of previous studies on LSSP and WCVRP.

2.2 Review of LSSP

This section begins with a discussion of the criteria used to select landfill sites. Then, it continues with the techniques used for determining the criteria' rank and screening the possible sites for new landfills. This section ends with the justification for using one of the MCDM approaches to weighing the criteria in addressing the LSSP as a preliminary step for this research.

2.2.1 Landfill Site Selection Criteria

The LSSP is a difficult task to complete because it is dependent on numerous factors and regulations. The LSSP's main goal is to guarantee that the landfill site is in the best possible location with the least amount of negative impact on the environment or the population.

A thorough evaluation process is required for landfill siting in order to identify the best available landfill location that meets government regulations while minimizing environmental, economic, health, and social costs. This procedure necessitates the evaluation of numerous criteria (Chang et al., 2008). When looking for a new landfill, these criteria must be considered. Each study's criteria differ and are influenced by the geographical conditions of the study area.

The research's criteria are divided into three clusters: environmental, economical, and social criteria. Evaluation methodologies or processes are designed to make the best use of available information while ensuring that the results are reproducible, allowing the outcomes to be verified and defended (Siddiqui et al., 1996).

Environmental Cluster

An environmental cluster must be undertaken because a landfill can impact the biophysical environment and ecosystem. This cluster is extensively used throughout GIS analysis. Table 2.1 presents 22 criteria under the environmental cluster identified in previous studies. The second column of Table 2.1 contains a description of each criterion.

Table 2.1

List of criteria under environmental cluster

Criteria	Description	References
Slope	The slope is essential since it influences the simplicity of engineering construction and the susceptibility of land sliding. Landfill sites with high altitudes and high slopes are not acceptable. Areas with a medium-altitude, surrounded by hills, and with no more than 20% slope are ideal for waste disposal.	(**Ahmad et al., 2014**; Chamchali & Ghazifard, 2020; **Din et al., 2008**; Güler & Yomralıoğlu, 2017; Karasan et al., 2018; Kareem et al., 2021; Karimi et al., 2019b; Rahmat et al., 2017; Sisay et al., 2021; **Sumiani et al., 2009**; Zarin et al., 2021)
Land use	Land usage is considered an environmental concern while constructing a new landfill site. Lands that are barren or have low value are suitable alternatives for landfilling.	(**Ahmad et al., 2014**; Ali et al., 2021; **Billa & Pradhan, 2013**; Chamchali & Ghazifard, 2020; **Din et al., 2008**; Güler & Yomralıoğlu, 2017; Karasan et al., 2018; Karimi et al., 2019; **Lunkapis et al., 2004**; Rahmat et al., 2017; **Sumiani et al., 2009**; Zarin et al., 2021)
Groundwater	A landfill site should not be located in areas with high groundwater pollution risks. The landfill sites harm aquifer and groundwater resources. Landfill leachate is seen as a long-term hazard to groundwater sources. Landfills should not be located on or near aquifers to prevent groundwater pollution.	(**Ahmad et al., 2014**; Ali et al., 2021; Chabuk et al., 2017; Chamchali & Ghazifard, 2020; Djokanović et al., 2016; Karasan et al., 2018; Karimi et al., 2019; Mohammadi Seif Abad et al., 2021; Rahmat et al., 2017)

Table 2.1 (Continued)

Geology	In geology, there are seven types of formations, which are alluvium, dolomite, limestone, volcanic, flysch, ophiolite, and metamorphic. Water adsorption is high in alluvium, dolomite, and limestone; making them unsuitable for landfill sites. Volcanic and flysch rocks are semipermeable and have low water absorption capacity. Meanwhile, ophiolite and metamorphic are impermeable; they are the best lithologic units for a landfill site.	(Bahrani et al., 2016; Beskese et al., 2015; Chamchali & Ghazifard, 2020; Ghobadi et al., 2013; Güler & Yomralıoğlu, 2017; Hafezi Moghaddas & Hajizadeh Namaghi, 2011; Karimi et al., 2019b; Korucu & Erdagi, 2012; Kumar & Hassan, 2013; Uyan, 2014; Yal & Akgün, 2013)
Surface water	Surface water is a significant consideration in deciding where to locate a landfill. The minimal distance from surface water should be considered to minimize surface water contamination from landfill leachate. Landfills should always be located as far away from surface water as feasible.	(**Ahmad et al., 2014**; Ali et al., 2021; Bahrani et al., 2016; Beskese et al., 2015; Chamchali & Ghazifard, 2020; **Din et al., 2008**; Güler & Yomralıoğlu, 2017; Karimi et al., 2019; **Lunkapis et al., 2004**; Rahmat et al., 2017; **Sumiani et al., 2009**; Torabi-Kaveh et al., 2016)
Topographical and geological condition	In landfill sites, the type and thickness of bedrock, as well as the geological genus, should be considered. Due to their broad gaps and high permeability, limestones and clay lands are ineffective for landfills, but metamorphic rocks exhibit dual behaviour depending on their source and are acceptable. Regions with poor geological conditions are given a caution sign indicating unsuitable.	(Abd-El Monsef & Smith, 2019; Arkoc, 2014; Delgado et al., 2008; Isalou et al., 2013; Korucu & Erdagi, 2012; Mohammadi Seif Abad et al., 2021; Torabi-Kaveh et al., 2016)

Table 2.1 (Continued)

River	Landfills are not permitted to be located on river or channel banks. The impact of these criteria is highly dependent on lithology. Thus, in highly cracked limestone with numerous and interconnected splits (e.g., width of this zone), it is critical to prevent contamination.	(Ali et al., 2021; A. J. Chabuk et al., 2017; Djokanović et al., 2016; Kareem et al., 2021; Sisay et al., 2021; Uyan, 2014; Zarin et al., 2021)
Drinking water sources	The landfill site must be more than 1 km away and downwards from aquifer recharge regions or drinking water sources.	(Delgado et al., 2008)
Soil type	Soil type is a factor that cannot be neglected in the landfill site selection process, in which it can prevent groundwater pollution from landfill leachates. Soil can be divided into several types: sandy regosols, Loessal sandy soil, Sandy loess soil, Loess soil, Sandy loess soil over loess, and clay loam. Soils can be classified based on the level of permeability. Soils with low permeability, clay, and clay loam are suitable for landfill construction.	**(Ahmad et al., 2014**; Bottero & Ferretti, 2010; Chabuk et al., 2017; Delgado et al., 2008; **Din et al., 2008**; El Baba et al., 2015; Hafezi Moghaddas & Hajizadeh Namaghi, 2011; Kareem et al., 2021; **Lunkapis et al., 2004**; Mohammadi Seif Abad et al., 2021; Rahmat et al., 2017; Sisay et al., 2021; **Sumiani et al., 2009**; Zarin et al., 2021)
Faultline	Earthquakes and earth movement have the potential to cause landfill damage and pollution leakage; consequently, avoiding faults is crucial in landfill site. The typical safe distance from a fault is 1000 m.	(Abd-El Monsef & Smith, 2019; **Ahmad et al., 2014**; Bahrani et al., 2016; Chamchali & Ghazifard, 2020; Gorsevski et al., 2012)

Table 2.1 (Continued)

Weather / Climate	Wind and rain are the two environmental elements that can influence site selection, particularly in coastal regions. Coastal disasters are a real risk if the location is exposed to high winds, and sufficient coastal protection is required. Besides, adequate storm water diversion is required in heavy rainfall locations to reduce leachate production.	(Beskese et al., 2015; Djokanović et al., 2016; Karimi et al., 2019b; Mohammadi Seif Abad et al., 2021; Mortazavi Chamchali et al., 2021; Ş. Şener et al., 2011; Vasiljević et al., 2012)
Sensitive ecosystems (lakes, dams, wetlands, ponds, reservoirs)	A landfill should not be built near any sensitive ecosystem, such as a lake, pond, dam or reservoir.	(**Ahmad et al., 2014**; Chang et al., 2008; **Din et al., 2008**; Donevska et al., 2012; **Lunkapis et al., 2004**; Rahmat et al., 2017; **Sumiani et al., 2009**; Uyan, 2014)
Pollution (water, air, noise)	The landfill site should be positioned in such a manner that it is acceptable to the public and helps to reduce pollution connected with noise, dust, smoke, traffic, and odor.	(El Baba et al., 2015; Tavares et al., 2011)
Infrastructures (gas pipelines, oil pipelines, powerlines, water pipelines)	Landfill sites are prone to spontaneous fires. Therefore, landfill sites should be located at a safe distance away from these infrastructure systems.	(Ali et al., 2021; Arkoc, 2014; Bahrani et al., 2016; A. J. Chabuk et al., 2017; Djokanović et al., 2016; Mortazavi Chamchali et al., 2021; Uyan, 2014)
Floodplain / flooding	Floods can spread pollutants when they pass over landfills. They may also disperse waste across the ecosystem downstream. As a result, flood-prone areas are unsuitable for landfilling.	(**Din et al., 2008**; Djokanović et al., 2016; Eskandari et al., 2016; Mortazavi Chamchali et al., 2021; **Sumiani et al., 2009**)

Table 2.1 (Continued)

Wind direction	Landfills should not be exposed to wind, or if this is not feasible, they should be located in the opposite direction of the most common wind.	(Djokanović et al., 2016; Eskandari et al., 2016; Kareem et al., 2021; Mortazavi Chamchali et al., 2021; Torabi-Kaveh et al., 2016)
Elevation	Surface processes, flood vulnerability, and some characteristics (slope, aspect, specific catchment region, & profile curvature) are all affected by elevation. This issue must be assessed in relation to the concerned location; greater elevation land increases transportation costs, while lower elevation land raises flood dangers. Thus, the constraints and values vary from region to region and are determined by the topography of each area.	(Ali et al., 2021; Gorsevski et al., 2012; Şener et al., 2011)
Soil permeability	If the landfill liner is unable to prevent leachate from leaking, the soil should be able to prevent it from infiltrating into groundwater (to the greatest extent practicable). Soil with permeability is considered impermeable in landfill design. Low permeability soil (clay) has the greatest value, high permeability soil (sand) has the lowest value, and other soils have intermediate values.	(Bahrani et al., 2016; Djokanović et al., 2016)
Soil stability	Long-term soil stability is important. An unstable location is more likely to have liner failure, resulting in leachate leakage and groundwater pollution. As a result, the location must be stable and secure.	(Djokanović et al., 2016)

Table 2.1 (Continued)

Lithology and stratification	Predicting leachate movement requires knowledge of lithology and stratification. Predicting leachate flow and contamination is a difficult process. As a result, areas with simple lithography are more suitable since it allows experts to better forecast the spread of contamination.	(Djokanović et al., 2016)
Land cover	Land cover is a vital consideration in landfill siting since landfill construction and management can affect land cover. Barren lands as suitable areas for landfill siting.	(Rahmat et al., 2017)
Existing landfill sites	A landfill site must be located far away from existing landfill sites to provide a safe distance between them. The spill over from a landfill site caused by natural hazard may affect the operation of a landfill site. Uncontrolled and unprocessed waste from landfill sites may potentially harm or poison the environment around a landfill.	(Asif et al., 2020)

Table 2.1 presents the criteria under environmental clusters emphasized in previous studies during the LSSP process. In total, 22 criteria were discovered and classified under environmental cluster after a comprehensive analysis. The third column of Table 2.1 shows the criteria emphasized for case studies in Malaysia based on past studies (refer to bold references).

Economical Cluster

The economical cluster must also be considered when locating landfill sites. The costs of acquiring, developing, and managing each site are frequently cited as economic issues in landfill siting (Erkut & Moran, 1991). All of these costs must be offset by the capital investment in the landfill or elsewhere; the project will fail to succeed. Table 2.2 presents seven criteria under the economical cluster identified from previous studies. The second column of Table 2.2 contains a description of each criterion.

Table 2.2

List of criteria under economical cluster

Criteria	Descriptions	References
Lifespan	The lifespan of landfills is important to be monitored in order to effectively manage the scarce resource as well as plan for future usage. Landfill site must have a minimal useful lifespan of 7 years.	(Banar et al., 2007; Delgado et al., 2008)
Land cost/price	The cost of land is a cost element that should be evaluated. The high land value raises the price of constructing landfill sites.	(Ali et al., 2021; Beskese et al., 2015; De Feo & De Gisi, 2010; Güler & Yomralıoğlu, 2017; Karasan et al., 2018; Korucu & Erdagi, 2012; Sisay et al., 2021; Wang et al., 2009)
Job opportunity	Residents might benefit from significant job opportunities during the establishment and administration of landfill facilities.	(Banar et al., 2007)
Construction costs	Field excavation and ground levelling, slope construction, groundwater pumping, and landfill supporting infrastructure are all part of the construction costs.	(Cao et al., 2006)
Building materials	The availability of construction materials such as borrow pits for liners, daily covers, and final cover, is critical to lower costs. Borrow pits for landfill covers are more significant than the others because a suitable cover may limit leachate development by avoiding surface water from infiltrating the landfill.	(Djokanović et al., 2016; Gorsevski et al., 2012; Şener et al., 2011)

Table 2.2 (Continued)

Solid waste transfer stations	Landfill sites located near solid waste transfer stations are more economically advantageous.	(Güler & Yomralıoğlu, 2017)
Operational costs	The total travel distance to transfer collected waste to landfill, the number of vehicles or drivers required for collection, the total working hours of drivers, and the total fuel consumption affect operational costs. Improvements in these aspects significantly affect operational expenditures.	Proposed in this present study

Table 2.2 presents the criteria under the economical cluster outlined in previous studies during the LSSP process. Seven criteria were discovered and classified under economical cluster after a comprehensive analysis.

Social Cluster

The largest barrier to properly locate landfill sites has been identified as social opposition to landfill sites. The "not in my yard backyard" issue is a major concern and constraint to landfill sites. The external expense and unfavorable features of landfills frequently lead to individuals perceiving hazards and risks that exceed long-term advantages (Erkut & Moran, 1991). Table 2.3 presents 12 criteria under social cluster identified from previous studies. The description of each criterion is shown in the second column of Table 2.3.

Table 2.3

List of criteria under social cluster

Criteria	Descriptions	References
Residential / Waste production areas	A landfill cannot be constructed near residential areas or waste production centres. When assessing the economic feasibility of a potential landfill site, 500 m buffer to these locations was more suitable and gave a higher score due to lower transportation costs.	(Abd-El Monsef & Smith, 2019; **Ahmad et al., 2014**; Ali et al., 2021; **Billa & Pradhan, 2013**; Bottero & Ferretti, 2010; **Din et al., 2008**; Karimi et al., 2019; Kumar & Hassan, 2013; **Lunkapis et al., 2004**; Mortazavi Chamchali et al., 2021; Rahmat et al., 2017; **Sumiani et al., 2009**; Uyan, 2014; Wang et al., 2009)
Settlements (urban and rural areas)	When locating a new landfill close to rural and urban areas, critical factors such as noise, property value reduction, odor, negative visual impacts, public resistance, potential environmental risks, and future urban development, should be addressed. Due of these considerations, a landfill should not be built near urban or rural areas. A landfill should not be positioned so far away that it raises transportation costs.	(**Ahmad et al., 2014; Billa & Pradhan, 2013; Din et al., 2008**; Güler & Yomralıoğlu, 2017; Karasan et al., 2018; Kareem et al., 2021; Karimi et al., 2019; **Lunkapis et al., 2004**; Rahmat et al., 2017; Şener et al., 2006; Sisay et al., 2021; **Sumiani et al., 2009**; Zarin et al., 2021)
Protected areas (historical and tourism areas)	Protection areas such as historical and tourism areas are not suitable for landfill sites.	(Bahrani et al., 2016; A. Chabuk et al., 2016; Güler & Yomralıoğlu, 2017; Karasan et al., 2018; Kareem et al., 2021; Mortazavi Chamchali et al., 2021)

Table 2.3 (Continued)

Park / Recreational areas	Landfills should not be built near or over recreational areas that attract the attention of the public. However, when its use as a landfill is terminated, this landfill site can be converted into a park or public recreational area.	(Bahrani et al., 2016)
Airport	Among the landfill phenomena are swarms of birds that endanger aircraft safety. Landfills must be positioned at a reasonable distance from airports.	(Abd-El Monsef & Smith, 2019; **Ahmad et al., 2014**; Arkoc, 2014; Djokanović et al., 2016; Güler & Yomralıoğlu, 2017; Karasan et al., 2019; **Lunkapis et al., 2004**; Şener et al., 2006; Sisay et al., 2021; Wang et al., 2009)
Transport infrastructure and access	Direct access to the site to prevent waste from being discharged before it reaches the landfill, as well as to reduce waste spillage, traffic congestion, and vehicle fuel consumption.	(Banar et al., 2007; Beskese et al., 2015; Chang et al., 2008; Karasan et al., 2019; Kumar & Hassan, 2013; Tavares et al., 2011; Wang et al., 2009)
Road access	The closeness of roadways must be considered while selecting a landfill location. A landfill should be positioned in an area accessible by alternate roads in all-weather situations. Landfill sites should not be located too distant from existing road networks to minimize the high cost of constructing connection roads.	(**Ahmad et al., 2014**; Ali et al., 2021; Bahrani et al., 2016; **Billa & Pradhan, 2013**; Chabuk et al., 2016; **Din et al., 2008**; Karasan et al., 2019; Kareem et al., 2021; Karimi et al., 2019; **Lunkapis et al., 2004**; Mortazavi Chamchali et al., 2021; Rahmat et al., 2017; Sisay et al., 2021; **Sumiani et al., 2009**; Torabi-Kaveh et al., 2016; Wang et al., 2009; Zarin et al., 2021)

Table 2.3 (Continued)

Highways	A 500 m buffer zone was established on each side of the highway. The greater the distance from highways, the less suitable the location.	(Arkoc, 2014; Korucu & Erdagi, 2012; Zarin et al., 2021)
Railways	Due of the negative aesthetic effects of landfills, they should not be positioned near railways where passengers might see or smell them. As a result, a buffer zone of 500 m is frequently proposed.	(A. Chabuk et al., 2016; Djokanović et al., 2016; Mortazavi Chamchali et al., 2021; Nas et al., 2010; Sadek et al., 2006; B. Şener et al., 2006; Uyan, 2014; Wang et al., 2009; Zarin et al., 2021)
Public acceptance	The selected landfill location should be socially acceptable.	(Banar et al., 2007; Karasan et al., 2019; Kharat et al., 2016)
Political influence	In SWM including site selection, the government is the main body that controls all decisions made around waste management in an effort to protect itself and control public response.	(Cheng et al., 2002, 2003)
Cultural sites	Cultural sites, particularly archaeological and religious landmarks, are vital for public spirit and the tourism sector; places near a cultural site are deemed undesirable.	(A. Chabuk et al., 2016; Djokanović et al., 2016; Ersoy et al., 2013; Eskandari et al., 2012)

Table 2.3 shows the criteria under social cluster emphasized in previous studies during the LSSP process. In total, 12 criteria were discovered and classified under social cluster after a comprehensive analysis. The third column of Table 2.3 shows the

criteria emphasized for case studies in Malaysia based on previous studies (refer to bold references).

This section highlights 22 criteria of the environmental cluster, 7 criteria of the economical cluster, and 12 criteria of the social cluster used for the landfill site selection conducted in many countries. This research focuses on the LSSP in Malaysia, thus some of the criteria are omitted to meet the Malaysia case. Based on the expert interviews and a government technical report entitled "Technical Guidelines for Sanitary Landfill, Design, and Operation" released by the Ministry of Housing and Local Government Malaysia (2004), 16 environmental criteria, 5 economical criteria, and 12 social criteria are selected in this research.

2.2.2 LSSP Techniques

This section explores the techniques used to solve LSSP, which have been organized into two main phases. The first phase focus on the techniques used to rank the LSSP criteria and the second phase focuses on the preliminary landfill site screening.

2.2.2.1 Ranking of Landfill Site Selection Criteria Techniques

This section examines MCDM methods including AHP, ANP, and integrated techniques such as fuzzy-based approaches for ranking LSSP criteria. The important weight is calculated using MCDM techniques to determine the ranking.

2.2.2.1.1 AHP

Thomas L. Saaty created the AHP in the 1970s. The AHP is a structured approach to dealing with complex decision problems. As shown in Figure 2.1, the decision problem is transformed to a smaller decision problem known as a decision hierarchy.

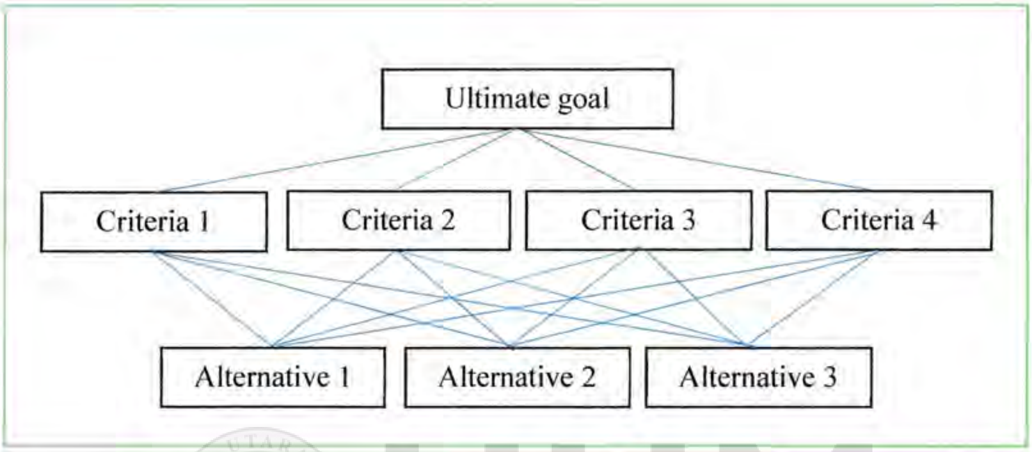

Figure 2.1. The decision hierarchy of AHP

According to Figure 2.1, the ultimate goal, which refers to the research decision, is at the top of the hierarchy. Following the transformation step, pairwise comparison is used to determine the fundamental ranking for criteria (Sener et al., 2006). A pairwise comparison of the criteria (the second level of the decision hierarchy) is performed to assess the relative importance of each criterion. Following that, a criterion comparison matrix is created, with eigenvectors generated to indicate criteria ranking. A pairwise comparison of alternatives (which is the third level of the decision hierarchy) by each crterion is performed to calculate the ratings associated with each criterion. Furthermore, the AHP can provide an overall ranking of the solutions by comparing the matrix between alternatives and information on the ranking criteria. The option with a greater eigenvector value is selected as the first option. (Sumathi et al., 2008).

Some previous studies relied solely on AHP to determine the significance of the selection criteria. For example, Güler and Yomralolu (2017) used AHP to determine criteria weights in order to find the best location for an alternate landfill site in Istanbul's province. The study was carried out in accordance with the country's regulations. Furthermore, the factors employed are selected by taking into account the characteristics of the study area. Under the main environmental and economic criteria, the study used eleven sub-criteria. Based on the evaluation results, the best region in terms of land use and environmental conditions was chosen. The cost of solid waste transportation from stations will be reduced by a nearby highway. It is far from any settlement.

In another study, Osra and Kajjumba (2020) evaluated twelve social-political and environmental criteria in Makkah, Saudi Arabia, to determine the best landfill site location. This study uses AHP to evaluate landfill site selection criteria that meet government regulations while minimizing economic, environmental, health, and social costs. The best sites for the MSW landfill in Makkah, according to the analysis, have a groundwater depth of 12 meters. Furthermore, these sites are unaffected by geological structures, and enough sand can be modified to act as a covering material. In terms of economics, the landfill is expected to last 20 years.

Asif et al. (2020) chose an environmentally friendly, economically practical, and socially desirable landfill location for Lahore, Pakistan. The weights were determined through an AHP-based pair-wise comparison method. The research considers nine criteria. The evaluation results show that protecting the groundwater table is more important than keeping a safe distance from roads. Seven candidate landfill sites were chosen for further investigation based on the findings. Meanwhile, landfill sites 2, 5, and 6 were the best in terms of area, distance from the city center, and nearby settlements.

Tercan et al. (2020) discovered the ideal locations for MSW landfill sites in three cities in southern Turkey (Antalya, Burdur, & Isparta). The AHP method is used to determines the relative importance of the criteria weights. For landfill selection, sixteen criteria were used, with the distance from surface water receiving the most weight, 0.185. Precisely, 3.75% of the study area, or 1377 km2, was deemed highly appropriate, with four potential landfill sites proposed.

Mortazavi Chamchali et al. (2021) took the initiative to use AHP to select and prioritize prone areas in Rudbar County, Iran, for the construction of a landfill. The criteria chosen are based on the Iranian standards to assess landfill site suitability in most countries worldwide. The evaluation results showed that the current wind direction criteria is the most important and gives the most weight, 0.6370.

In Ethiopia, Sisay et al. (2021) used AHP to calculate weights for each criterion considered and to handle large and conflicting criteria. Based on environmental pollution and aesthetic value, landfill sites near settlements are not preferred because they will have negative effects on human health. To avoid this sort of problem, a landfill located far from the settlement is suitable. Meanwhile, from an economic standpoint, a larger size landfill is preferable to a small size landfill because a large size landfill can be used for a longer period and can reduce landfill reconstruction costs.

Rahmat et al. (2017) aimed to discover a suitable solid waste landfill site in Behbahan City of Iran. In the study, ten criteria are considered and classified into three main groups which are environmental, socio-cultural, and technical-economical. The AHP method is used to determine the weights of these criteria and their relative importance to one another. The evaluation revealed that groundwater is the most important criterion in choosing a landfill site. However, several criteria related to wind direction, land ownership, as well as political and management difficulties that have been proposed in the study by Alavi et al. (2013) were considered to choose the best site among the alternative sites.

Al-Anbari et al. (2018) discovered the suitable landfill site in Al-Kufa City, Iraq's southernmost city. The study employed eleven criteria. The AHP method was used to weigh the criteria under consideration. According to the evaluation results, the most important criteria that receive a higher value are urban centres (0.32), main rivers (0.21), and roads (0.09). Furthermore, they presented several criteria for future consideration, such as construction material availability and agricultural areas.

Karimi et al. (2019) presented the discovery of municipal landfill locations in Javanrood County, Iran. The study employed nine criteria. The weights of the criteria were calculated using an AHP-based pairwise comparison. The weighting results show that groundwater, surface water, and geology were assigned the highest value in terms of the importance of water resources in the study area. Finally, the findings revealed that 7% of the study area could be used as a landfill.

Several previous studies, on the other hand, linked MCDM techniques with fuzzy approaches to overcome the absence of specific data from uncertainties. For example, Karasan et al. (2018) used Pythagorean fuzzy AHP to calculate criteria weights for landfill selection evaluation. The research was carried out in Istanbul, Turkey. Five alternatives are assessed using twelve sub-criteria divided into four distinct groups: environmental impact, social factors, economic conditions, and operational activities. Sub-criteria for environmental protection are included in the first group. The second group includes sub-criteria concerning society and urban life. In contrast, the third and fourth categories include sub-criteria for landfill cost and operation. According to the evaluation results, social factors (0.398) are the most important main criteria, followed by environmental impact (0.335).

Pasalari et al. (2019) identified the best landfill sites for Shiraz county in southern Iran by taking into account fifteen sub-criteria described in the literature and associated with an Iranian environmental protection organization. Each criterion's weight was calculated using fuzzy AHP. The distance to residential areas and ground waters were identified as the most important criteria for landfill site selection, with weights of 0.36 and 0.28, respectively.

Şener and Şener (2020) considered eleven criteria In choosing appropriate suitable landfill sites in the Burdur Lake basin. These criteria were divided into three categories (environmental, hydrogeological and economic) based on the general characteristics ofthe study area and Turkish regulations. The significance and weight of each criterion were determined using the fuzzy-AHP method. The evaluation discovered that hydrogeological (0.486) and distance from surface waters (0.644) are the most effective primary criteria and criteria. However, with 0.124 crisp weight, socioeconomic was found to be the least useful main criterion in the study, and curvature was found to be the least preferred criterion with 0.042 crisp weight. Despite being deemed of moderate importance, environmental criteria were assigned weights that were nearly identical to hydrogeological criteria (0.361). Among the environmental criteria, the land use criterion received the highest weight (0.638), while the aspect criterion received the lowest weight (0.107).

Ali and Ahmad (2020) identified appropriate landfill candidate sites and selected the best alternatives for the Kolkata Municipal Corporation in India. The study employed twenty criteria and twenty alternatives. The fuzzy AHP has been employed to determine the relative importance of these criteria. The evaluation results show that proximity to ponds/lakes has the highest suitability weight for hydrological criteria (0.5269). Meanwhile, slope (0.4502) is higher for topographic and climatic criteria, land use (0.3352) is higher for land criteria, proximity to major roads (0.4410) is higher for accessibility-related criteria, and proximity to sensitive areas (0.4639) is higher for infrastructure-related criteria.

Mallick (2021) has also used fuzzy AHP for criterion weighting to find the best landfill site for Abha-Khamis-Mushyet, which is located in Saudi Arabia's Aseer region. The study looks at ten criteria, which are divided into environmental and socioeconomic categories. Because landfills can cause hazardous leakage and pollution that must be prevented from reaching water supplies such as wetlands and wadies, the drainage density was given the most weight in the evaluation. Following that are land use/cover, geology, road distance, and topography (elevation).

2.2.2.1.2 ANP

ANP is a mathematical theory introduced by Thomas L. Saaty that has been successfully used in various fields to identify decision-making priorities for multiple criteria without constructing a one-way hierarchical relationship between decision levels (Esquirol et al., 2009; Golubic et al., 2009). ANP is an attempt to improve the AHP for complex issues with a non-hierarchical structure using analysis performed by the human brain (Chung et al., 2009). ANP uses a thorough framework to take into account all interactions and connections between the various decision-making levels that make up the network structure (De Bacquer et al., 2009).

Several studies used ANP to prioritize the LSSP criteria when it came to LSSP. Banar et al. (2007), for example, sought to identify an appropriate location for the disposal of municipal solid waste in Eskisehir City, Turkey. The ANP method was applied to determine each criterion's weights and relative importance. These criteria were examined in terms of benefit, opportunity, cost, and risk factor. Six criteria and four alternatives were used. The evaluation's findings indicate that the proposed landfill location is competent and has a 30-year useful life, as well as employment opportunities have been ranked as the most advantageous criteria in terms of benefit. Distance of transportation and the distance of alternative sites to the city was considered the most important criteria in terms of costs. Lastly, in terms of risk, ecological risk is the most important criterion which consists of the utilization structure of currently used landfill, alternative sites and plant cover.

In another study, Isalou et al. (2013) tried to locate a suitable landfill site for the Kahak Town of Iran. Six different criteria classified under two groups (natural and topography, and general acceptation) were used to achieve their goals. The weight of each criterion was evaluated using a fuzzy ANP model considering the minimum negative effect on the study area.

On the other hand, Afzali et al. (2014) investigated the feasibility of an inter-municipal solid waste landfill site for the city of Khomeynishahr and its six neighboring cities, which have a population of around 500,000 people. For prioritizing the associated criteria and selecting a suitable landfill site, an integration of Boolean logic, Fuzzy logic, and ANP was used. Seven criteria and eight alternatives are considered in the study. The evaluation revealed that the most important criteria in selecting a landfill site were residential area (0.11576), groundwater (0.10946), and land use (0.10736).

Jamshidi-Zanjani and Rezaei (2017) solved a municipal LSSP in the Markazi province of Iran's Central Province. Twelve criteria are taken into account, which are broken down into environmental and economic categories. The combination of ANP and a fuzzy linguistic quantifier was used to calculate final weights and criteria priorities. The evaluation results revealed that groundwater, surface water, and land use were given higher priority, indicating that they are suitable for landfill site selection.

2.2.2.1.3 Integrated MCDM Techniques

According to the extensive review conducted in this research, several previous studies demonstrated the integration of multiple MCDM techniques to tackle LSSP. For example, Alkaradaghi et al. (2019) discovered a suitable landfill site in northern Iraq's Governorate of Sulaymaniyah. Thirteen criteria were used, all obtained from various government departments and international organizations. Several MCDM techniques, including AHP, SAW, Ratio Scale Weighting (RSW), and Straight Rank Sum (SRS) were used to calculate the criteria weights for each criterion. According to the evaluation of all methods considered, 80% of the investigated area was appropriate for landfill construction.

Asefi et al. (2020) discovered the potentially best-suited landfills in the Australian city of New South Wales. The AHP-DEMATEL integration technique is used. AHP is used to define the criteria as well as rank and prioritize the alternatives. Meanwhile, DEMATEL is used to analyze the causal relationship between the criteria and to calculate the criteria weights. When existing landfills match the ranked areas, the results of criteria evaluations show that geological and geomorphological factors, as well as economic factors, are extremely important to planners.

Rahimi et al. (2020) presented a framework comprising the Fuzzy Best-Worst Method (BWM) and Fuzzy MULTIMOORA techniques for MSW LSSP application in Mahallat city located in the northwest of Iran. In the study, fourteen criteria are considered. These criterion weights were calculated using the group fuzzy BWM. The criteria evaluation shows that the most important criteria of landfill sites are surface water, followed by groundwater and protected areas. Then, the candidate sites were evaluated and ranked using the group fuzzy MULTIMOORA. The findings from the selected candidates, "Site A8," which is located near the Mahallat urban area, emerged as the best location to dispose of MSW.

Ali et al. (2021) identified a suitable sanitary landfill site in Memari Municipality, West Bengal, India. In the study, the AHP was used to weigh the selected criteria, while the F-TOPSIS was used to address decision-making uncertainty and prioritize the best site. Twelve criteria must be fulfilled. AHP's final suitability map yielded seven viable landfill candidate sites, which were then ranked using F-TOPSIS based on expert input. Finally, candidate sites 2 and 7 were identified as the best candidates for new landfill sites.

Mohammadi Seif Abad et al. (2021) employed hybrid techniques to choose an appropriate location for the MSW landfill site in Iran's Zanjan Plain. As a result, the AHP method was used to assess the criterion. The PROMETHEE technique was then used to identify the best landfill locations while keeping the scientific limits and characteristics of the area in the forefront. The study took ten criteria into account. The findings indicated that the techniques might be used to choose the best alternative landfill site.

Zarin et al. (2021) used fuzzy logic, AHP, and WLC to evaluate the suitability of solid waste landfill sites in Islamabad, Pakistan. The AHP was used to determine the relative importance of the criteria, and the criterion factors were then standardized using fuzzy set theory. All criterion elements were then integrated using AHP and the fuzzy logic-WLC approach to generate a land suitability map. Finally, the locations were discovered by intersecting two combined suitability index layers. The findings demonstrated that combining fuzzy logic, AHP, and WLC techniques can yield adequate results for determining the best location for solid waste landfill sites.

2.2.2.2 Preliminary Site Screening Techniques

The process of removing inappropriate locations while retaining viable landfill sites for further evaluation is referred to as preliminary site screening (Charnpratheep et al., 1997). As a result, the literature depicts a variety of strategies for carrying out the preliminary site screening phase.

2.2.2.2.1 Geographic Information System

GIS is a computer-based system that incorporates data input, storage and management, data manipulation and analysis, as well as data output in spatial, attribute or both formats to facilitate decision making (Malczewski, 1999). The GIS has been regarded as an important tool to support decision-makers in resolving different challenges associated with the selection of a landfill site. Besides saving time, GIS provides us with a digital data bank that will help in the long-term monitoring of the proposed landfill site (Sumathi et al., 2008).

In order to create more accurate findings, GIS might be used with other solution methodologies. For example, Sadek et al. (2006) employed vector-based GIS to determine the potential alternative site for landfill siting in Lebanon. This approach is commonly used in constraint mapping activities, so as to conduct a preliminary site screening analysis. This is performed to reduce the number of potential sites and keep just those that are suitable. In a nutshell, the potential site has become a small number of alternatives, all of which meet the predefined criteria and are then analyzed and ranked. In order to build composite site suitability maps, the adopted criteria are applied to spatial data through if/then queries, buffer capabilities, map stacking, and intersections.

Delgado et al. (2008) concentrated on identifying landfill sites in Mexico's Cuitzeo Lake Basin that conform to Mexican environmental rules and are inter-municipal in nature. The idea of inter-municipal was developed as a proxy criterion connected to the previously described economic restrictions. To achieve this goal, three spatial analysis models in GIS were employed, namely Boolean logic, binary evidence, and overlapping index.

Adeli and Khorshiddoust (2011) considered geomorphological knowledge to select the best location for sanitary landfill construction in Azerbaijan province in Iran by using GIS. Moghaddas and Namaghi (2011) used GIS-based landfill-suitability zonation methods to identify acceptable hazardous waste landfill sites in Iran's Khorasan Razavi region. Arkoc (2014) used the point count index and constraint overlaying GIS techniques to assess and select areas for an MSW landfill site in Turkey.

In Trabzon Province, Turkey, Yildirim (2012) described raster-based GIS strategies for landfill site selection. This strategy produces a cost surface map with pixel-based values for the regions. This strategy was used to evaluate two landfill sites that had previously been evaluated using the traditional site selection method. The suitability values for the two landfills on the cost surface map indicated that they are not suitable for landfill siting. As a result, the new strategy produced more effective results than the traditional methods.

Afzali et al. (2014) used GIS geographical to identify suitable landfill sites for the city of Khomeynishahr and its six adjacent cities (i.e., Gaz, Dolatabad, Shahinshahr, Habibabad, Gomshecheh, & Gorgab). Abujayyab et al. (2017) developed an integrated spatial data-mining model for landfill site selection in the northern part of Peninsular Malaysia. Non-specialist users were the audience for the proposed toolbox. The model enabled the user to create suitability maps neural networks, which were deployed to train the model. The model was divided into nine phases and split across Matlab and

Python-ArcGIS. To use as input data and to create the training and testing datasets, exactly 22 criteria were chosen.

RS is a geographic device that assesses the attributes of objects on the Earth's surface using data from planes and satellites. This method can also analyze photos and track both long-term and short-term changes caused by human activity on Earth (Schowengerdt, 2006). Several previous studies had combined GIS and RS to solve the LSSP problem. These integrated approaches have evolved into powerful tools for preliminary research due to their ability to handle massive amounts of geographical data from a variety of sources (Abd-El Monsef, 2015; Şener et al., 2011).

In addition, GIS-assisted RS innovations have been used to monitor the environmental consequences of landfills through the processing of satellite images of the landscape, primarily to find suitable landfill locations in surrounding areas (Shahabi et al., 2014). Together, GIS and RS provide an excellent framework for acquiring, storing, summarizing, analyzing and displaying data (Paul et al., 2014). Additionally, GIS data can be updated periodically to simulate real-time changes in the characteristics of the study area.

2.2.2.2.2 Other Techniques

Several previous studies did not conduct preliminary site screening to acquire candidate landfill locations. Local authorities in the study region, on the other hand, have given a list of landfill candidate locations for further evaluation. For example, Banar et al. (2007) used data from a pre-assessment to identify four alternative locations in Turkey recommended by the Metropolitan Municipality of Eskisehir. The four sites refer to Site 1 (Cavlum site), Site 2 (Sultandere site), Site 3 (Current site), and Site 4 (Satilmisoglu site).

Bottero and Ferretti (2010) used three potential site locations to be used as landfills identified by the Torino Regional Authority located in Italy. The three sites are located in the municipalities of Ivrea, Rivarolo Canavese, and Settimo Torinese. Meanwhile, Kahraman et al. (2018) used three possible alternative site locations determined by Istanbul Metropolitan Municipality in Turkey. The three sites are Gümüşp1nar (A1), Dağyenice (A2), and Çiftalan (A3). Next, Badi and Kridish (2020) used five site locations suggested by the Municipal councils in Libyan cities, in order to select the best site among them.

Based on the review in this section, GIS is the most preferable technique to propose candidate locations for the new landfills. However, there are also previous studies that consider candidate sites based on the suggestion from the experts such as Banar et al. (2007), Bottero and Ferretti (2010), Kahraman et al. (2018), and Badi and Kridish (2020).

As this research did not contribute any new knowledge on GIS or propose a new approach to identify potential locations, the candidate landfills used in this research were manually identified by using Google Earth. The selection of locations is focused on the Kubang Pasu, Kedah area which is based on a number of specific criteria, such as unused land, agricultural land, and not being close to populated areas. These candidate landfill sites used in this research were also agreed by the experts for testing purposes. The distribution of the candidate landfills is illustrated in Chapter 3, Figure 3.4.

2.3 Review of WCVRP

This section starts with a brief discussion of solving WCVRP as arc and node routing problems. Next, the objectives and WCVRP constraints are presented. Finally, the techniques for solving WCVRP are discussed.

2.3.1 Arc and Node Routing Problems

Routing problems have captivated the interest of numerous researchers and practitioners over the last 60 years due to their enormous economic effects and the mathematical complexities encountered in their research and solution. There are two types of routing problems; (1) node routing problems (NRP), in which customers are represented by nodes in a network, and (2) arc routing problems (ARP), in which the service is performed on the arcs or edges of a network (Corberán et al., 2020).

Table 2.4

Type of WCVRP based on Golden et al. (2002)

Classification	Type of waste	Type of bin	Location	Type of problem
Residential	Household	Bins	Street	Arc routing
Commercial	Commercial	Large containers	Commercial	Node routing
Roll-on-roll-off	Construction	Large trailers or containers	Construction sites	Node routing

Table 2.4 presents the type of WCVRP based on Golden et al. (2002). Based on Table 2.4,WCVRP is an example of a routing problem that can be solved as an NRP or an ARP depending on the type of waste and how it is collected. The WCVRP is solved as an ARP if the collection of household waste (i.e., residential waste) occurs along a street network where the exact location of each customer is unknown. On the other hand, if waste is collected from point to point and the exact location of the customer is known, the WCVRP is solved as NRP. This is also supported by Babaee Tirkolaee et al. (2019), who stated that generally, ARP is employed for residential waste collection, where waste is placed in a bin or garbage bags and can be discovered along streets as network arcs. Several previous studies on ARPs for waste collection are reviewed.

For example, Mofid-Nakhaee and Barzinpour (2018) used an integrated approach of ALNS and whale algorithm to solve a multi-compartment capacitated ARP with intermediate facilities. The proposed algorithm was developed to solve an actual situation in the Tehran municipality. Computational results revealed that hybrid ALNS with whale algorithm produced higher quality solutions compared to ALNS alone. The solution also suggested that multi-compartment vehicles are less pricy than using single-compartment vehicles, while reducing the total distance travelled.

Babaee Tirkolaee et al. (2019) presented a multi-objective invasive weed optimization inspired by urban WCVRP for a multi-trip periodic capacitated ARP with uncertainty demand. They created ten test problems in various dimensions to assess the algorithm's quality. Each test problem's characteristics are presented. Computational results showed that they reduce the total cost (traversing and vehicle usage costs) as well as the longest tour distance of vehicles (makespan). Meanwhile, the NRP is directly associated with commercial waste, such as waste generated by restaurants, organizations, and institutions; that is deposited in large containers. These containers represent the customer's nodes where the exact location of these containers is known. In this research, the WCVRP is solved as NRP because the waste is collected from node to node, with the coordinate of each node is known.

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2.3.2 Classification of Waste Collection Vehicle Routing Models, Objectives, and Constraints

The classification of WCVRP is divided into three sections: waste collection vehicle routing models, objectives, and constraints involved.

2.3.2.1 Waste Collection Vehicle Routing Models

The WCVRP is a subgroup of vehicle routing problem (VRP). The WCVRP is a routing vehicle that collects waste from a specific set of nodes (customers) and unloads it at designated landfill sites. In WCVRP, a set of vehicles, similar to VRP, has fixed capacity and is occasionally limited to maximum trip lengths. Likewise, WCVRP considers similar objectives as VRP, such as minimizing overall travel distance and time, number of vehicles, and waste container fill rate. The significant difference between WCVRP and VRP is all vehicles are permitted to make multiple visits to landfill sites and must discard all collected waste before returning to the depot (Buhrkal et al., 2012).

The WCVRP has several variations depending on the type of constraints considered, such as WCVRP with time windows (WCVRPTW) (Buhrkal et al., 2012; Kim et al., 2006), rollon–rolloff WCVRP (Wy et al., 2013), and eco-efficient WCVRP (Molina et al., 2019).

The WCVRPTW is one of the most applicable models to real-world problems. Though since time windows are included, the opening and closing times for delivering services to a customer must be addressed. Between its opening and closing times, a vehicle can begin serving a customer at any time. A waiting time must also be added to the total travel time if a vehicle arrives before customer's has opened. If a vehicle arrives after a customer's closure time, another vehicle must be assigned to serve the customer (Liang et al., 2021).

The WCVRPTW is represented as a network graph $G = (V, A)$, with nodes 1 to N, representing a subset of nodes, nodes $N + 1$ to $N + M$ representing disposal sites , and $N + M + 1$ representing the lunch break period. Following that, 0 denotes the depot in the vertex set of $V = 0, 1, 2, \ldots, N, N + 1, \ldots, N + M + 1$, and A denotes a set of arcs. Each node in V has a time window $[a_i, b_i]$ that represents the earliest and the latest service time. The depot time windows $[E, L]$ show the earliest and the latest visit times that are possible (Sahoo et al., 2005).

K is the set of vehicles, N_k is the actual number of disposal trips for vehicle k, and C is the vehicle capacity. X_{ijk} is the decision variable, and it is equal to 1 if vehicle k visits arc (i, j) for $(i, j) \in A$ and $k \in K$, otherwise it is 0. The time variable w_{ik} represents the start time at node i if it is served by vehicle k. Finally, D_{ik} denotes the total demand at node i for vehicle k In this research, the mathematical model of WCVRPTW with lunch break, adopted from Sahoo et al. (2005), is as follows:

Objective function

Minimize

$$\sum_{k\in K}\sum_{(i,j)\in A} t_{i,j}x_{i,j,k} \tag{2.1}$$

Subject to

$$\sum_{k\in K}\sum_{(i,j)\in A} x_{i,j,k} = 1 \quad \forall i \in 1, 2, \ldots, N \tag{2.2}$$

$$\sum_{j=1}^{N} x_{0,j,k} = 1 \quad \forall k \in K, \tag{2.3}$$

$$D_{i,k} \leq C \quad \forall k \in K, i \in 1,2,\ldots,N,N+M+1, \tag{2.4}$$

$$D_{m,k} = 0 \quad \forall k \in K, m \in 0,N+1,N+2,\ldots,N+M, \tag{2.5}$$

$$\begin{gathered} D_{i,k} + d_j - D_{j,k} \leq \left(1 - x_{i,j,k}\right) Big\ M \quad \forall k \in K, \\ i \in 0,1,2,\ldots,N,N+M+1, j \in 0,1,2,\ldots,N,N+M+1, \end{gathered} \tag{2.6}$$

$$\sum_{j=1}^{N} d_j \sum_{i=1}^{N+M+1} x_{i,j,k} \leq C^{*} N_k \quad \forall k \in K, \tag{2.7}$$

$$\sum_{i \in 1,\ldots,N,N+M+1} \sum_{m=N+1}^{N+M} x_{i,m,k} = N_k \quad \forall k \in K, \tag{2.8}$$

$$\sum_{m=N+1}^{N+M} \sum_{j \in 1,\ldots,N,N+M+1} x_{m,j,k} = N_k - 1, \quad \forall k \in K, \tag{2.9}$$

$$\sum_{m=N+1}^{N+M} x_{m,0,k} = 1 \quad \forall k \in K, \tag{2.10}$$

$$\sum_{i=1}^{N+M} x_{i,N+M+1,k} = 1 \quad \forall k \in K, \tag{2.11}$$

$$\sum_{j=0}^{N+M} x_{N+M+1,j,k} = 1 \quad \forall k \in K, \tag{2.12}$$

$$\sum_{i=0}^{N+M+1} x_{i,j,k} = \sum_{i=0}^{N+M+1} x_{j,i,k} \quad \forall k \in K,\ j \in 0, 1, \dots, N + M + 1, \tag{2.13}$$

$$w_{i,k} + s_i + t_{i,j} - w_{j,k} \le \left(1 - x_{i,j,k}\right) Big\ M \quad \forall k \in K, (i,j) \in A, \tag{2.14}$$

$$w_{i,k} + s_i + s_{N+M+1} + t_{i,j} - w_{j,k} \le \left(2 - x_{i,N+M+1,k} - x_{N+M+1,j,k}\right) Big\ M,$$

$$\forall k \in K, (i,j) \in A, \tag{2.15}$$

$$a_i \sum_{j=1}^{N+M+1} x_{i,j,k} \le w_{i,k} \le b_i = \sum_{j=1}^{N+M+1} x_{i,j,k} \quad \forall k \in K, i \in 0, 1, \dots, N + M + 1, \tag{2.16}$$

$$E \le w_{i,k} \le L \quad \forall k \in K, i \in 0, 1, \dots, N + M + 1, \tag{2.17}$$

$$x_{i,j,k} \in \{0, 1\}, \quad \forall k \in K, (i,j) \in A \tag{2.18}$$

$$N_k \ge 0, Integer, \forall k \in K, \tag{2.19}$$

$$D_{i,k} \ge 0, \qquad \forall k \in K,\ i \in 0, 1, \dots, N + M + 1, \tag{2.20}$$

Where,

V = a set of nodes

A = a set of arcs

M = number of disposals

N = number of customers

E = depot opens at E

L = depot closes at L

K = a set of vehicles

N_k = number of disposal trips for vehicle k

C = vehicle capacity

$x_{i,j,k}$ = 1 if vehicle k travels from node i to node j, otherwise, 0

$w_{i,k}$ = start time at node i served by vehicle k

$D_{i,k}$ = total demand for vehicle k at node i

$t_{i,j}$ = travel time from node i to node j

a_i = earliest service time at node i

b_i = latest service time at node i

s_i = total service time of node i

The objective function in equation (2.1) attempts to reduce travel time and vehicle usage. Equation (2.2) ensures that each customer is serviced precisely once; equation (2.3) specifies that each vehicle route must begin at the depot, and equation (2.4) specifies that the amount of waste collected at each customer must not exceed vehicle capacity. After disposing of all waste at the landfill, the vehicle capacity must be reset to zero, as shown in equation (2.5). Equation (2.6) ensures that the collected waste accurately matches the incremental volume of a specific customer when the vehicle visits that customer. Next, equation (2.7) calculates the actual number of disposal trips.

Equation (2.8) describes a scenario in which the number of trips made by customers to disposal sites for a vehicle equals the number of actual disposal trips.

The condition in Equation (2.9) is that the number of trips from the disposal sites to the customers is one less than the number of disposal trips. Equation (2.10) ensures that the final journey from a disposal location along that vehicle route must return to the depot. The lunch time added for each route is represented by Equations (2.11) and (2.12). If a vehicle arrives at a customer, it must depart and leave the customer as represented in equation (2.13). The travel time between before and after lunch hour stops is considered in Equation (2.15). The time constraints on both the route and the vehicle are met are shown in equations (2.14) to (2.17). Finally, equations (2.18) to (2.20) are non-negative binary conditions on the variable set.

2.3.2.2 Objectives involved in WCVRP

The goal of WCVRP is to determine waste transportation routes, subject to various constraints, so as to accomplish several objectives, mostly related to cost. Many studies have been conducted to accomplish the objectives of WCVRP. For example, Kim et al. (2006) solved WCVRP by minimizing vehicles use and travel time, as well as by maximizing route compactness and vehicles workload balance. Ombuki-Berman et al. (2007) addressed WCVRP by minimizing vehicle use and travel distance, while maximizing route compactness and balancing vehicle workload.

In the metropolitan region of Barcelona (Spain), Bautista et al. (2008) solved an urban WCVRP by minimizing the total cost connected with the total length of the routes.

Arribas et al. (2010) addressed an urban WCVRP in Santiago (Chile) by minimizing collection distance, time, and costs while improving the existing solid waste collection system. The WCVRP was solved by Benjamin and Beasley (2010) by reducing the number of vehicles used and the distance travelled. Buhrkal et al. (2012) solved the WCVRP by minimizing the total travel cost associated to the driven distance and the number of vehicles used.

Meanwhile, Minh et al. (2013) solved WCVRP with time windows and conflict by minimizing total moving distance, waiting time, moving time, and vehicle use. In Egypt, Moustafa et al. (2013) solved WCVRP by minimizing travel time, travel distance, and vehicle use. Wy et al. (2013) solved rollon-rolloff WCVRP by reducing the number of vehicles and total route time while meeting all customer demands.

Campos and Arroyo (2016) determined feasible routes for the vehicles by minimizing the total travel cost related to distance and number of vehicles used. Dotoli and Epicoco (2017) handled hazardous WCVRP with multiple time windows in Italy by minimizing total travel distance, while maximizing total collected waste and the economic value of each vehicle withdrawal. The WCVRP was solved by Grakova et al. (2018) by balancing vehicle workload and minimizing global transportation costs based on global distance travelled.

Babaee Tirkolaee et al. (2019) addressed multi-trip WCVRP with time windows in Iran by minimizing the total cost, which included vehicle usage costs, traversal costs, and penalty costs for exceeding acceptable time windows (soft time window). In

Spain, Molina et al. (2019) solved eco-efficiency WCVRP by minimizing total travel distance, climate change costs, and air pollution costs. Qiao et al. (2020) explored the WCVRP model by reducing the total waste collection management costs, including vehicle fixed costs, fuel consumption costs, carbon emission costs, and penalty costs. In Indonesia, Nurprihatin and Lestari (2020) solved WCVRP by minimizing costs and travel distance.

In recent year, Hurkmans et al. (2021) addressed a multi-objective residential WCVRP by minimizing travel time and overlap, while balancing workload that affected each other through integrated territory planning and VRP. From the economic and environmental stance, Liu and Liao (2021) established an optimization model for two-echelon collaborative WCVRP with the goal of minimizing total costs and carbon emissions.

Table 2.5 summarizes the objectives that have been previously met in previous studies to solve WCVRP. It can be concluded that most objectives have been related to the operational costs involved in providing waste collection services.

Table 2.5

List of objectives previously considered in solving WCVRP

Objectives	**References**
Minimize number of vehicles used	(Benjamin & Beasley, 2010; Buhrkal et al., 2012; Campos & Arroyo, 2017; Kim et al., 2006; Minh et al., 2013; Moustafa et al., 2013; Ombuki-Berman et al., 2007; Wy et al., 2013)

Table 2.5 (Continued)

Minimize total travel time	(Arribas et al., 2010; Hurkmans et al., 2021; Kim et al., 2006; Minh et al., 2013; Moustafa et al., 2013; Wy et al., 2013)
Minimize total travel distance	(Arribas et al., 2010; Bautista et al., 2008; Benjamin & Beasley, 2010; Buhrkal et al., 2012; Campos & Arroyo, 2017; Dotoli & Epicoco, 2017; Grakova et al., 2018; Moustafa et al., 2013; Nurprihatin & Lestari, 2020; Ombuki-Berman et al., 2007; Wy et al., 2013)
Minimize total costs	(Arribas et al., 2010; Liu & Liao, 2021; Nurprihatin & Lestari, 2020)
Minimize penalty costs	(Babaee Tirkolaee et al., 2019; Qiao et al., 2020)
Minimize carbon emission costs	(Liu & Liao, 2021; Qiao et al., 2020)
Minimize total vehicles usage costs	(Babaee Tirkolaee et al., 2019)
Minimize traversal costs	(Babaee Tirkolaee et al., 2019)
Minimize overlap	(Hurkmans et al., 2021)
Minimize waiting time	(Minh et al., 2013)
Minimize climate change costs	(Molina et al., 2019)
Minimize air pollution costs	(Molina et al., 2019)
Minimize fuel consumption costs	(Qiao et al., 2020)
Minimize vehicle fixed costs	(Qiao et al., 2020)
Maximize route compactness	(Kim et al., 2006; Ombuki-Berman et al., 2007)
Maximize total collected waste	(Dotoli & Epicoco, 2017)
Maximize total economic value of each vehicle's withdrawals	(Dotoli & Epicoco, 2017)

Table 2.5 (Continued)

Balancing vehicles workload	(Grakova et al., 2018; Hurkmans et al., 2021; Kim et al., 2006; Ombuki-Berman et al., 2007)

Table 2.5 shows that a total of 18 objectives have been taken into account in previous studies while attempting to solve WCVRP. Apparently, certain objectives in the WCVRP studies have been often highlighted, such as to minimize vehicle use, total travel time, and total travel distance. Therefore, these three objectives are crucial for waste collection process.

The constraints listed in past studies to solve WCVRP are discussed next.

2.3.2.3 Constraints in WCVRP

Some constraints must be determined to yield good and feasible routes when solving WCVRP. Table 2.6 lists the constraints previously considered in solving WCVRP.

Table 2.6

List of constraints considered previously in solving WCVRP

	Constraints	**References**
Depot/Customer/Landfill site	Time windows	(Babaee Tirkolaee et al., 2019; Benjamin & Beasley, 2010; Buhrkal et al., 2012; Campos & Arroyo, 2017; Kim et al., 2006; Minh et al., 2013; Moustafa et al., 2013; Nurprihatin & Lestari, 2020; Wy et al., 2013)

Table 2.6 (Continued)

	Single depot	(Benjamin & Beasley, 2010; Buhrkal et al., 2012; Kim et al., 2006; Wy et al., 2013)
	Service time	(Benjamin & Beasley, 2010; Buhrkal et al., 2012; Kim et al., 2006)
	Service types of customer demands	(Wy et al., 2013)
	Types and sizes of containers	(Wy et al., 2013)
	Disposal site types	(Wy et al., 2013)
	Multiple hard time windows	(Dotoli & Epicoco, 2017)
	Intermediate facilities	(Nurprihatin & Lestari, 2020)
Vehicle	Driver' lunch break	(Benjamin & Beasley, 2010; Buhrkal et al., 2012; Campos & Arroyo, 2017; Dotoli & Epicoco, 2017; Kim et al., 2006; Ombuki-Berman et al., 2007; Wy et al., 2013)
	Vehicle capacity	(Benjamin & Beasley, 2010; Buhrkal et al., 2012; Dotoli & Epicoco, 2017; Grakova et al., 2018; Kim et al., 2006; Ombuki-Berman et al., 2007)
	Routing time limit per vehicle	(Buhrkal et al., 2012; Kim et al., 2006; Ombuki-Berman et al., 2007)
	Traffic regulations	(Bautista et al., 2008)
	Traffic congestion	(Arribas et al., 2010)
	Traffic direction	(Arribas et al., 2010)
	Turn restriction	(Arribas et al., 2010)

Table 2.6 (Continued)

	Vehicle availability	(Dotoli & Epicoco, 2017)
	Heterogeneous vehicle	(Dotoli & Epicoco, 2017; Nurprihatin & Lestari, 2020)
	Soft time restrictions for vehicles	(Dotoli & Epicoco, 2017)
	Driver working time	(Grakova et al., 2018)
Operational	Multiple disposal trips	(Babaee Tirkolaee et al., 2019; Benjamin & Beasley, 2010; Buhrkal et al., 2012; Campos & Arroyo, 2017; Kim et al., 2006; Minh et al., 2013; Molina et al., 2019; Nurprihatin & Lestari, 2020; Ombuki-Berman et al., 2007; Wy et al., 2013)
	Route capacity	(Benjamin & Beasley, 2010; Buhrkal et al., 2012; Kim et al., 2006; Ombuki-Berman et al., 2007)
	Conflicts between waste properties	(Minh et al., 2013)
	Multiple container storage yards	(Wy et al., 2013)
	Split delivery	(Nurprihatin & Lestari, 2020)

Table 2.6 lists the constraints considered in previous studies while solving WCVRP. The constraints are divided into three categories: (1) depots, customers, and landfill site, (2) vehicle, and (3) operational. Based on the extensive review, 24 constraints were discovered, eight of which are classified under the first group. Next, 11

constraints are classified under the second group and the remaining constraints are classified under the third group.

In summary, for the first group (depots, customers, & landfill site), the constraints often encountered in previous studies were related to time windows. As for the second group (vehicle), the constraints that were often considered were driver's rest time and vehicle capacity; whereas multiple disposal trips for the third group (operational).

Finally, it can be concluded here that the constraints involved in the WCVRP are mostly due to the limited resources available for the solved problem. Thus, in order to construct good feasible routes to solve WCVRP, all the constraints must be satisfied. The more constraints involved, the more complicated the WCVRP can be.

Next, the solution techniques that have been considered in previous studies in solving WCVRP are presented.

2.3.3 WCVRP Techniques

Waste collection has long been acknowledged as one of the most challenging operational challenges for local governments throughout every country, as well as the most expensive operating costs in terms of waste management (Faccio et al., 2011). Commercial waste, residential waste, and roll-on-roll-off waste collections are the three primary types of waste collection. Many researchers have applied many approaches to solve WCVRP, such as heuristic algorithms and metaheuristics.

Kim et al. (2006) proposed a set of WCVRP benchmark problems and solved them using several heuristic algorithms. An extended insertion algorithm and a clustering-based approach were among the heuristics that had been tested. The construction route was improved using SA metaheuristics. Although the number of vehicles accumulated by the clustering-based algorithm is sometimes greater than that required by the insertion algorithm, its solution typically performs better in terms of route compactness.

Ombuki-Berman et al. (2007) used Kim's WCVRP benchmark problems to test a multi-objective GA for waste collection VRPTW. However, Kim et al. (2006) pointed out they ignored route compactness and workload balancing. The findings demonstrated the feasibility of using a multi-objective GA to solve a large-scale practical problem.

Bautista et al. (2008) presented a methodology for solving an urban WCVRP in Sant Boi de Llobregat, part of the Barcelona metropolitan area (Spain). The solutions to the problem were obtained using two constructive heuristics (nearest neighbor & nearest insertion heuristic) based on ACO, while different neighbourhood strategies were tested. The proposed methods yielded significantly better outcomes than those that were previously employed in the municipality.

Arribas et al. (2010) proposed a three-phase methodology to design an urban solid waste collection system. This methodology includes bin clusterisation and local search improvement, TS in GIS environment, and vehicle fleet design based on integer programming model with the branch-and-bound method. The findings showed that the proposed technique worked well and improved the existing solid waste collection distance, time, and costs. In comparison to the existing scenario, the overall monthly expenditures were cut by nearly 50% due to reduction in the number of vehicles and staff size.

Benjamin and Beasley (2010) used the same WCVRP benchmark problems as deployed by Kim et al. (2006). A greedy heuristic was utilized to produce an initial solution. Three metaheuristics, such as TS, variable neighbourhood search (VNS), and VNTS, were utilized to enhance the initial solution. In comparison to Kim et al. (2006), these metaheuristics used 5.6% less distance, whereas VNS was the most productive algorithm.

Buhrkal et al. (2012) solved WCVRP with time windows using a greedy heuristic proposed by Benjamin and Beasley (2010) and ALNS. They put the algorithm through its paces using the same benchmark problems proposed by Kim et al. (2006) as well as examples supplied by a Danish garbage collection company. The analysis revealed that ALNS outperformed Benjamin and Beasley's VNTS.

Minh et al. (2013) resolved the WCVRP's conflicts, time windows, and multiple landfills. (2013). An initial population was generated using Solomon's insertion heuristic. To improve the solution, the memetic algorithm, which employs both global and local search techniques, as well as the -interchange mechanism, was developed. Kim et al. proposed WCVRP benchmark problems for testing the algorithms. (2006).

The analysis indicated that if the conflict matrix had high density, both travel distance and number of vehicles used were large, while computation time in each benchmark was not proportional to the density of the conflict matrix.

Wy et al. (2013) proposed a rollon–rolloff WCVRP that involved large containers that collected massive volumes of waste at construction sites and shopping malls. For the problem, a large neighbourhood search based on iterative heuristic technique was developed. They created 34 benchmark problem instances to assess the efficacy of the algorithm: 14 of type A drawn from an actual waste collection firm in the US and 20 of type B that were artificially constructed. The results showed that the suggested algorithm offered substantially superior solutions for the benchmark data in terms of number of vehicles required and total route time than the current practice.

Benjamin and Beasley (2013) improved the heuristic algorithm that they developed in 2010 to address waste collection VRP by taking into account the elements that affected the actual difficulties encountered throughout the waste collection procedure. It was carried out by employing a disposal facility procedure to evaluate the routes acquired from the preceding initial solution. The solutions demonstrated that the proposed procedure yielded better routes than the previous algorithms.

Fouladi et al. (2013) proposed a mixed-integer nonlinear programming model for SWM and reverse supply chain problems. Their research goals were to reduce the cost of waste collection and transportation for recycling process. The route was designed based on the resemblance of trashcans. The suggested model was tested using the

LINGO 0.9 program, and the results revealed that the model maintained waste quality, enhanced recovery rate, and lowered disposal rate.

Das and Bhattacharyya (2015) presented a traveling salesman problem-based strategy to optimize MSW collection and transportation routes. The suggested approach optimized a municipal SWM system in terms of transportation route length. They structured the problem of MSW collection and transportation into a mixed-integer formulation. The suggested strategy had reduced more than 30% of the total traveling distance.

Gutierrez et al. (2015) demonstrated how to integrate the Internet of Things (IoT) with data access networks. An IoT prototype integrated with sensors that can read, collect, and transmit waste volume data over the Internet was used to demonstrate a waste collection solution based on delivering intelligence to the waste bin. The shortest path spanning tree algorithm was used in conjunction with GIS data from the city's streets to determine the shortest distance between two waste bins. By using open data from the city of Copenhagen, a realistic scenario was built to reveal the potential offered by these types of efforts and smart city solutions were developed.

Campos and Arroyo (2016) used a heuristic to solve WCVRP, which is a combination of the iterated local search metaheuristic and the variable neighbourhood descent local search. The greedy heuristic provided by Benjamin and Beasley (2010) was used to create the initial solution. The benchmark problems given by Kim et al. (2006) were used. The solutions derived from the benchmark problems deriving from the literature were competitive and several improved solutions were obtained.

Mat et al. (2017) used the nearest greedy algorithm for the initial route construction phase to solve WCVRP in a district in Northern Peninsular Malaysia. The findings showed that the proposed algorithm offered superior solutions, with a distance of less than 11.07% obtained when compared to the real distance of the current system.

Sackmann et al. (2017) developed a cluster first route second approach for WCVRP with time windows and multiple landfill sites. The algorithm is made up of a capacitated k-means algorithm and an extended savings algorithm. The algorithm was applied to evaluate five days of waste collection and two types of waste yield coherent waste collection subareas determined by the clustering algorithm. The more requesters that must be handled, the better the resulting solutions compared to the present manually designed clusters.

Babaee Tirkolaee et al. (2019) presented a mixed-integer linear programming model for heterogeneous multi-trip VRPs with time windows for urban waste collection in Iran. An innovative random generator algorithm was developed to obtain the initial solutions and all the initial solutions were one by one improved with SA algorithm. The analysis showed that the proposed algorithm yielded short computational time.

Nevrlý et al. (2019) presented several heuristic algorithms for waste collection arc routing problem. The initial solution was implemented using two algorithms: route-merging and path-scanning. The solution was then enhanced using local search and crossover algorithms. The given algorithm was tested on the Jihlava actual network, which had 1,467 vertices and 3,529 edges. The proposed algorithm resulted in 7% reduction in total travel distance.

Molina et al. (2019) focused on developing waste collection routes as a performance measure, with eco-efficiency as the primary focus. The COPERT model was used to calculate fuel consumption, CO2 emissions, and pollutant emissions. Initial solutions were generated using a semi-parallel construction algorithm. The initial solutions were then improved using the VNTS algorithm. This algorithm was validated in a real-world scenario in Alcalá de Guadara, a municipality in the Seville metropolitan region (Spain). According to the findings, replacing the existing vehicle with a vehicle of the same capacity and low-emission vehicle technology significantly reduced carbon dioxide and pollutant emissions.

Hashim et al. (2019) used fuel- and distance-based methods to examine carbon dioxide emissions of waste collection problem. Both strategies were selected for their applicability and suitability in estimating carbon dioxide for waste collection problem. When compared to the fuel-based method, the distance-based method emitted less carbon dioxide (about 7.1%) and less fuel use (about 1.77% fuel saving).

Marković et al. (2019) investigated a VRP in which demand and travel time between nodes are represented as normal-distributed stochastic variables. To solve the problems, they used heuristic and metaheuristic algorithms. The initial solution was obtained using the Clark and Wright savings algorithm. To improve this solution, the 2-OPT local search algorithm and the improved HSA were used.

Aliahmadi et al. (2020) investigated a fuzzy optimization method for the multi-trip municipal capacitated node routing problem. Due to the model's complexity, a GA was used. Meanwhile, in the following year, Aliahmadi et al. (2021) created a novel non-dominated sorting GA II-based bi-objective credibility-based fuzzy model for MSW collection with hard time windows. Both studies were carried out in a neighbourhood in Tehran, Iran.

Nurprihatin and Lestari (2020) created a WCVRP model with multiple trips, time windows, a heterogeneous fleet, and intermediate facilities. On actual data from Jakarta's Cakung district, the nearest neighbour algorithm was used to evaluate the model. The findings revealed that the proposed route resulted in the global best solution.

Qiao et al. (2020) proposed a two-phase algorithm for dealing with the capacitated VRP model. Three variables (economic, environmental, and social) were considered to assess the sustainability of the collection process. PSO was used in the first phase to find an initial best solution. TS was used to improve the initial solution obtained in the first phase.

Stanković et al. (2020) presented a capacitated distance-constrained VRP for MSW collection. The problem was solved on the Nis territory of Serbia. Four metaheuristic algorithms (GA, SA, PSO, & ACO) were used. The computational findings showed that by implementing the proposed algorithms, fuel cost was lowered by 10%.

Wu et al. (2020) proposed a low-carbon VRP model with chance constraints in a waste management system. The model combined carbon emission costs with traditional waste management costs in the scenario of smart bin implementation. Chance-constrained programming was used to convert an uncertain waste generation rate to a definite one. A hybrid algorithm based on PSO and SA was used to solve the model.

Zhang et al. (2020) solved WCVRP with multiple trips and demands using a parallel SA algorithm. The proposed algorithm was tested in Beijing's Xuanwu District using an international benchmark dataset and a real-world scenario. The computational results demonstrated that the proposed algorithm was superior, as it reduced the number of collection vehicles by one in four instances. In practice, the number of vehicles used and the travel time were reduced by 30% and 12%, respectively.

Hurkmans et al. (2021) used k-means and ALNS algorithms to solve a multi-objective residential waste collection problem with integrated territory planning. They pointing out that successful territory planning requires three factors: minimal overlap, minimal travel time, and a balanced workload. It was discovered that the proposed algorithms produced high-quality results in a reasonable amount of time.

Liu and Liao (2021) investigated a two-echelon collaborative WCVRP. A k-means clustering and a hybrid heuristic based on the Clarke and Wright algorithm with the ALNS algorithm were used to solve this problem. Following that, an improved

Shapley value model was built to calculate the costs and amount of carbon emissions reduction.

Yuliza et al. (2021) proposed a robust optimization model with time windows for the problem of waste transportation. To solve the problem, the nearest neighbour and cheapest insertion heuristic algorithms were used. The model was applied to the real-world situation in Palembang's Sako district. As a result, in their study, the cheapest insertion heuristics outperformed the nearest neighbour method..

Table 2.7 summarizes the past studies discussed in this section. The first column presents the techniques used to solve the WCVRP, while the second column shows the location of the solved problem. The references listed in the last column indicate the past studies that used WCVRP benchmark problems proposed by Kim (2006).

Table 2.7

Techniques used in WCVRP

Solution techniques	Case study location/benchmark	References
• Insertion algorithm • Clustering-based algorithm	WCVRP benchmark problems	**Kim et al. (2006)**
• Genetic algorithm	WCVRP benchmark problems	**Ombuki-Berman et al. (2007)**
• Nearest neighbour algorithm • Nearest insertion algorithm • Local search • Ant colonies optimisation	Barcelona, Spain	Bautista et al. (2008)

Table 2.7 (Continued)

• Clustering-based algorithm • Local search • GIS • Branch and bound	Santiago, Chile	Arribas et al. (2010)
• Greedy algorithm • Tabu search • Variable neighbourhood search • Variable neighbourhood tabu search	WCVRP benchmark problem	**Benjamin & Beasley (2010)**
• Technology traceability systems • Nearest neighbour algorithm	Northern Italy	Faccio et al. (2011)
• Greedy algorithm • Adaptive large neighbourhood search	Real life WCVRP benchmark problem and Danish Instances	Buhrkal et al. (2012)
• Iterative heuristic • Large neighbourhood search	Their own created benchmark data	Wy et al. (2013)
• Disposal facility positioning procedure	WCVRP benchmark problem	**Benjamin & Beasley (2013)**
• Mixed-integer nonlinear programming	Danish instances	Fooladi et al. (2013)
• TSP-based strategy	Kolkata, India	Das & Bhattacharya (2015)

2.4 Plant Propagation Algorithm (PPA)

The PPA, a new metaheuristic, was developed by Salhi and Fraga (2011). The PPA is a nature-inspired algorithm that mimics how plants propagate, specifically the strawberry plant, by colonizing new areas with favorable growing conditions. Plants, like animals, survive by devising strategies to overcome adversity. The strawberry plant has a survival and expansion strategy that includes sending short runners to exploit the local region if conditions are favorable, as well as sending long runners to explore new and more remote areas, such as running away from unfavorable current conditions.

A basic PPA was developed and tested on continuous optimization situations. The proposed algorithm was applied to a challenging process design problem that occurred in the purification of chlorobenzene, a problem with significant nonlinear behaviour and a narrow viable zone. The pseudocode of PPA proposed by Salhi and Fraga (2011) is illustrated in Figure 2.2.

```
Require: objective $f(x), x \in R^n$

    Generate a population $P = \{p_i, i = 1, \dots, m\}$
    $g \leftarrow 1$
    for $g \leftarrow 1$ to $g_{max}$ do
        compute $N_i = f(p_i), \forall p_i \in P$
        sort $P$ in descending order of $N$
        create new population $\emptyset$
        for each $p_i, i = 1, \dots, m$ do {best $m$ only}
            $r_i \leftarrow$ set of runners where both the size of the set and the distance for each
            runner (individually) is proportional to the fitness $N_i$
            $\emptyset \leftarrow \emptyset \cup r_i$ {append to population; death occurs by omission above}
        end for
        $P \leftarrow \emptyset$ {new population}
    end for
    return $P$, the population of solutions
```

Figure 2.2. The pseudo-code of PPA

Based on Figure 2.2, the algorithm begins with a population of plants, each representing a solution in the search space. In the search space, p_i is the solution of plant i. m denotes the population size. The algorithm process stops when g (generation counter) reaches its maximum value, g_{max}. The plants in a population are evaluated and sorted (in ascending/descending order) based on their fitness values and the problem is classified as either a minimum or maximum problem. A plant's fitness value is related to the number of runners it has, while the length of each runner is inversely proportional to its fitness value. A new population is formed by adding new solutions to the existing population. To maintain consistent population size, solutions with lower fitness values are discarded (Salhi & Fraga, 2011).

Some studies have applied the PPA. For example, Sulaiman et al. (2014) proposed a modified version of the PPA, namely the modified PPA. The enhancements involve the method through which new solutions at the end of runners are computed. The technique was evaluated on a larger test bench with a large number of functions with interesting properties, such as multi-modality and non-separability high dimensions, up to 100. On the majority of the test functions, the improved algorithm beat the artificial bee colonies. The improved approach provides a robust, simple solution to solve nonlinear, non-convex high-dimensional optimization problems.

Sulaiman et al. (2014) implemented PPA to address seven well-known challenging restricted optimization issues occurring in engineering design with continuous domains. From the analysis, PPA was discovered either close to the best-known answers or optimum. The findings were compared with other methods depicted in the literature.

Plant propagation by seed dispersion is a new variant of the PPA described by Sulaiman and Salhi (2015). The proposed algorithm is put through its paces on both unconstrained and constrained benchmark problems. The statistics (best, worst, mean, & standard deviation) of the generated solutions are compared. When compared with other algorithms, its performance indicated its superiority.

The PPA in the travelling salesman problem was studied by Selamoğlu and Salhi (2016). The study focused on how to use the concept of short and long runners while looking for Hamiltonian cycles in complete graphs. The concept of k-optimality was used in the algorithm. The algorithm performance was compared with that of GA, SA, PSO, and the New Discrete Firefly Algorithm (New DFA) on a standard set of test problems.

2.5 Summary

Most previous studies used a variety of environmental, economic, and social criteria for LSSP, as discussed in Section 2.2.1. Those studies, however, omitted information about the resources required in the process of finding a new landfill site, which could cause problems during the implementation phase. Furthermore, resource requirements must be determined early in the project lifecycle because these demands frequently exceed original projections, and failure to obtain resource commitments may depress project efforts (Reel, 1999; Somers & Nelson, 2001). In order to solve LSSP, resource requirements (e.g., vehicles, drivers, and fuel) that aid in waste transportation were considered in this research. This information may help decision-makers estimate the total operational costs associated with each potential landfill site.

The discussion on LSSP techniques in Section 2.2.2 shows that AHP is the most desirable MCDM method to address the importance of landfill site selection criteria. Some studies solely used AHP to solve the LSSP (Güler & Yomralıoğlu, 2017; Osra & Kajjumba, 2020), other studies (i.e., Karasan et al., 2018; Mallick, 2021) include fuzzy-based in the AHP, and there are also studies that integrated AHP with other MCDM techniques (i.e., Asefi et al., 2020; Mohammadi Seif Abad et al., 2021). Whereas, GIS is the most preferable technique for screening potential landfill sites.

GIS and MCDM techniques are the two current and widely used tools to address LSSP issues. The GIS was utilized in the preliminary site selection process to generate a list of possible sites. Meanwhile, MCDM was used to assess alternate sites discovered by GIS analysis. However, these current techniques were used to propose only a single landfill site based on the highest score. Thus, this research considered multiple landfill sites to solve LSSP based on the resources required for each landfill site.

As for waste collection vehicle routing problems, the greedy heuristic is one of the techniques that can be used to construct initial vehicle routes. Therefore, this technique was employed to develop an initial solution in this research. Next, PPA was deployed in this research to solve the WCVRP benchmark problems. The PPA solution was then compared against previous studies that used the same benchmark problem (see Table 2.6). The quality of PPA in solving WCVRP was evaluated in terms of the resources required for waste collection, such as total travel distance, total fuel consumption, total travel time, number of vehicles needed, and average working hours needed for each driver to complete the collection process.

The next two chapters focus on the methodologies to solve the problems. The methodology to solve LSSP is explained in Chapter 3. This method aims to achieve research objectives 1 to 3. Whereas, the methodology for solving WCVRP is explained in Chapter 4. This method achieves research objectives 4 and 5.

CHAPTER THREE
METHODOLOGY OF LANDFILL SITE SELECTION MODEL

3.1 Introduction

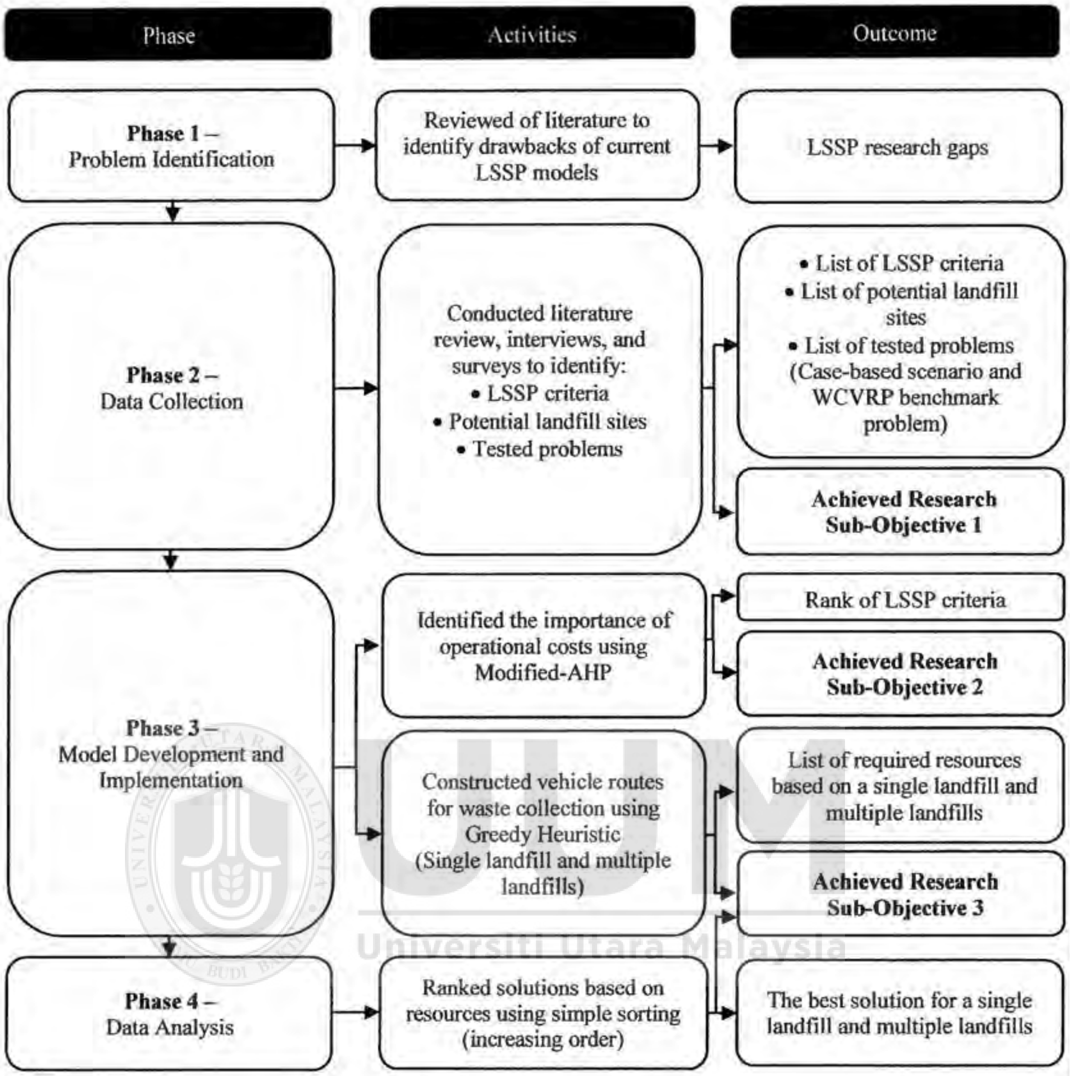
This chapter discusses the methodology used to accomplish research objectives 1, 2, and 3 in relation to LSSP. It starts with a research framework that consists of four phases. Next, it continues with the research process that describes in detail the activities, techniques, and outputs of each phase.

3.2 Research Framework

Figure 3.1 illustrates the research framework to solve LSSP with the lowest operational costs associated with resources. The framework presents four phases, namely: problem identification, data collection, model development and implementation, as well as data analysis. For each phase, the description of research activities, the developed technique, and the generated outputs are listed in details.

3.3 Research Process

This section describes the research framework of LSSP. The four phases involved in solving the LSSP are as follows: problem identification, data collection, model development and implementation, as well as data analysis. The phases were deployed to achieve research objectives 1, 2, and 3 in relation to LSSP. Further description of each phase is explained from Section 3.3.1 to Section 3.3.4.



RESEARCH OBJECTIVES:

The main objective of this research is to develop a greedy heuristic for multiple landfill site selection and to improve WCVRP solutions by using PPA. To achieve the main objective, the following specific objectives must be fulfilled:

1. To identify the criteria that must be considered in selecting new landfill sites in Malaysia.
2. To determine the level of importance of landfill site selection criteria including the new criterion, operational cost by using Modified-AHP.
3. To propose multiple landfill sites with the minimum total operational costs by using a greedy heuristic.
4. To develop PPA for improving WCVRP solutions.
5. To evaluate the quality of the WCVRP solution using PPA in terms of total travel distance, the number of vehicles/drivers required, total working hours of drivers, and total fuel consumption using a case-based scenario and benchmark problem set by Kim et al. (2006).

Figure 3.1. Research framework of LSSP

3.3.1 Phase 1: Problem Identification

The research started with an extensive review of the literature on SWM and the best methods for managing such waste in a sustainable manner. Sustainable SWM must strike a balance between the necessity to save resources and the equally crucial duty of environmental protection. It is vital to achieve this balance within the existing waste hierarchy while also employing available resources efficiently and tackling current difficult situations.

Typically, in the existing SWM operational elements; waste generation, collection, and disposal systems are designed separately, even though the three activities are tightly interrelated and can influence each other. Among these, waste collection and landfilling are among the most essential services in most countries, including Malaysia, where huge operational expenditures are required.

The aim of this phase is to identify the drawbacks of the current LSSP models. Based on the comprehensive review conducted, the first issue is related to LSSP criteria, which is composed of environmental, economical, and social criteria. Landfill lifetime, land cost, job opportunities, construction expenses, and building materials are the common criteria of economical clusters. Meanwhile, operational costs linked with resources employed during waste collection services have been overlooked in previous studies, and are proposed in this research. The total travel distance to transport the collected waste to the landfill, the number of vehicles/drivers needed for collection, the total working hours of drivers, and the total fuel consumption are all significant criteria that can influence the total operational costs.

In the second issue, previous studies proposed a single landfill site based on the highest score (ranking). None has considered the selection of multiple landfill sites. Thus, this research proposes a new approach for solving multiple LSSP, which is expected to assist the authorities. If the current model, which is based on the scoring approach, is used to choose multiple landfill sites, the chosen sites may be a bad selection owing to the overlapping covered areas.

Therefore, the main objective of this research work is to develop a model for LSSP that satisfies the resource needs restrictions that contribute to low operating costs, while concurrently decreasing government expenditure on SWM. In addition, this study introduces a new approach for solving multiple LSSP that gives another alternative to the waste management team.

3.3.2 Phase 2: Data Collection

Data collection is the systematic gathering and evaluation of information on subjects of interest in order to answer specific research questions, test hypotheses, and produce results. Data for this research were gathered in two stages. Primary and secondary data are the two types of information gathered. To collect primary data, expert interviews were conducted. The 12 experts involved in this research were from SWCorp, which is under MHLG Malaysia.

SWCorp is a corporation charged with ensuring that SWM and public cleaning services are implemented effectively and extensively in order to meet the needs of consumers and the community. Two experts were interviewed in order to gain a better understanding of the existing SWM practices and challenges in Malaysia. The content of the interview is presented in Figure 3.2.

The content of the interview topics:

- Personal information of the experts: name, age, gender, work position, and duration of service with the organization
- Their duties and involvement in the LSSP process
- The existing LSSP practices in Malaysia
- The required criteria typically considered in LSSP from a practical standpoint
- The relevant resources that should be considered in LSSP from the experts' standpoint
- The organizational technical guidelines prescribed by experts for better LSSP procedures

Figure 3.2. The content of the interview topics

Next, secondary data were obtained from a report published by Ministry of Housing and Local Government entitled "The Technical Guideline for Sanitary Landfill, Design, and Operation" in 2004. Some secondary data were collected from the literature and a website suggested by the experts.

The investigation of the actual LSSP process sought to match and validate the knowledge obtained from the literature. Collaborative actions made with these experts had improved the research findings. The proposed operational cost criteria related to resources had been based on ideas gathered from the literature and practical, which were integrated to build a new model for LSSP.

In this research, two datasets were used to test the proposed algorithm: WCVRP benchmark problem set introduced by Kim et al. (2006) and a case-based scenario in Kubang Pasu District, Kedah. The details of the datasets are presented in the next sub-section. Figure 3.3 summarizes the research data.

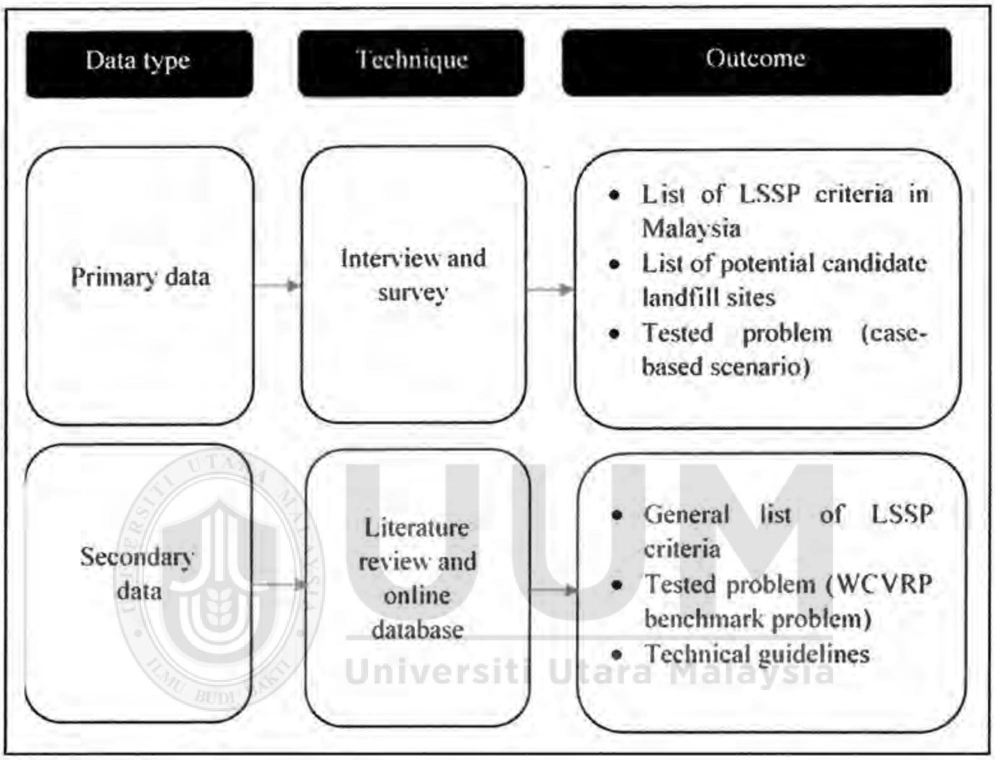


Figure 3.3. Lists of primary and secondary data

3.3.2.1 A WCVRP Benchmark Problem

The WCVRP benchmark problem used in this research was presented by Kim et al. (2006). It consists of 10 problem sets involving up to 2092 customers and 19 waste disposal facilities. The benchmark can be retrieved at: https://sites.google.com/site/logisticslaboratory/research/research-areas/waste_collection_vrptw_benchmark. The problem sets consist of customers, number of disposal sites, vehicle capacity, and route capacity per day. The characteristics of the problem sets are presented in Table 3.1.

Table 3.1

The characteristics of WCVRP benchmark problem

Dataset name	**Number of customers**	**Number of landfill sites**	**Vehicle capacity (yard)**	**Route capacity/day (yard)**
102	99	2	280	400
277	275	1	200	2200
335	330	4	243	400
444	442	1	200	400
804	784	19	280	10000
1051	1048	2	200	800
1351	1347	3	255	800
1599	1596	2	280	800
1932	1927	4	462	2000
2100	2092	7	462	2000

The dataset name indicates the total number of nodes that are considered in each problem. For example, dataset 102 has 102 nodes, representing 99 customers, two landfill sites, and one depot ($99 + 2 + 1 = 102$). The vehicle has a 280-yard capacity, with a total waste collection capacity of 400 yards per day. The number of depots is one for all datasets, and the maximum number of customers served by each vehicle daily is 500. The driver is given a one-hour lunch break. There is no limit to the number of homogeneous vehicles. The coordinates obtained from the problem sets are in feet for each node (depot/customers/disposal sites), and the distance between nodes is calculated (in miles) using Manhattan distance as follows:

$$d_{i,j} = \sum_{i=1,j=1}^{n} |x_{i1} - y_{j1}| + |x_{i2} - y_{j2}| \tag{3.1}$$

The formula to estimate distance in feet is given in Equation (3.1). Distance in feet is converted to miles (1 feet = 0.000189394 miles). For each problem set, the distance matrix ($n \times n$) is developed, where n is the total number of nodes (depot/disposal facility/customer). For problem set 102, the distance matrix (102×102) is created.

The constraints related to depot, customers, landfill site, vehicle capacity, and operation of the WCVRP benchmark problem are listed in Table 3.2.

Table 3.2

Constraints related to WCVRP (Source: Mat et al., 2018)

Constraints	Descriptions
For depot/customer/landfill site:	• Total number of customers to be served • Total number of depot • Total number of landfill sites • Time windows • Demand (waste to be collected from customers) • Service time
For vehicle:	• Maximum number of customers served per day • Capacity of vehicle (maximum weight allowed) • Driver's lunch break • Speed (speed allowed for vehicle to carry waste)
For operational:	• Each vehicle must start and end at the depot • Each customer should be served exactly once • The amount of waste collected from customers cannot exceed the allocated load for a vehicle • The vehicle must be emptied if the capacity is full before continuing servicing customers or before returning to the depot upon completing collection

3.3.2.2 A Case-based Scenario

The second test problem used to test the proposed algorithms was a case-based scenario inspired by real data gathered in Kubang Pasu District, Kedah; comprising of 146 residential areas with 18749 housing units. Information about the distribution of residential areas, housing units, and candidate landfill sites for each city within the Kubang Pasu District are presented in the second to forth columns of Table 3.3.

Table 3.3

Information regarding the research area for the case-based scenario

Cities	Number of residential areas	Number of housing unit	Candidate landfill sites (ID)
Jitra	116	15356	C1, C4
Kodiang	6	383	C2
Changlun	19	2363	-
Bukit Kayu Hitam	5	647	C3, C5
Total	146	18749	5

Table 3.3 provides detailed information on the research areas for the case-based scenario. This information includes residential areas, housing units, and candidate landfill sites. All information provided is based on their total numbers in the following cities (Jitra, Kodiang, Changlun, & Bukit Kayu Hitam). In Jitra City, for example, there are 116 residential areas, 15356 housing units, and two candidate landfills (ID1 & ID4). The total number of residential areas in the four cities of Kubang Pasu District is 146, the total number of housing units is 18749 units, and the number of candidate landfills is five. The location of the candidate landfill was manually identified using Google Earth based on a number of specific criteria, such as unused land, agricultural land, and not close to populated areas. These candidate landfill sites were also agreed by the experts for testing purposes.

In this research, a dataset for the case-based scenario was created based on the information acquired from expert interviews, government reports, and government website. The characteristics of the dataset are given as follows:

- The number of customers is 146.
- The number of depots is one.
- The number of candidate landfill sites is five.
- Time windows of nodes (depot/customers/candidate landfill sites): 8 am to 9 pm
- The vehicle's capacity to serve customers is limited to 7000 kg.
- The total waste collection capacity is 100000 kg per day.
- The driver's lunch break is one hour.
- Each house has a servicing time of 20 seconds.
- The average amount of waste per household is 4 kg.
- The vehicle's maximum speed is 40 km/h.

The following list is the similarity characteristics of WCVRP benchmark problem, and the case-based scenario used in this research:

i) Single depot
ii) Multiple landfills
iii) A set of customers
iv) The location coordinate of each node is available. Both cases are solved as node routing problems.
v) Time windows of nodes
vi) Limited vehicles capacity

vii) One hour driver's lunch break

viii) Service time of each customer

ix) Total waste of each customer

x) Static speed limit of the vehicles

Figure 3.4 shows the distribution of customers, possible landfill sites, and a depot.

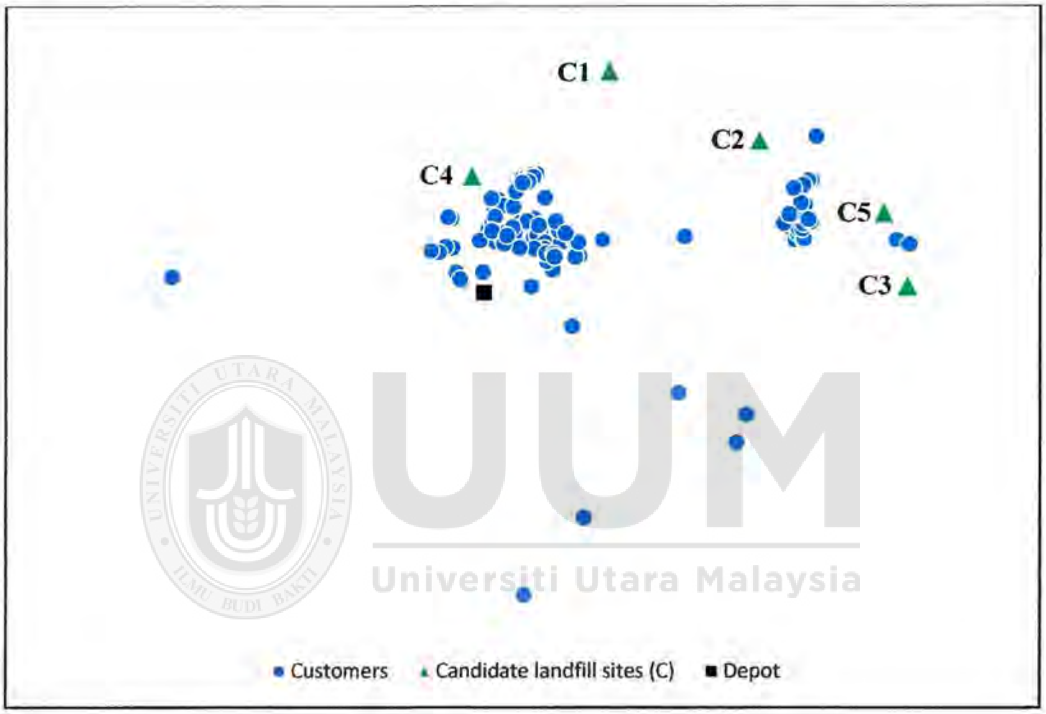


Figure 3.4. Distribution of nodes for the case-based scenario in Kubang Pasu, Kedah

Figure 3.4 shows the distribution of nodes (customers, candidate landfills, & depots) for the case-based scenario in Kubang Pasu district located in Kedah. The four cities in Kubang Pasu involved in this case-based research are Jitra, Kodiang, Changlun, and Bukit Kayu Hitam. This case involved 146 customers, five candidate landfill sites, and a single depot. The number of residential areas involved is as follows: 116 units (Jitra), 6 units (Kodiang), 19 units (Changlun), and 5 units (Bukit Kayu Hitam). As for the candidate landfill sites, 2 units (C1 & C4) were located in Jitra, 1 unit (C2) in Kodiang, and 2 units (C3 & C5) in Bukit Kayu Hitam. The depot is located in Jitra.

3.3.3 Phase 3: Model Development and Implementation

This section describes the two techniques used to solve LSSP. First, the Modified-AHP was used to estimate the weight of LSSP criteria including the new criterion introduced in this research. Second, the greedy heuristic algorithm was used to provide information on the resources required by each candidate landfill sites. The procedures of each technique adopted in this research are explained in the next sub-sections:

3.3.3.1 Modified-AHP Technique (M-AHP)

The previous chapter concluded that AHP is one of the best MCDM techniques for determining the significance of landfill site selection criteria. However, there is a weakness in using AHP related to consistency issues. Consistency is important because inconsistent pairwise comparisons indicate a poor judgmental process, and subsequently, the pairwise comparison process needs to be reconstructed. One of the methods for dealing with inconsistency is to use the Modified-Analytic Hierarchy Process (M-AHP) technique developed by Balhuwaisl. (2013). Therefore, this research employs the M-AHP to assess the importance of landfill site selection criteria, including a new criterion, operational cost. Other researchers such as Nazri, Ahmad, and Shariffuddin (2019) and Eddy, Nazri, and Mahat (2020) also applied the M-AHP to solve MCDM problems. They have proven that using the M-AHP by Balhuwaisl (2013) provides consistent feedback from respondents.

In the study by Balhuwaisl (2013), a pre-assessment step before performing pairwise comparisons was carried out. During this pre-assessment, experts must rate each criterion on a scale of 1 to 9, with 1 being the least important criterion and 9 being the most important criterion. These ratings are then analyzed using a straightforward mathematical algorithm to generate a pairwise comparison matrix. The weights for each criterion are then calculated using the existing AHP method to determine the criteria's priority. Figure 3.5 depicts the general steps used to develop the M-AHP model, and the following sub-sections provide a detailed explanation of each step.

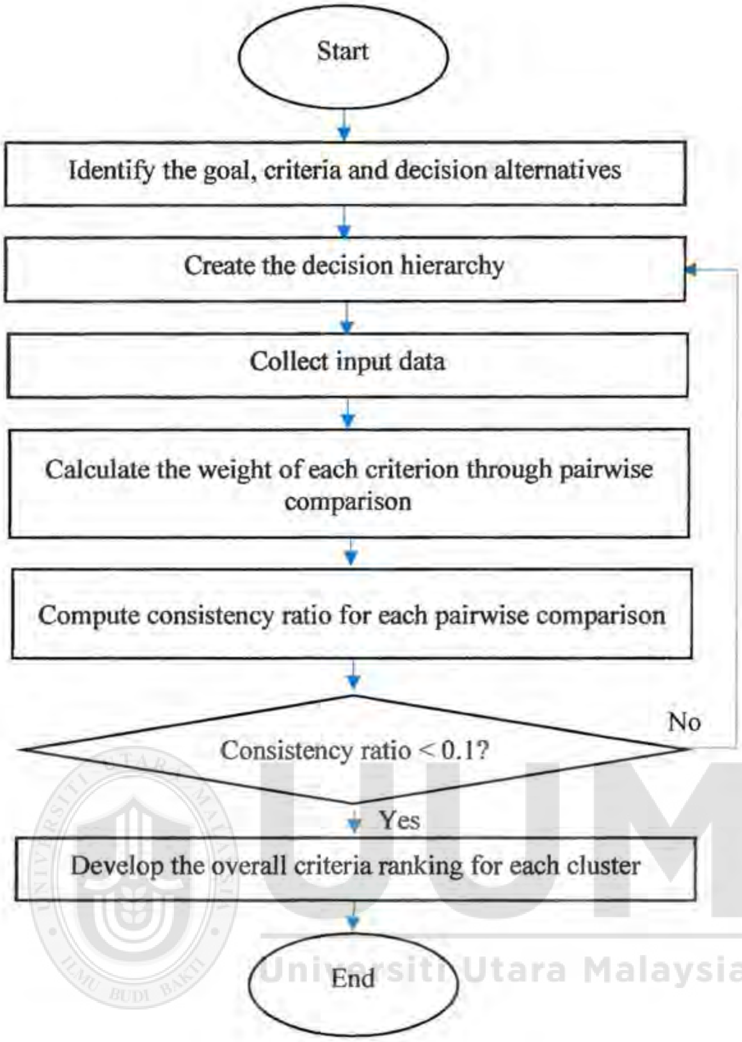


Figure 3.5. Modified-AHP flowchart

3.3.3.1.1 Identify the goal and criteria

In general, the first step when developing an AHP model is to transform the decision problem into three key components: (1) goals, (2) criteria/sub-criteria, and (3) decision alternatives. The first component includes the desired outcome or in a simple word, the objective to be achieved. The second component includes a measure of goal-related criteria or characteristics. Finally, the third component includes the desired options or choices for achieving the goal. However, this research only focuses on components one and two. The third component is discussed in the heuristic greedy algorithm (refer to Section 3.3.3.2).

In this research, the first component (the goal) is to determine the level of importance of landfill site selection criteria for selecting new landfill sites. Whereas, for the second component (the criteria), a total of thirty-three criteria were considered and classified into three main clusters, namely environmental, economical, and social. Sixteen of them are associated with the environmental cluster, twelve with the social cluster and the remaining five with the economical cluster. Each criterion has been thoroughly explained in Chapter 2 in Section 2.2.1.

3.3.3.1.2 Create the decision hierarchy

The second step is to transform the decision problem into a hierarchy. According to Saaty (2001), the simplest way to structure a decision problem is as a three-level hierarchy. Decision goals are at the top level, followed by criteria at the second level, and alternatives at the third level. This decision hierarchy is the basic picture used by the human mind to comprehend a decision problem.

Since the alternatives are not discussed in this section, thus, the decision hierarchy for this research is formed up to the second level as illustrated in Figure 3.6.

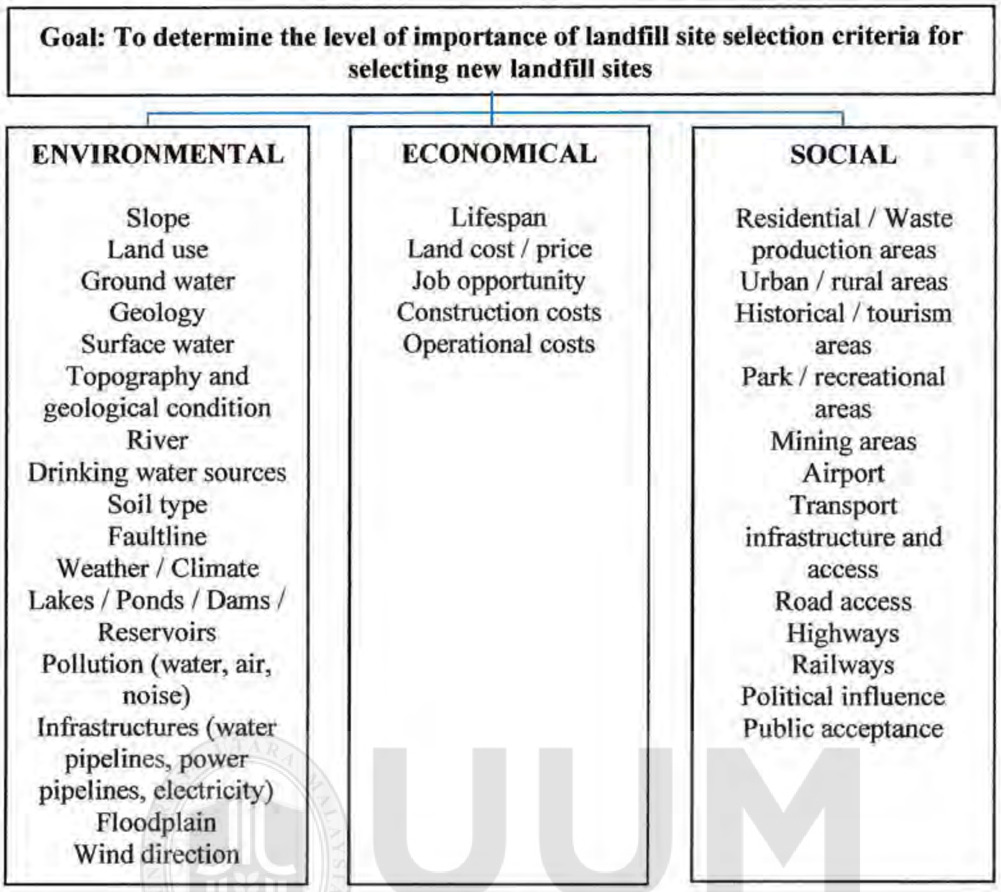


Figure 3.6. The decision hierarchy of LSSP

Based on Figure 3.6, the decision hierarchy has two levels. The first level of the hierarchy demonstrates that the overall goal is to determine the level of importance of LSSP criteria in selecting new landfill sites. The second level contains the three main clusters: environmental, economical, and social clusters. This level includes all the criteria of each cluster which contribute to the achievement of the overall goal.

3.3.3.1.3 Collect input data

In this step, the input data, which refer to the LSSP criteria, were collected via a questionnaire (see Appendix A). The questionnaire was specifically designed to facilitate pairwise comparisons while also addressing the issue of inconsistency (Balhuwaisl, 2013). Then, the questionnaire was transformed into a Google Form (see Appendix B) to make it easier for the respondents to fill out the survey. The respondents were SWCorp experts from various states in Peninsular Malaysia. They are required to make comparative judgements using a scale with values ranging from 1 to 9, with 1 representing the equally preferred and 9 representing extremely preferred. Using M-AHP, a specially designed questionnaire allows respondents to rate the level of importance of the criteria towards the overall goal by using a value between 1 and 9 (See Table 3.4). This is to assess the respondent's logical thinking in determining the importance of criteria towards the overall goal (Balhuwaisl, 2013; Engku Abu Bakar, Balhuwaisl, & Mat Kasim, 2016).

Table 3.4

The preference scale for pairwise comparison

***Preference level**	**Numeric value**
Equally preferred	1
Equally to moderately preferred	2
Moderately preferred	3
Moderately to strongly preferred	4
Strongly preferred	5
Strongly to very strongly preferred	6
Very strongly preferred	7
Very strongly to extremely preferred	8
Extremely preferred	9

*The preference level can be substituted with importance level, significance level or any other relevant level

Based on the respondent's feedback on the criteria, a rating table for each respondent as shown in Table 3.5 is created. Table 3.5 is an example of rating table of Respondent 1. The remaining eleven respondent's rating tables are included in Appendix C. The

'X' mark in Table 3.5 represents the rating of each criterion in relation to the overall goal.

Table 3.5

Rating table for criteria

Criteria	**Rating**								
	1	2	3	4	5	6	7	8	9
C_1		X							
C_2			X						
C_3				X					
C_4					X				
C_5						X			
C_6							X	X	
C_7									X
C_8							X		
C_9					X				

3.3.3.1.4 Calculate the weight of each criterion through pairwise comparison

The weight of each criterion is calculated in the fourth step. The previously obtained rating tables are transformed into a pairwise comparison matrix. A simple mathematical algorithm for determining the weight of each criterion is proposed by Balhuwaisl (2013). Suppose here, the respondents rate the criterion i as a_i and criterion m as a_m. Meanwhile, y_{im} is the comparison value between criterion i and criterion m will be determined as illustrated in Equation 3.1 to Equation 3.5.

$$\text{if } i \leq m \tag{3.1}$$

$$\text{let } b = a_i - a_m \tag{3.2}$$

$$\text{if } b < 0\text{, then } y_{im} = \frac{1}{1-b} \tag{3.3}$$

$$\text{if } b = 0, \text{ then } y_{im} = 1 \tag{3.4}$$

$$\text{if } b > 0, \text{ then } y_{im} = b + 1 \tag{3.5}$$

Where, $y_{im,}$ the value in the matrix.

Then, the input data gathered from the respondents was then transformed into a pairwise comparison matrix, as shown in Table 3.6.

Table 3.6

The pairwise comparison

	$\boldsymbol{C_1}$	$\boldsymbol{C_2}$	$\boldsymbol{C_3}$	$\boldsymbol{C_4}$	...	$\boldsymbol{C_m}$
$\boldsymbol{C_1}$	1	y_{12}	y_{13}	y_{14}	...	y_{1m}
$\boldsymbol{C_2}$	$1/y_{12}$	1	y_{23}	y_{24}	...	y_{2m}
$\boldsymbol{C_3}$	$1/y_{13}$	$1/y_{23}$	1	y_{34}	...	y_{3m}
$\boldsymbol{C_4}$	$1/y_{14}$	$1/y_{24}$	$1/y_{34}$	1	...	y_{4m}
...	...	...	...	...	1	...
$\boldsymbol{C_m}$	$1/y_{1m}$	$1/y_{2m}$	$1/y_{3m}$	$1/y_{4m}$	...	1

After obtaining the pairwise comparison matrix, the weight of each criterion is calculated using the existing AHP method.

3.3.3.1.5 Compute consistency ratio for each pairwise comparison

The next step is a critical process in which the consistency of the decision makers' pairwise judgement is compared. Due to the difficulty of achieving perfect consistency with so many pairwise comparisons, some degree of inconsistency can be expected in almost any set of pairwise comparisons. Balhuwaisl (2013) proposes the M-AHP as a strategy for measuring the degree of consistency among respondents' pairwise comparisons. If the level of consistency is unacceptable, the decision maker should return to the pairwise comparison and revise it before proceeding to the M-AHP analysis. M-AHP provides a measure of consistency for the pairwise comparison by computing the CR.

Composite Reliability (CR) determines an acceptable level of consistency. The values of CR is determined as follows:

$$CI = \frac{(lambda_{max} - n)}{(n-1)}$$

$$CR = \frac{CI}{RI}$$

Where, CI represents the consistency index, $lambda_{max}$ represents the maximum eigenvalue of the judgement matrix, and RI represents the random index. The CR should be less than 0.1 to get a consistent result. However, if the CR is more than 0.1, the result is inconsistent and decision hierarchy need to rebuild.

However, that is not an issue because by using this M-AHP technique, all paired matrices produce consistent pairwise comparisons, $CR < 0.1$.

3.3.3.1.6 Develop overall criteria ranking of each cluster

Following the completion of the consistency calculation for all levels, the overall criteria ranking was calculated to determine which criterion was most important for each cluster. The greedy heuristic algorithm was used in this research to determine the best location for a landfill.

3.3.3.2 Greedy Heuristic Algorithm

In this research, a new LSSP model is proposed after taking into account a new criterion within the economical cluster, which refers to operational costs associated with resources. This research improved the problem by proposing two LSSP models: single-based LSSP and multiple-based LSSP. To accomplish this, the greedy heuristic algorithm from Mat et al. (2017, 2018) was used to generate solutions for the case-based scenario in Kubang Pasu District, Kedah, as well as the real-life WCVRP benchmark problem initiated by Kim et al. (2006).

The greedy heuristic was used in this research to construct vehicle routes to solve WCVRP. A new set of preliminary solutions was developed based on the number of candidate landfill sites. For example, for a single selection model, if five potential landfill sites were identified, five solutions were created for comparison purposes. Meanwhile, for the multiple LSSP model, if five candidate landfill sites were discovered, a pair for each vehicle route was developed.

Figure 3.7 illustrates the flowchart of the greedy heuristic applied to solve the WCVRP.

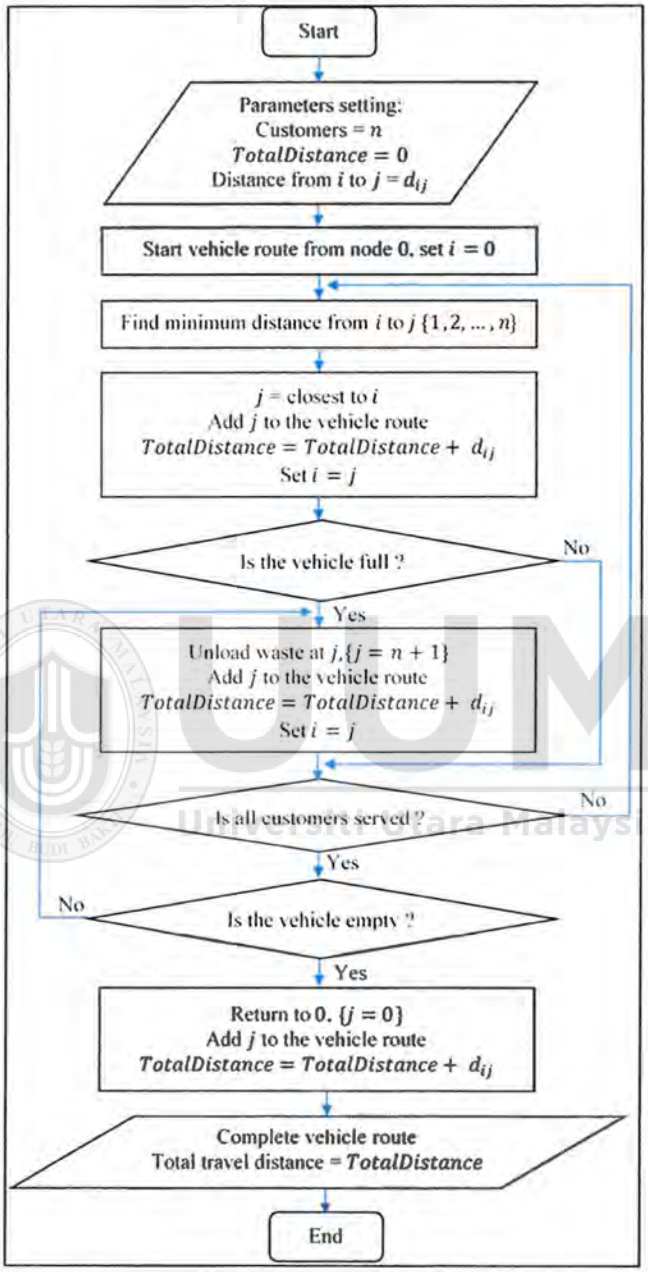


Figure 3.7. Greedy algorithm flowchart for WCVRP (Source: Mat et al., 2018)

Based on Figure 3.7, the description of the greedy algorithm is as follows:

Step 1: The algorithm starts by setting the parameters depending on which dataset (refer to Table 3.1) to be solved. The total number of nodes is computed as $\{n + one\ depot + one\ landfill\ site\}$, where n represents the total number of customers served. Each node is specified by its ID, where ID 0 is for the depot, $\{1, 2, \ldots, n\}$ for customers, and $\{n + 1\}$ for the landfill site. In addition, the total distance travelled is also set to zero, *TotalDistance = 0.*

Step 2: A new vehicle route is constructed, where the first node of the route is the depot ($i = 0$).

Step 3: Find the next customer to be visited. The next customer = j is the closest to node i (the minimum distance from node i to node j, d_{ij})

Step 4: Add customer j to the vehicle route. Update the total distance travelled, *TotalDistance = TotalDistance +* d_{ij}. Set node i = node j.

Step 5: Check the capacity of the vehicle. If the vehicle is full, then go to Step 6, else go to Step 7.

Step 6: Unload the waste at the landfill site (node $j = n + 1$). Add node j to the vehicle route. Update the total distance travelled, *TotalDistance = TotalDistance +* d_{ij}. Set node i = node j. Go to Step 7.

Step 7: Check if all customers have been visited. If yes, go to Step 8, else go to Step 3.

Step 8: Check if the vehicle is empty. If yes, go to Step 9, else go to Step 6.

Step 9: Return to the depot (node $j = 0$). Add node j to the vehicle route. Update the total distance travelled, *TotalDistance* = *TotalDistance* + d_{ij}. Set node i = node j.

Step 10: The solution is completed. Display *TotalDistance* and vehicle route. Terminate algorithm.

The greedy heuristic algorithm is run separately for each landfill site candidate (refer to Table 3.3) with a different location (refer to Figure 3.4) to obtain the information related to waste collection resources such as the total distance travelled.

3.3.4 Phase 4: Data Analysis

The AHP technique was applied in this research to calculate the weight of LSSP criterion. The AHP was executed manually using Microsoft Excel. Meanwhile, the greedy heuristic algorithm was used to calculate the resources and to assess the possible landfill locations. The greedy heuristic algorithm was implemented in C++. The solutions on resources were then ranked using simple sorting (increasing order). The best solution for a single landfill and multiple landfills had been discovered. This indicates that sub-objective 3 is accomplished.

3.4 Summary

In this chapter, the LSSP model was solved using the AHP technique and greedy heuristic algorithm. The AHP was used to weigh and rank the selection criteria. Next, the greedy heuristic algorithm was deployed to evaluate the potential landfill sites based on resource requirements. In summary, this chapter has answered the specific objective mentioned in the first chapter. The objective is to develop a resource-based selection model using MCDM and greedy heuristic algorithm. The next chapter presents the methodologies for constructing the WCVRP model.

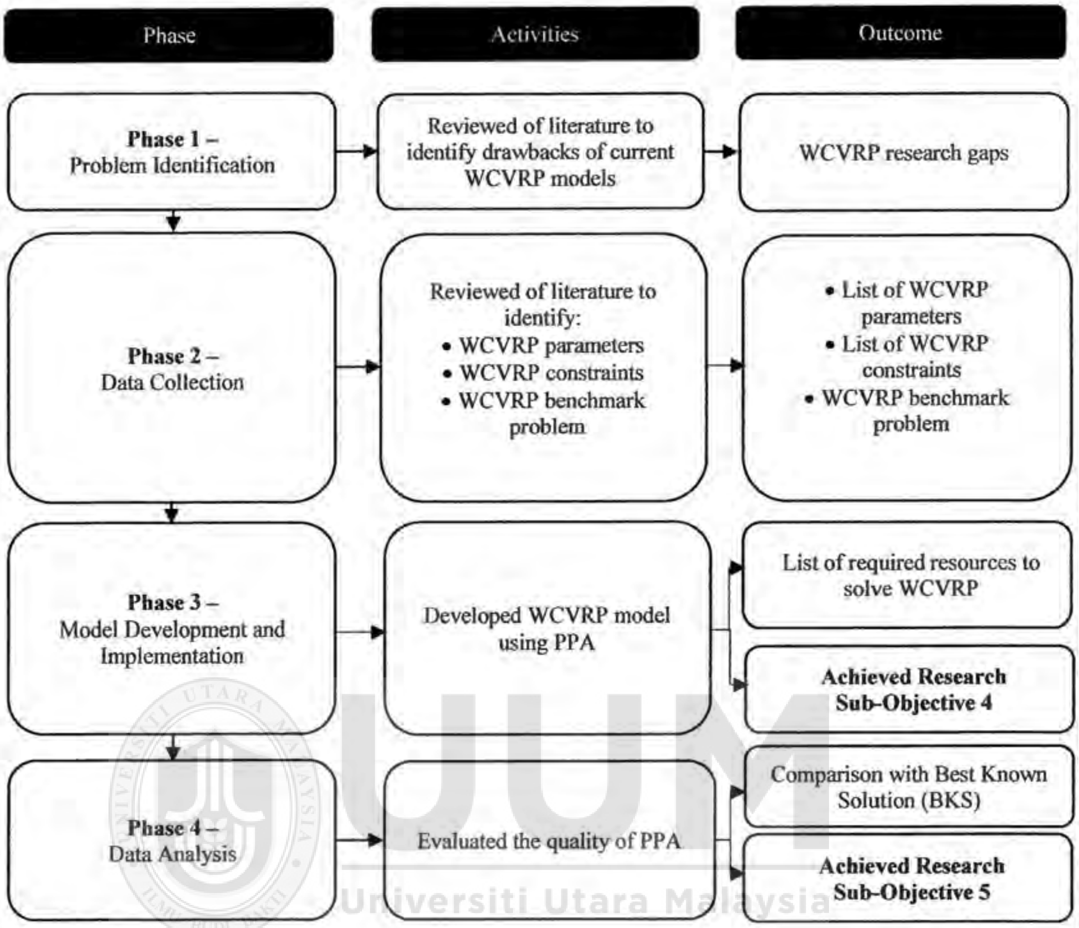
CHAPTER FOUR
METHODOLOGY OF WASTE COLLECTION VEHICLE ROUTING MODEL

4.1 Introduction

This chapter describes the methodology used to achieve research objectives 4 and 5 in relation to WCVRP. It starts with a research framework that consists of four phases. After that, it continues with the research process that describes in detail the activities, techniques, and outputs of each phase.

4.2 Research Framework

Figure 4.1 illustrates the research framework to solve WCVRP with the lowest operational costs associated with resources. The framework is composed of four phases, including problem identification, data collection, model development and implementation, as well as data analysis. Each phase consists of three important parts, which are activity, technique used to solve the activity, and output obtained from the activity.



RESEARCH OBJECTIVES:

The main objective of this research is to develop a greedy heuristic for multiple landfill site selection and to improve WCVRP solutions by using PPA. To achieve the main objective, the following specific objectives must be fulfilled:

1. To identify the criteria that must be considered in selecting new landfill sites in Malaysia.
2. To determine the level of importance of landfill site selection criteria including the new criterion, operational cost by using Modified-AHP.
3. To propose multiple landfill sites with the minimum total operational costs by using a greedy heuristic.
4. To develop PPA for improving WCVRP solutions.
5. To evaluate the quality of the WCVRP solution using PPA in terms of total travel distance, the number of vehicles/drivers required, total working hours of drivers, and total fuel consumption using a case-based scenario and benchmark problem set by Kim et al. (2006).

Figure 4.1. Research framework of WCVRP

4.3 Research Process

This section describes the research framework of WCVRP. The four phases involved in solving the WCVRP are as follows: problem identification, data collection, model development and implementation, as well as data analysis. The phases were executed to achieve research objectives 4 and 5, which are related to WCVRP. More description of each phase is explained from Section 4.3.1 until Section 4.3.4.

4.3.1 Phase 1: Problem Identification

The research work began by reviewing several theoretical studies related to WCVRP in order to understand the problem structures discussed in Chapter One. The research gap was identified after the literature review. Apparently, most studies have applied heuristic and metaheuristic algorithms to tackle problems related to WCVRP. Here, it can be concluded that no study has deployed PPA to address WCVRP. As such, this research had examined the quality of PPA in solving WCVRP.

4.3.2 Phase 2: Data Collection

In this research, a WCVRP benchmark problems was used to evaluate the quality of PPA in solving WCVRP. This benchmark problems was obtained from Kim et al. (2006), which contained 10 datasets. The details of each dataset are discussed in Chapter Three (see sub-section 3.3.2.1).

4.3.3 Phase 3: Model Development and Implementation

This section describes the process of using PPA to solve the WCVRP benchmark problem. First, the constructive heuristic algorithm, which is the RIC-based greedy algorithm was used to generate a set of initial solutions. Following that, the PPA developed by Salhi and Fraga (2011) was used to improve the initial solutions. The following subsections explain the procedures for each algorithm used in this research.

4.3.3.1 The RIC-based Greedy Algorithm

The RIC-based greedy algorithm used in this research refers to the modified version of Benjamin and Beasley (2010, 2013). This modified algorithm was used to construct a set of initial solutions for the PPA. This algorithm randomly selected the first customer for route 1 for each set of the initial solutions. Following that, the next customer on the current route was chosen based on who was closest to the previous customer in terms of travel time. The flowchart for the RIC-based greedy algorithm is illustrated in Figure 4.2

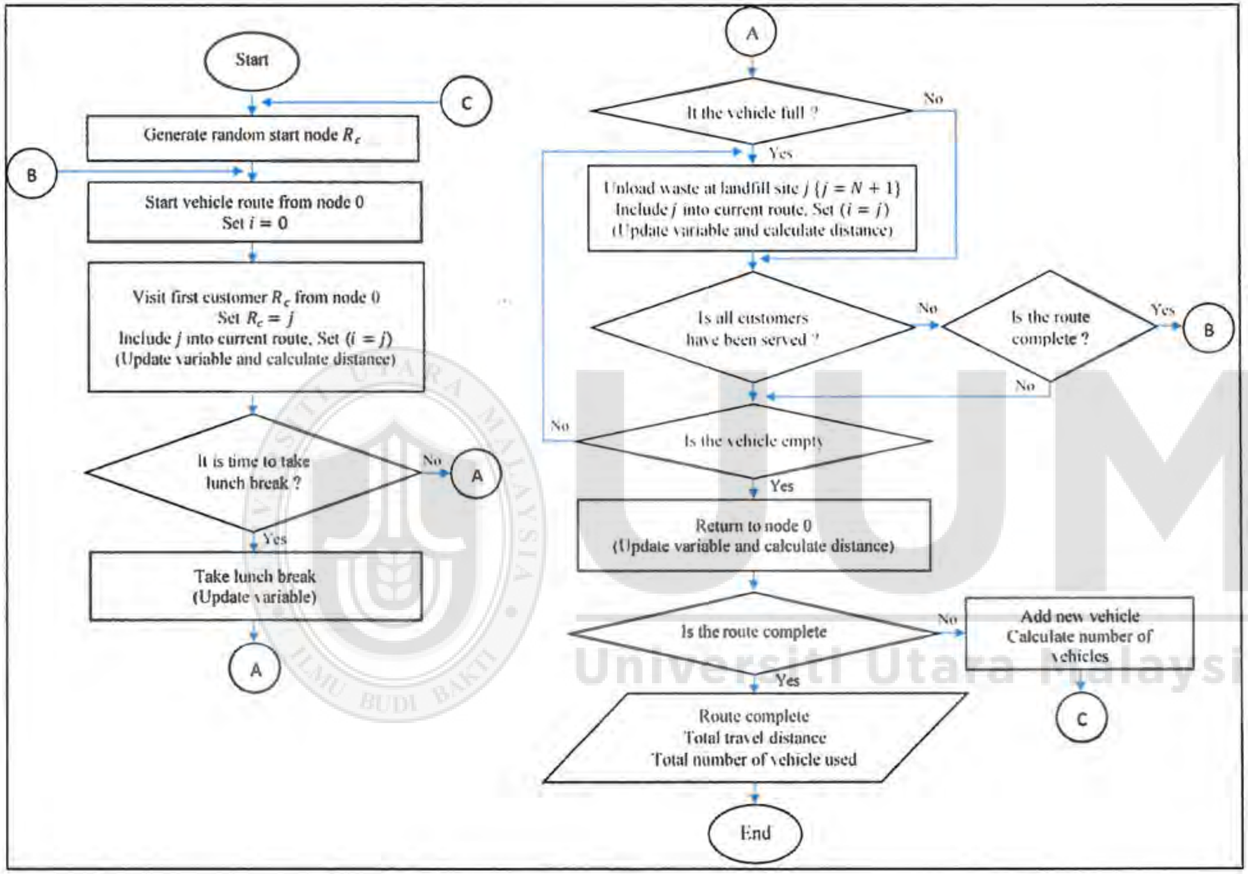


Figure 4.2. The RIC-based greedy algorithm flowchart

The WCVRP is defined on a graph $G = (V, A)$, with $V = \{0, 1, \dots, N, N + 1\}$ as a set of nodes, where node 0 represents depot, node $N + 1$ represents landfill site, the remaining nodes $\{1, \dots, N\}$ represent customers, and A is the edge set of nodes. Based on Figure 4.2, the description of the RIC-based greedy algorithm is as follows:

Step 0: The algorithm starts by setting the parameters and variables as listed below:

- N = number of customers
- $[E_i, L_i]$ = time windows of node i (i.e., customers and landfills)
- $[E_0, L_0]$ = time windows of the depot
- S_i = service time of node i
- Q_i = demand of node i
- T_{ij} = travel time from node i to node j
- D_{ij} = distance from node i to node j
- $T = E_0$, current time
- C = vehicle capacity
- $totalVehicle = 0$

Step 1: Generate the first customer to be visited, R_c randomly.

Step 2: A new vehicle route is constructed, where the first node of the route is the depot (node $i = 0$).

Step 3: From the depot, visit R_c (node j). Add node j to the vehicle route.

Step 4: Update the following variables:

- total travel distance, $D_{total} = D_{total} + D_{ij}$

- total customer visited, $S_{total} = S_{total} + 1$
- total load carried by vehicle per day, $Q_{total} = Q_{total} + Q_j$
- vehicle current load, $Q_{current} = Q_{current} + Q_j$
- $T = T + T_{ij} + S_i$
- node i = node j.

Step 5: Check the lunch break. If the current time T is between the lunch periods, then go to Step 5, else go to Step 6.

Step 5: Take a lunch break. Update $T = T + 1$ hour lunch break.

Step 6: Check the capacity of the vehicle. If the vehicle is full, then go to Step 7, else go to Step 8.

Step 7: Unload the waste at the landfill site (node $j = N + 1$). Add node j to the vehicle route. Update the following variables:

- total travel distance, $D_{total} = D_{total} + D_{ij}$
- total load carried by vehicle per day, $Q_{total} = Q_{total} + Q_j$
- vehicle current load, $Q_{current} = 0$
- $T = T + T_{ij} + S_i$
- node i = node j.

Step 8: Check if all customers have been served. If yes, go to Step 10, else go to Step 9.

Step 9: Check if the route is complete. If yes, go to Step 2. Else, go to Step 10.

Step 10: Check if the vehicle is empty. If yes, go to Step 11, else go to Step 7.

Step 11: Return to the depot (node $j = 0$). Add node j to the vehicle route. Update the following variables:

- total travel distance, $D_{total} = D_{total} + D_{ij}$
- $T = T + T_{ij}$
- node i = node j.

Step 12: Check if the route is complete. If yes, go to Step 14. Else, go to Step 13.

Step 13: Add a new vehicle. Update total vehicle, *totalVehicle* = *totalVehicle* + 1. Go to Step 1.

Step 14: Solution is completed. Display complete routes, total travel distance, D_{total} and, the total vehicles used, *totalVehicle*.

The solution obtained from the RIC-based greedy algorithm is presented in Chapter 5 (see Section 5.3.1).

4.3.3.2 The Plant Propagation Algorithm

The PPA was proposed by Salhi and Fraga (2011), which mimics the process by which plants survive by spreading locations with favorable growing conditions. Plants, like animals, survive by adapting to their surroundings. For example, the strawberry plant has a survival and expansion strategy that involves sending short runners to exploit the local area if conditions are favorable, and sending long runners to explore new and more isolated areas, i.e. to run away from a less favorable current area. (Selamoglu & Salhi, 2016).

The PPA was used in this study to improve the initial solutions in terms of total travel distance, total fuel consumption, total travel time, total number of vehicle used, and driver's working hours (average). Figure 4.3 displays the flow chart of PPA for solving WCVRP.

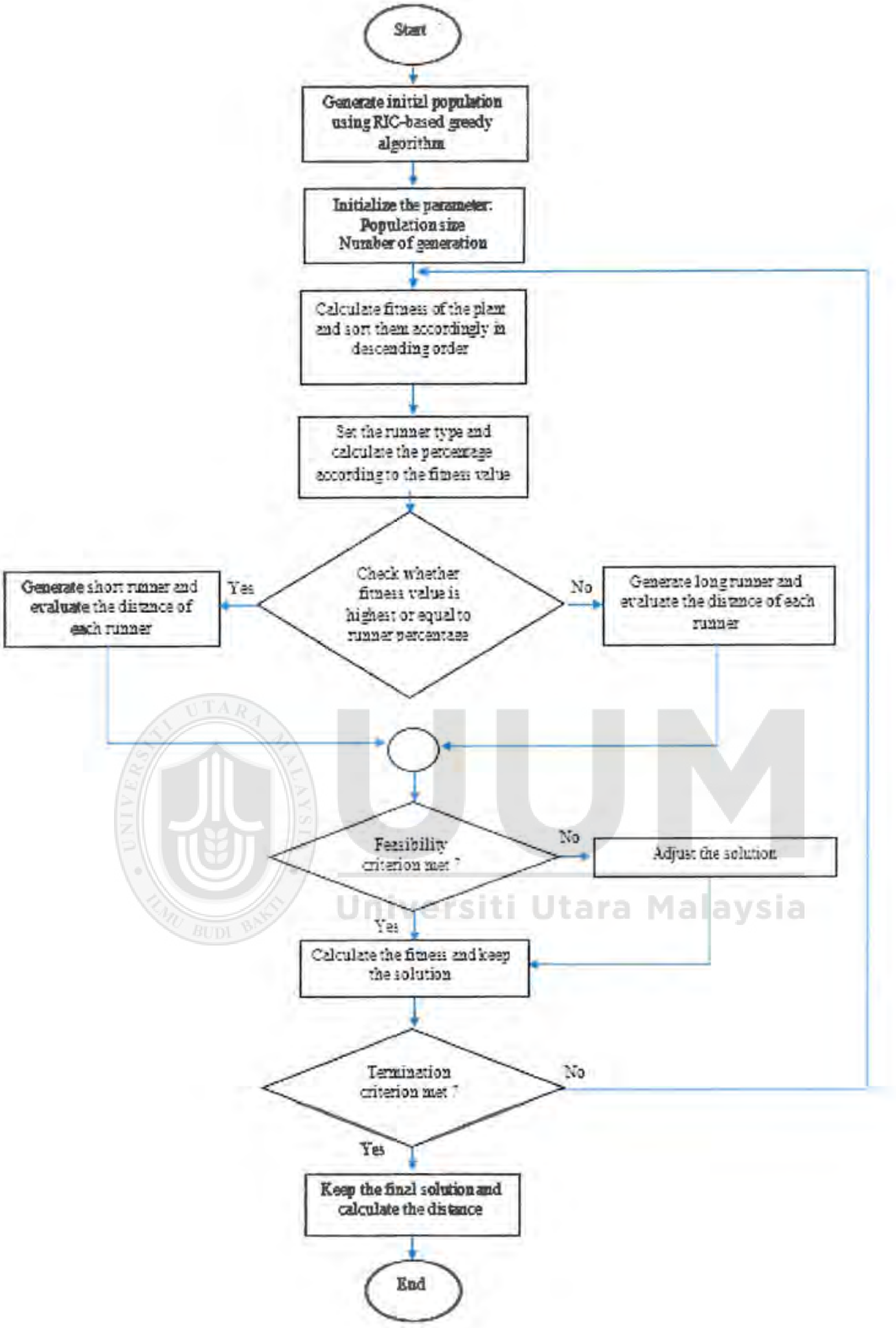


Figure 4.3. The flowchart of PPA for solving WCVRP

Based on Figure 4.3, the description of the PPA algorithm is as follows:

Step 1: The algorithm starts by generating the initial population P ($P = X_i, \{i = 1, \dots, PS\}$ using RIC-based greedy algorithm. X_i represents a set of vehicle route and PS denotes the population size of plant P.

Step 2: The parameter is setting up to test the dataset. The population size is 20. The maximum number of generations (g_{max}) is 100 This indicates that the whole process are executed 100 times.

Step 3: The fitness of plants, $f(X_i)$, and mapping fitness of plants, $N(X_i)$, were calculated based on the following equations.

$$f(X_i) = \frac{Z_{max} - Z}{Z_{max} - Z_{min}} \tag{4.1}$$

Equation (4.1) is a formula for calculating the fitness plants, $f(X_i)$. Z_{max} is the maximum objective function (total distance travel) from population P. Z_{min} is the minimum objective function, and Z_i is the current value of the plant's objective function. This calculation is illustrated in the following table.

For example, we have 5 plants ($A, B, C, D, \& E$) in population P. From Table 4.1, $Z_{max} = 500$, $Z_{min} = 100$, and current value of plant $A = 100$.

Table 4.1

Sample of population P

Plant / vehicle route	Objective function value	Fitness function value $f(x_i)$
A	100	1
B	200	0.75
C	300	0.5
D	400	0.25
E	500	0

$$N(X_i) = \frac{1}{2}(\tanh(4f(X_i) - 2) + 1) \tag{4.2}$$

Equation (4.2) is a formula for calculating the mapping fitness of plant, $N(X_i)$. After calculating the fitness and mapping fitness of plant, population P was sorted in ascending order (for minimization) of fitness value. The new population P_1 was created.

Step 4: The runner type is identified for each plant x_i based on $f(X_i)$. Runner percentage, (rp) also been identified. rp is used to identify whether the plant needs long runners or short runners to explore new areas. The identification of the runners is in the next step.

Step 5: Check value of $f(X_i)$ for each plant. If $f(X_i)$ value is greater or equal to rp, $(X_i \geq rp)$ then short runners is generated (Go to Step 6). Else, long runners would be generated (Go to Step 7). As an example, by referring to the $f(X_i)$ in Table 4.1, if rp is 70%. Then Plant A and B will generates short runners. Meanwhile, others plant (C, D and) would generate long runners.

Step 6: A new plant are generated by sending short runners from the main plant. The procedure for short runners consists of five main steps:

Step A: Generate a random number, *r*

Step B: Find the position of the random number *r*

Swap the position of the random number *r*. Three conditions need to be fulfilled to swap the random number position.

Condition to swap:

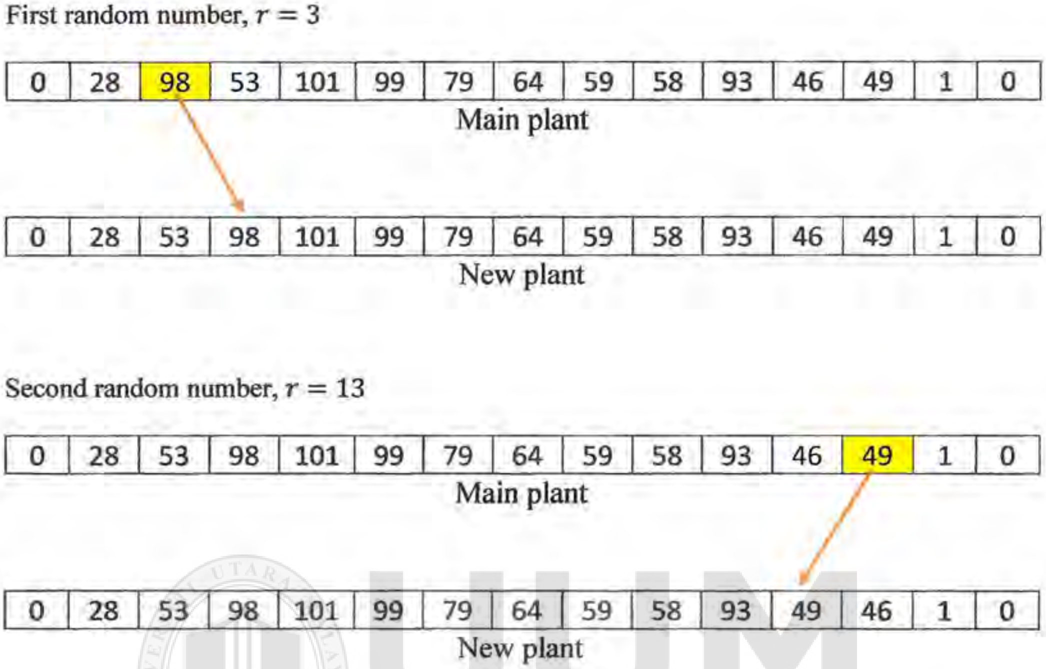
- Must swap with random number position next to *r*, which is $r + 1$
- But, if $r + 1$ is depot or disposal, then swap with random number position before *r*, which is $r - 1$
- Check the time windows constraint during the swapping process, if satisfied then go to the next step. If violated, then go back to ***Step A***.

Step C: Calculate the total distance of the plant

Step D: Check the total distance of the new plant, if less than or equal to the main plant, then replace it. Proceed for generating the next random number.

Step E: Repeat step 1 until the random number is searched 5 times

An illustration of a new plant generated by sending a short runner from the main plant is displayed in Figure 4.4.



First random number, $r = 3$

0	28	98	53	101	99	79	64	59	58	93	46	49	1	0

Main plant

0	28	53	98	101	99	79	64	59	58	93	46	49	1	0

New plant

Second random number, $r = 13$

0	28	53	98	101	99	79	64	59	58	93	46	49	1	0

Main plant

0	28	53	98	101	99	79	64	59	58	93	49	46	1	0

New plant

Figure 4.4. Illustration of new plants generated by sending short runners from the main plant

Based on the plants depicted in Figure 4.4, node 0 is a depot, node 1 is a disposal, and other nodes are the customers. For example, for the main plant, the vehicle starts from a depot and then continues to collect waste from customers 28, 98, 53, 101, 99, 79, 64, 59, 58, 93, 46, and 49. Next, unloads the waste at disposal 1, and returns to the depot.

To generate a new plant, suppose the first random number is $r = 3$. Referring to the main plant, the 3rd node is customer 98. Then, customer 98 will be swapped with the next node (i.e., position $r + 1 = 4$). The swapping process proceeded since the next node, $r + 4$ is customer 53. Thus, a new plant is generated. If the new plant is feasible and better than the main plant, (i.e., the total distance travelled is less than the main plant), the new plant is accepted and the main plant = new plant is updated.

For the second random number, $r = 13$, the 13th node is customer 49. However, the swapping process cannot proceed with the next node because the 14th node is disposal 1. Thus, in this case, customer 49 is swapped with the 12th node (i.e., $r - 1 = 12$) which is customer 46. The procedure is repeated until five feasible new plants are generated, and the main plant is updated.

Step 7: A new plant are generated by sending long runners from the main plant. The procedure for long runner is similar to the short runner procedure. However, the random number is searched 10 times, which is higher than that of the short runner. This provides an opportunity for the main plant to explore the search space to improve solutions from the main plant.

Step 8: Check the feasibility of each solution from Step 6 and Step 7. If the solution is feasible, then go to Step 9, else the solution is adjusted until feasible.

Step 9: The value of $f(X_i)$ for new plant from both runner types is calculated and the solution is stored.

Step 10: Check if the termination criterion met. If yes, go to Step 11, else go to Step 3.

Step 11: The solution completed. Terminate the algorithm. All variables involved updated. The total travel distance, total fuel consumption, total travel time, number of vehicles used, are displayed.

4.3.4 Phase 4: Data Analysis

After completing the experiment, the computational results were obtained and are presented in Chapter Five.

4.4 Summary

In this chapter, the WCVRP was solved using metaheuristic algorithms. First, a constructive heuristic algorithm, namely RIC-based greedy algorithm, was used to generate several initial solutions. The initial solution was then improved by using PPA. As such, this chapter has answered the specific objective mentioned in the first chapter. The objective is to develop a resource-based WCVRP model using PPA. The next chapter presents the computational results for several models of landfill site selection and waste collection routing problems.

CHAPTER FIVE
RESULTS AND DISCUSSIONS

5.1 Introduction

This chapter is divided into two sections. The first section presents LSSP findings, including the profile of respondents, criteria used for LSSP, the rank of the criteria, and solutions from single and multiple LSSP models. The second section presents WCVRP findings, such as PPA solutions, and a comparison of PPA with solutions from prior research work.

5.2 Results for LSSP

This section presents results related to LSSP. It starts with an overview of the profile of respondents, followed by a set of criteria used for LSSP in Malaysia, the rank of the LSSP criteria, and finally, the computational results of resources-based analysis for single and multiple landfill sites for LSSP.

5.2.1 Overview of Respondents' Profile

In this research, the respondents were experts from SWM and SWCorp, which are under the MHLG. The data collection took about eight months due to time restrictions and the COVID-19 pandemic that affected the country. The data were gathered in two phases.

In the initial phase, face-to-face interviews were conducted with three experts from SWCorp Kedah located in Alor Setar. The main goal of the interviews is to finalize the LSSP criteria used in Malaysia, including the new criterion introduced in this study (i.e., the operational cost associated with resources).

In the second phase, a survey via questionnaire was conducted. The AHP questionnaire was developed for SWM experts specialized in LSSP. The AHP questionnaire was distributed via email to 41 experts from SWCorp Malaysia. All experts involved in this research are suggested from SWCorp Kedah due to their involvement in the decisions on landfill sites issues in Malaysia. Unfortunately, only 12 experts responded to the questionnaire. Of these 12 experts, six experts were from the headquarters, three experts were from Melaka, two experts were from Kedah, and one expert was from Perlis.

The main purpose of this survey is to determine the importance of the LSSP criteria finalized from the initial phase. A description of these experts in terms of their attachment to the SWCorp branch, their position, and their working experience is presented in Table 5.1.

Table 5.1

Description of experts' profile

Experts ID	**SWCorp Branches**	**Position**	**Working experiences (Years)**
1	WP Kuala Lumpur	Technical	3
2	WP Kuala Lumpur	Quantity Surveyor	6
3	WP Kuala Lumpur	Technical	6
4	WP Kuala Lumpur	Engineer	3
5	WP Kuala Lumpur	Engineer	11

Table 5.1 (Continued)

6	WP Kuala Lumpur	Engineer	12
7	Melaka	Engineer	4
8	Melaka	Engineer	9
9	Melaka	Engineer	11
10	Kedah	Engineer	5
11	Kedah	Technical	5
12	Perlis	Engineer	12

The experts listed in Table 5.1 were requested to rate the importance of each criterion in selecting a new location for a landfill facility in Malaysia. Google Forms was used as the medium to deliver the AHP questionnaire via email. Their responses were based on their expertise and experience with the LSSP procedure. Most of the experts involved in this study survey were engineers (66.67). Regarding working experience, 41.67% of the experts had between 3 and 5 years of working experience, while 58.33% of the respondents had more than 5 years of work experience. Next, half of the experts held a bachelor's degree, while others possessed master's degrees and diplomas.

5.2.2 LSSP Criteria Used in Malaysia

In the pilot study, the LSSP criteria gathered from the literature and government report entitled "Technical Guidelines for Sanitary Landfill, Design, and Operation" were assessed by the experts. Table 5.2 lists the LSSP criteria acquired from the literature that may influence LSSP in Malaysia.

Table 5.2

List of criteria that may influence LSSP in Malaysia

LSSP Criteria
Environmental Cluster
River
Groundwater/Surface water
Drinking water source
Slope
Agricultural areas
Soil permeability
Fault line
Elevation
Flooding
Climate/Rainfall
Land use
Drainage/Pipeline systems
Power lines
Forests
Economical Cluster
Residential areas
Waste production centre
Financial/Cost
Social Cluster
Urban area/Rural area
Park/Recreational areas
Historical and tourism centre
Restricted areas/Unstable areas
Road access
Highways
Railways
Airport
Political

Table 5.2 presents the LSSP criteria that may influence LSSP in Malaysia, which were identified from the literature review. These criteria are categorized under three clusters, namely environmental, economical, and social clusters. As shown above, 14 criteria are classified under the environmental group, three criteria under the economical group, and nine criteria under the social group. All these criteria were given to experts during the first phase of interviews to select and finalize the list of final criteria that may affect the LSSP process in Malaysia. Apart from the list

provided, the experts were also asked to suggest other criteria that were not listed but could affect the selection process.

In conclusion, a technical report was recommended by the experts. Based on the discussion and the reference of the technical report, 16 criteria were finalized for the environmental cluster, 5 criteria for the economical cluster, and 12 criteria for the social cluster were identified. Table 5.3 summarizes this research's criteria after the selected experts' interview sessions.

Table 5.3

The summary of criteria used in this research after the interview with experts

Cluster	**Number of sub-criteria identified**	**Number of sub-criteria eliminated**	**Number of new sub-criteria added**	**Total sub-criteria**
Environmental	14	1	3	16
Economical	3	-	2	5
Social	9	-	3	12

The summary of LSSP criteria used in this research after the interview with experts is as stated in Table 5.3. For the environmental cluster, 14 sub-criteria were identified. Of these 14 criteria, two criteria were combined and three new sub-criteria were added. The total sub-criteria under the environmental cluster is 16. As for economical and social clusters, two and three new sub-criteria were added, respectively, under both clusters. As such, the total sub-criteria for both clusters were 5 and 12. The finalized LSSP criteria for landfill siting in Malaysia are presented in Table 5.4.

Table 5.4

The finalized selection criteria for landfill siting in Malaysia

Main criteria	Sub-criteria
Environmental	1. Slope
	2. Land use
	3. Groundwater
	4. Geology
	5. Surface water
	6. Topography and geological condition
	7. River
	8. Drinking water sources
	9. Soil type
	10. Faultline
	11. Weather / Climate
	12. Lakes / Ponds / Dams / Reservoirs
	13. Pollution (water, air, noise)
	14. Infrastructures (water pipelines, power pipelines, & electricity)
	15. Floodplain
	16. Wind direction
Economical	1. Lifespan
	2. Land cost / price
	3. Job opportunity
	4. Construction cost
	5. Operational cost
Social	1. Residential / Waste production areas
	2. Urban / Rural areas
	3. Historical / Tourism areas
	4. Park / Recreational areas
	5. Mining areas
	6. Airport
	7. Transport infrastructure and access
	8. Road access
	9. Highways
	10. Railways
	11. Political influence
	12. Public acceptance

Table 5.4 presents 16 environmental, five economical, and 12 social criteria, which can be considered for solving LSSP in Malaysia. This output has achieved research objective 1. The bold criteria represent additional criteria obtained from a government technical report entitled "Technical Guidelines for Sanitary Landfill, Design, and Operation" released by the Ministry of Housing and Local Government Malaysia

(2004) and recommendations from experts during interviews conducted with SWCorp Kedah. The criteria weighting through M-AHP-based pairwise comparison is presented in the next section.

5.2.3 Criteria weighting through pairwise comparison

The respondent was asked to evaluate each criterion regarding the importance of selecting a new landfill site. The respondent verbal description of the level of importance for each criterion is evaluated based on a scale of 1 (least important) to 9 (extremely important). The first respondent analyzed the criteria as shown in Table 5.5(a) until Table 5.5(c). While for the evaluations gathered from other respondents are in Appendix C. The 'X' mark represented the level of importance of each criterion towards the overall goal.

Table 5.5(a)

Rating table for the environmental cluster for Respondent 1

Criteria	Rating								
	1	2	3	4	5	6	7	8	9
C_1							X		
C_2								X	
C_3									X
C_4							X		
C_5									X
C_6							X		
C_7									X
C_8									X
C_9									X
C_{10}							X		
C_{11}									X
C_{12}							X		
C_{13}									X
C_{14}							X		
C_{15}							X		
C_{16}						X			

Table 5.5(b)

Rating table for the economical cluster for Respondent 1

Criteria	Rating								
	1	2	3	4	5	6	7	8	9
C_1									X
C_2									X
C_3							X		
C_4									X
C_5								X	

Table 5.5(c)

Rating table for the social cluster for Respondent 1

Criteria	Rating								
	1	2	3	4	5	6	7	8	9
C_1									X
C_2									X
C_3									X
C_4									X
C_5							X		
C_6									X
C_7								X	
C_8							X		
C_9							X		
C_{10}							X		
C_{11}									X
C_{12}									X

The respondents' ratings are transformed into a matrix form and then mathematically modified to determine the weights. The ratings were analyzed using the formula described in Chapter 3 (Section 3.3.3.1.4) and then converted into a converted pairwise comparison table, as shown in Table 5.6(a) until Table 5.6(c).

Table 5.6(a)

Converted pairwise comparison table for the economical cluster for Respondent 1

		CRITERIA				
		C_1	C_2	C_3	C_4	C_5
CRITERIA	C_1	1	1	3	1	2
	C_2	1	1	3	1	2
	C_3	1/3	1/3	1	1/3	½
	C_4	1	1	3	1	2
	C_5	1/2	1/2	2	1/2	1

Table 5.6(b)

Converted pairwise comparison table for the environmental cluster for Respondent 1

		CRITERIA															
		C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}	C_{11}	C_{12}	C_{13}	C_{14}	C_{15}	C_{16}
	C_1	1	1/2	1/3	1	1/3	1	1/3	1/3	1/3	1	1/3	1	1/3	1	1	2
	C_2	2	1	1/2	2	1/2	2	1/2	1/2	1/2	2	1/2	2	1/2	2	2	3
	C_3	3	2	1	3	1	3	1	1	1	3	1	3	1	3	3	4
C	C_4	1	1/2	1/3	1	1/3	1	1/3	1/3	1/3	1	1/3	1	1/3	1	1	2
R	C_5	3	2	1	3	1	3	1	1	1	3	1	3	1	3	3	4
I	C_6	1	½	1/3	1	1/3	1	1/3	1/3	1/3	1	1/3	1	1/3	1	1	2
T	C_7	3	2	1	3	1	3	1	1	1	3	1	3	1	3	3	4
E	C_8	3	2	1	3	1	3	1	1	1	3	1	3	1	3	3	4
R	C_9	3	2	1	3	1	3	1	1	1	3	1	3	1	3	3	4
I	C_{10}	1	1/2	1/3	1	1/3	1	1/3	1/3	1/3	1	1/3	1	1/3	1	1	2
A	C_{11}	3	2	1	3	1	3	1	1	1	3	1	3	1	3	3	4
	C_{12}	1	1/2	1/3	1	1/3	1	1/3	1/3	1/3	1	1/3	1	1/3	1	1	2
	C_{13}	3	2	1	3	1	3	1	1	1	3	1	3	1	3	3	4
	C_{14}	1	1/2	1/3	1	1/3	1	1/3	1/3	1/3	1	1/3	1	1/3	1	1	2
	C_{15}	1	1/2	1/3	1	1/3	1	1/3	1/3	1/3	1	1/3	1	1/3	1	1	2
	C_{16}	1/2	1/3	1/4	1/2	1/4	½	1/4	1/4	1/4	1/2	1/4	1/2	1/4	1/2	1/2	1

Table 5.6(c)

Converted pairwise comparison table for the social cluster for Respondent 1

		CRITERIA											
		C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}	C_{11}	C_{12}
CRITERIA	C_1	1	1	1	1	3	1	2	3	3	3	1	1
	C_2	1	1	1	1	3	1	2	3	3	3	1	1
	C_3	1	1	1	1	3	1	2	3	3	3	1	1
	C_4	1	1	1	1	3	1	2	3	3	3	1	1
	C_5	1/3	1/3	1/3	1/3	1	1/3	1/2	1	1	1	1/3	1/3
	C_6	1	1	1	1	3	1	2	3	3	3	1	1
	C_7	1/2	1/2	1/2	½	2	1/2	1	2	2	2	1/2	1/2
	C_8	1/3	1/3	1/3	1/3	1	1/3	1/2	1	1	1	1/3	1/3
	C_9	1/3	1/3	1/3	1/3	1	1/3	1/2	1	1	1	1/3	1/3
	C_{10}	1/3	1/3	1/3	1/3	1	1/3	1/2	1	1	1	1/3	1/3
	C_{11}	1	1	1	1	3	1	2	3	3	3	1	1
	C_{12}	1	1	1	1	3	1	2	3	3	3	1	1

All of the calculations used by Respondent 1 to determine the weights and consistency ratios for the criteria are presented in Appendix D.

5.2.4 Rank of LSSP Criteria

The AHP technique was used to provide weights to the identified selection criteria presented in Table 5.7.

Table 5.7

The final weights for all clusters

Expert	Environmental	Economical	Social
1	0.3211	0.3425	0.3364
2	0.3551	0.2706	0.3743
3	0.3333	0.3333	0.3333
4	0.3349	0.3366	0.3285
5	0.3400	0.3478	0.3122
6	0.3476	0.3363	0.3161
7	0.3715	0.3105	0.3179
8	0.3527	0.3574	0.2900
9	0.3465	0.3606	0.2930
10	0.3376	0.3513	0.3111
11	0.3681	0.3525	0.2794
12	0.3506	0.3264	0.3230

The final weights of all respondents for each criterion of a cluster are obtained using Microsoft Excel and presented in Appendix E. Table 5.7 displays the final weights assigned to each expert in this research for the three clusters of LSSP criteria (environmental, economical, & social). For example, the analysis revealed that the weights provided by the first expert for environmental, economical, and social clusters were 0.3311, 0.3425, and 0.3364, respectively. The final rank of criteria is presented in Table 5.8.

Table 5.8

Rank of criteria

Criteria	Weight	Rank
Environmental	0.3466	1
Economical	0.3355	2
Social	0.3179	3

Referring to Table 5.8, the environmental criteria emerged as the most significant criteria for selecting landfill sites, with a weighted value of 0.3466, followed by economical criteria (0.3355) and social criteria (0.3179). The rank of criteria under the environmental cluster is shown in Table 5.9.

Table 5.9

The rank of Environmental sub-criteria

Sub-criteria ID	Sub-criteria name	Weight	Rank
A1	Slope	0.0546	14
A2	Land use	0.0637	6
A3	Groundwater	0.0793	4
A4	Geology	0.0510	11
A5	Surface water	0.0779	5
A6	Topography	0.0595	8
A7	River	0.0865	2
A8	Drinking water sources	0.0823	3
A9	Soil type	0.0516	10
A10	Fault line	0.0492	15
A11	Weather/Climate	0.0501	13
A12	Lakes/Ponds/Dams/Reservoirs	0.0615	7
A13	Pollution (water, air, & noise)	0.0905	1
A14	Infrastructures (water pipelines, power pipelines, & electricity)	0.0508	12
A15	Floodplain	0.0584	9
A16	Wind direction	0.0332	16

CR = 0.0049

Table 5.9 presents the rank details for the environment sub-criteria. The environmental criteria have 16 sub-criteria. Based on this cluster, the three most important sub-criterion for this cluster are pollution (water, air, & noise) with a weight of 0.0905, followed by river (0.0865) and drinking water sources (0.0823). The consistency ratio is 0.0049. Next, the rank details for economical sub-criteria are presented in Table 5.10.

Table 5.10

The rank of Economical sub-criteria

Sub-criteria ID	**Sub-criteria name**	**Weight**	**Rank**
B1	Lifespan	0.2834	1
B2	Land cost	0.2319	2
B3	Job opportunity	0.1156	5
B4	Construction cost	0.1873	3
B5	Operational cost	0.1819	4
CR = 0.0042			

Table 5.10 shows the rank details for the economical sub-criteria. The economic criteria have five sub-criteria. For this cluster, the three most important sub-criterion are lifespan, with a weight of 0.2834, followed by land cost (0.2319), construction cost (0.1873), operational cost (0.1819), and job opportunity (0.1156). Notably, the new sub-criteria proposed in this research ranked fourth, with a slight difference between the most significant sub-criteria and the new sub-criteria (0.1015). The consistency ratio is 0.0042. This output has achieved research objective 2. Next, the rank details for social sub-criteria are shown in Table 5.11.

Table 5.11

The rank of Social sub-criteria

Sub-criteria ID	**Sub-criteria name**	**Weight**	**Rank**
C1	Residential/Waste production areas	0.1136	1
C2	Urban/Rural areas	0.1060	3
C3	Historical/Tourism areas	0.0928	6
C4	Park/Recreational areas	0.0882	7
C5	Mining areas	0.0672	10
C6	Airport	0.0759	8
C7	Transportation infrastructure and access	0.0943	5

Table 5.11 (Continued)

C8	Road access	0.0977	4
C9	Highways	0.0463	11
C10	Railways	0.0382	12
C11	Political influences	0.0710	9
C12	Public acceptance	0.1087	2

CR = 0.0061

Table 5.11 presents the rank details for the social sub-criteria. The social criteria have 12 sub-criteria. For this cluster, the three most important sub-criterion are residential/waste production areas with a weight of 0.1136, followed by public acceptance (0.1087) and urban/rural areas (0.1060). The consistency ratio is 0.0061. The results discussed in this section have achieved research objective 2, which is to identify the importance of operational costs in selecting new landfill sites by using AHP.

5.2.5 Computational Results of Resources-based Solutions for LSSP

This section presents the computational results of single and multiple LSSP solutions for the case-based scenario and the WCVRP benchmark problem. The greedy heuristic algorithm used to construct both solutions was executed in C++ language on an Intel® Core ™ i7-8550U CPU @ 1.99 GHz with 8.00 GB memory.

5.2.5.1 Case-based Scenario

This section discusses the single landfill site solution, as presented in Table 5.12.

Table 5.12

Computational results of a single LSSP model for a case-based scenario

Landfill ID	**Total distance (km)**	**Total fuel used (litre/km)**	**Total travel time (secs)**	**Total driver**	**Average working hours per driver**	**Computational time (secs)**
1	1004.16	375.05	74874.8	11	12	0.195
2	953.734	356.22	71114.7	11	12	0.187
3	973.978	363.78	72624.2	11	12	0.177
4	**655.562**	**244.85**	**48881.7**	**11**	**12**	**0.157**
5	1011.05	377.63	75388.8	11	12	0.291

The computational results reported in Table 5.12 demonstrate the resources required to serve 146 housing areas in Kubang Pasu based on five candidates for new landfill locations. The information on the resources is presented in columns 2 to 6. The last column in Table 5.12 shows the computational time of the greedy algorithm used to construct the solution.

Based on Table 5.12, the location of landfill 4 emerged as the best choice with minimum resources when compared to other candidates. In other words, if landfill 4 is selected to build a new landfill, the resource required to complete the waste collection refers to the total distance traveled by all drivers being 655.562 km with 48881.7 seconds of travel time. The fuel used for this solution is 244.85 liters/km. The second choice is landfill 2, followed by landfills 3, 1, and 5. Referring to Table 6.10, all candidates need 11 drivers to complete the waste collection with an average of 12 working hours. Next, a multiple landfill site solution is presented in Table 5.13.

Table 5.13

Computational results of multiple LSSP model for case-based scenario

Landfill ID	Total distance (km)	Total fuel used	Total travel time (secs)	Total number of vehicle	Average working hours per driver	Computational time (secs)	Landfill used (ID)
Solutions for two landfills							
1, 2	957.077	357.47	71364	11	12	0.254	1,2
1, 3	983.452	367.32	73330.7	11	12	0.279	1,3
1, 4	751.771	280.79	56055.5	11	12	0.27	1,4
1, 5	978.473	365.46	72959.4	11	12	0.155	1,5
2,3	961.636	359.17	71704	11	12	0.191	2,3
2,4	658.776	246.05	49121.4	11	12	0.166	2,4
2,5	969.158	361.98	72264.8	11	12	0.158	2,5
3,4	**656.941**	**245.37**	**48984.5**	**11**	**12**	**0.154**	**3,4**
3,5	1005.72	375.64	74991.2	11	12	0.159	3,5
4,5	1004.7	375.26	74915.2	11	12	0.167	4,5
Solutions for three landfills							
1,2,3	948.096	354.11	70694.4	11	12	0.272	1,2,3
1,2,4	747.704	279.27	55752.2	11	12	0.167	1,2,4
1,2,5	946.486	353.51	70574.3	11	12	0.158	1,2,5
1,3,4	843.842	315.17	62920.7	11	12	0.22	1,3,4
1,3,5	978.473	365.46	72959.4	11	12	0.286	1,5
1,4,5	723.93	270.39	53979.6	11	12	0.159	1,4,5
2,3,4	732.443	273.57	54614.3	11	12	0.295	2,3,4
2,3,5	969.539	362.12	72293.3	11	12	0.158	2,3,5
2,4,5	**687.373**	**256.73**	**51253.7**	**11**	**12**	**0.161**	**2,4,5**
3,4,5	708.386	264.58	52820.5	11	12	0.158	3,4,5
Solutions for four landfills							
1,2,3,4	744.195	277.96	55490.6	11	12	0.159	1,2,3,4
1,2,3,5	940.913	351.43	70158.8	11	12	0.159	1,2,3,5
1,2,4,5	**699.125**	**261.12**	**52130**	**11**	**12**	**0.16**	**1,2,4,5**
1,3,4,5	720.138	268.97	53696.8	11	12	0.166	1,3,4,5
2,3,4,5	707.458	264.24	52751.3	11	12	0.159	2,3,4,5
Solutions for five landfills							
1,2,3,4,5	719.21	268.62	53627.6	11	12	0.161	1,2,3,4

Table 5.13 shows the computational results of four sub-solutions for multiple landfill site selection (i.e., solutions for two, three, four, & five new landfills). When compared to other combination landfills, two landfills (landfills 3 & 4) appear to be the best alternative sites based on the analysis for the proposed solution. The total distance driven by all drivers was 656.941 km. However, to complete the waste collection procedure, the local authorities would need to recruit 11 drivers for all landfills.

Based on Table 5.13, the number of new landfills that will be opened does not influence the number of drivers needed or the average working hours of drivers. This is because; Kubang Pasu only has 11 vehicles for collecting waste. So, if a new landfill is built, the same vehicles will be dispatched to the site to unload waste.

In conclusion, based on the discussion of solutions presented in Tables 5.12 and 5.13, the solution for a single landfill site is better than that for multiple landfill site selection. Hence, for the case-based scenario applied in this research, the best location to open a new landfill site is landfill 4. This is because; it demands fewer resources when compared to other solutions in terms of total distance, total travel time, and the fuel used to collect waste from customers.

5.2.5.2 WCVRP Benchmark Problem

This section starts with a discussion of a single landfill site solution, as presented in Table 5.14. The computational results in Table 5.14 demonstrate the resources required to serve all customers of each dataset if each candidate site was chosen as a landfill site. The information of the resource is presented in columns 3 to 7. Column 8 shows the computational time of the greedy algorithm used to construct the solution. The last column in Table 5.14 shows the ranks of the candidate landfill sites based on total distance.

Table 5.14

Computational results of a single LSSP model for WCVRP benchmark problems

Dataset	Landfill candidate (ID)	*TD (miles)	*TFC (litre/ mile)	*TT (secs)	*TV	*AWH / driver	*CT (secs)	Rank
102	**1**	**257.21**	**154.61**	**23149.1**	**3**	**4**	**0.06**	**1**
	2	701.66	421.76	63149.1	3	8	0.06	2
277	1	473.83	284.81	42644.2	3	7	0.58	1
335	**1**	**213.28**	**128.20**	**19194.9**	**6**	**5**	**0.70**	**1**
	2	552.35	332.01	49711	6	6	0.75	2
	3	688.37	413.77	61953	6	7	0.70	3
	4	865.45	520.21	77890.6	6	7	0.64	4
444	1	92.93	55.86	8363.99	11	1	1.50	1
804	1	1545.27	928.84	139074	7	9	3.50	4
	2	2582.25	1552.16	232403	10	9	3.34	14
	3	**801.05**	**481.50**	**72094.8**	**6**	**8**	**3.30**	**1**
	4	1781.39	1070.77	160325	8	9	3.72	6
	5	1987.39	1194.60	178865	8	9	5.38	9
	6	2037.66	1224.81	183390	8	10	3.50	11
	7	2582.25	1552.16	232403	10	9	3.42	14
	8	805.48	484.16	72493.1	5	10	3.62	2
	9	**801.05**	**481.50**	**72094.8**	**6**	**8**	**3.92**	**1**
	10	1495.67	899.03	134611	7	9	3.47	3
	11	1754.50	1054.61	157905	8	9	3.62	5
	12	1818.47	1093.06	163662	8	9	4.03	7
	13	3670.64	2206.38	330358	10	10	3.51	14
	14	2448.19	1471.58	220337	10	9	3.33	13
	15	2007.04	1206.41	180634	8	10	3.81	10
	16	2074.75	1247.11	186728	8	9	3.41	12
	17	1781.39	1070.77	160325	8	9	3.63	6
	18	1886.26	1133.81	167963	8	9	3.67	8
	19	1545.27	928.84	139074	7	9	4.26	4
1051	**1**	**3048.53**	**1832.44**	**274368**	**18**	**7**	**6.16**	**1**
	2	3101.20	1864.10	279108	18	8	7.83	2
1351	1	1290.81	775.89	116173	8	8	10.08	2
	2	1382.95	831.28	124466	8	8	9.58	3
	3	**1040.01**	**625.14**	**93600.5**	**8**	**7**	**9.69**	**1**
1599	1	3012.37	1810.70	271113	18	9	13.93	2
	2	**1847.19**	**1110.32**	**166248**	**15**	**10**	**26.40**	**1**
1932	1	1431.17	860.26	128805	16	13	41.40	3
	2	1384.60	832.27	124614	16	13	48.20	2
	3	1431.89	860.69	128870	16	13	19.58	4
	4	**1368.36**	**822.51**	**123152**	**16**	**13**	**42.20**	**1**
2100	1	3258.36	1958.56	293252	20	10	26.96	4
	2	5203.36	3127.68	468303	25	9	23.97	7
	3	**2300.23**	**1382.64**	**207021**	**18**	**10**	**31.01**	**1**
	4	3687.20	2216.33	331848	21	10	30.69	6
	5	3502.47	2105.29	315222	21	10	24.14	5
	6	2949.76	1773.07	265478	19	10	28.49	3
	7	3005.00	1806.27	270450	19	10	22.39	2

*TD = Total distance, TFC = Total fuel consumption, TT = Total travel time, TV = Total number of vehicle, AWH = Average working hour per driver, and CT = Computational time

The data set with 102 nodes provides the resource required for 99 customers served by 2 landfill potential sites. From the analysis, if site 1 is chosen, the waste management team would need to recruit three drivers to serve the customers, with a total distance driven by all the drivers at 257.21 miles. The total fuel usage is 154.61 liters per mile, while the total travel time is 23149.1 secs. Meanwhile, if site 2 is chosen, they would have to hire the same number of drivers, but the overall distance would have been more than that for site 1 (an increment by 172.8%).

If site 1 is chosen, the average working hour per driver is 4 hours. However, the average working hour for site 2 is 8 hours because the location of landfill site 2 is far from the customers. Furthermore, the waste management team was offered two options: site 1 or site 2. If site 1 is chosen, they may save three times the resources necessary (i.e., gasoline usage) when compared to site 2, where all drivers will need to travel a greater distance.

When looking at problem set 804, two possible sites (3 & 9) are offered. Both sites would need equal amounts of resources (6 drivers, 8 hours of working duration per driver in average, & 801.05 miles in total travel distance). As a result, the authorities are given the choice of selecting either Site 3 or Site 9 as the landfill site. If the authorities have limited resources, such as drivers, they may select site 8, which would require only five drivers to serve 784 customers. When compared to sites 3 and 9, the overall travel distance of all drivers would be 805.48 miles, displaying an increase of 4.43 miles (0.55%). Next, a multiple landfill sites solution is given in Table 5.15.

The computational results in Table 5.15 demonstrate the resources needed to serve all customers of each dataset if multiple candidate sites are chosen as landfill site. The information of the resource is presented from columns 3 to 7. Column 8 shows the computational time of greedy algorithm used to construct the solution. The last column in Table 5.15 shows the chosen landfill ID that had been applied to solve each dataset.

Table 5.15

Computational results of a multiple LSSP model for WCVRP benchmark problems

Data set	**Landfill candidate (ID)**	***TD (miles)**	***TFC (litre/ mile)**	***TT (secs)**	***TV**	***AWH / driver**	***CT (secs)**	***LU (ID)**
102	1,2	206.80	124.30	18611.8	3	5	0.08	1,2
277	1	473.83	284.81	42644.2	3	7	0.58	1
335	1,2,3,4	213.28	128.20	19194.9	6	5	0.70	1
444	1	92.93	55.86	8363.99	11	1	1.50	1
804	1,2,3,…, 19	863.33	518.94	77699.6	6	9	3.57	3,8,9,10,11,17
1051	1,2	2645.07	1589.92	238057	17	7	8.79	1,2
1351	1,2,3	984.30	591.65	88586.9	8	6	10.47	1,2,3
1599	1,2	1578.13	948.60	142032	14	10	20.86	1,2
1932	1,2,3,4	1346.11	809.13	121150	16	13	27.67	1,2,3
2100	1,2,3,…,7	1823.59	1096.14	164123	16	11	32.70	1,2,3,5,6,7
Total	45	10227.37	6147.55	920463.4	100	74	106.92	27

*TD = Total distance, TFC = Total fuel consumption, TT = Total travel time, TV = Total number of vehicle, AWH = Average working hour per driver, CT = Computational time, and LU = Landfill used

According to Table 5.15, dataset 102 has two landfill candidates and both landfill sites were chosen to be utilized to serve 99 customers. The collection process requires the use of three vehicles. The total travel distance is 206.80 miles. The fuel usage is 124.30 liters/mile. The total travel time is 18611.8 secs. The average working time for each driver is five hours.

Dataset 335 has four landfill candidates for a total of 330 customers. However, the analysis revealed that just one location "ID 1" was chosen to serve all customers. This is because; site "ID 1" is close to all the customers. The collection process requires the use of six vehicles. The total travel distance is 213.28 miles. The fuel usage estimate is 128.20 liters/mile. The total travel time is 19194.9 secs. The average working time for each driver is five hours.

Dataset 804 has 19 landfill candidates for a total of 784 customers. However, the analysis revealed that six locations "ID 3, 8, 9, 10, 11, & 17" were chosen to serve all customers. The collection process requires the use of six vehicles. The total travel distance is 863.33 miles. The fuel usage estimate is 518.94 liters/mile. The total travel time is 77699.6 secs. The average working time for each driver is nine hours.

Dataset 1932 has four landfill candidates for a total of 1927 customers. However, the analysis revealed that three locations "ID 1, 2, & 3" were chosen to serve all customers. The collection process requires the use of 16 vehicles. The total travel distance is 1346.11 miles. The fuel usage estimate is 809.13 liters/mile. The total travel time is 121150 secs. The average working time for each driver is 13 hours.

Dataset 2100 has seven landfill candidates for a total of 2092 customers. However, the analysis revealed that six locations "ID 1, 2, 3, 5, 6, & 7" were chosen to serve all customers. The collection process requires the use of 16 vehicles. The total travel distance is 1823.59 miles. The fuel usage estimate is 1096.14 liters/mile. The total travel time is 164123 secs. The average working time for each driver is 11 hours.

Overall, the total number of vehicles needed to solve the benchmark problem is 100 vehicles. The total distance travelled and the total travelling time of all vehicles are 10227.37 miles and 920463.4 seconds, respectively. The total landfill candidate is 45, but only 27 locations were chosen to dispose waste from customers. The average computational time is 10.692 seconds (106.92/10).

The comparison between solutions of single and multiple landfill sites by dataset are summarized in Table 5.16.

Table 5.16

The comparative results of single and multiple landfill sites for WCVRP benchmark problems

Dataset		***TD (miles)**	***TFC (litre/mile)**	***TV**	***AWH**	***LU (ID)**
102	Single	257.21	154.61	3	4	1
	Multiple	206.80	124.30	3	5	1, 2
277	Single	473.83	284.81	3	7	1
	Multiple	473.83	284.81	3	7	1
335	Single	213.28	128.20	6	5	1
	Multiple	213.28	128.20	6	5	1
444	Single	92.93	55.86	11	1	1
	Multiple	92.93	55.86	11	1	1
804	Single	801.05	481.50	6	8	3, 9
	Multiple	863.33	518.94	6	9	3, 8, 9, 10, 11, 17
1051	Single	3084.53	1832.44	18	7	1
	Multiple	2645.07	1589.92	17	7	1, 2
1351	Single	1040.01	625.14	8	7	3
	Multiple	984.30	591.65	8	6	1, 2, 3
1599	Single	1847.19	1110.32	15	10	2
	Multiple	1578.13	948.60	14	10	1, 2
1932	Single	1368.36	822.51	16	13	4
	Multiple	1346.11	809.13	16	13	1, 2, 3
2100	Single	2300.23	1382.64	18	10	3
	Multiple	1823.59	1096.14	16	11	1, 2, 3, 5, 6, 7

*TD = Total distance, TFC = Total fuel consumption, TV = Total number of vehicle, AWH = Average working hour per driver, and LU = Landfill used

Table 5.16 presents the comparison between single and multiple landfill sites in terms of total travel distance, total fuel consumption, number of vehicle used, and average working hours for each drivers. For dataset 102, multiple landfill sites yielded better results to construct new landfills when compared to single landfill site. The total travel distance is 206.80 miles. The total fuel consumption is 124.30 litre/mile. Three vehicles are required for both single and multiple waste collection purpose. The average working hour is extra one hour compared to single landfill.

For datasets 277, 335, and 444, they presented similar results for single and multiple landfill sites. This is because; datasets 277 and 444 only have a single landfill site. Meanwhile, dataset 335 has four candidate landfills but only one landfill is suitable for the particular dataset. For dataset 277, the total travel distance is 473.83 miles. The total fuel consumption is 284.81 litre/mile. Seven vehicles are required for waste collection. The average working hour is 7 hours. The total distance for dataset 335 is 213.28 miles. The total fuel consumption is 128.20 litre/mile. The total number of vehicle needed is six and the average working hour is 5 hours. For dataset 444, the total travel distance is 92.93 miles. The total fuel consumption is 55.86 litre/mile, while 11 vehicles are required for waste collection. The average working hour is only 1 hour.

For dataset 804, the single landfill site produced better results when compared to multiple landfill sites. The total travel distance is 801.05 miles. The total fuel consumption is 481.50 litre/mile. Six vehicles are required for both single and multiple sites for waste collection purpose. The average working hour is 8 hours.

For datasets 1051, 1351, 1599, and 1932, multiple landfill sites produced better solution when compared to single landfill site in term of total travel distance, total fuel consumption, and total number of vehicle required for waste collection. The average working hour for both single and multiple landfill sites is similar.

Lastly, dataset 2100, multiple landfill sites gave better solution than single landfill site in terms of total travel distance (1823.59 miles), total fuel consumption (1096.14 litre/mile), and total number of vehicle required for waste collection (16). However, the average working time for multiple landfill sites is extra 1 hour when compared to single landfill site.

In conclusion, location of customers and candidate landfills exert an impact when proposing single or multiple landfill site(s).

5.3 Results for WCVRP

This section presents results related to WCVRP. It starts with the comparative results of resources-based analysis between the initial solution and the best solution from PPA. Next, comparative results between PPA and best-known solution (BKS) obtained from the previous studies are presented.

5.3.1 WCVRP Benchmark Problem

The comparison of computation results for solving WCVRP using RIC and PPA are shown in Table 5.17. The purpose of this comparison is to examine how effective PPA is at improving the initial solution generated by RIC. For each dataset, the PPA was run 100 times and the best solution of the results is presented in Table 5.17. Table 5.17 consists of eight columns. The name of the dataset is represented in Column 1. Column 2 is the start node, which refers to the first customer on route 1 randomly generated by RIC. The resource information is presented from Column 3 to Column 7. The computational time of RIC and PPA utilized to create the solution is shown in Column 8.

Based on the computational results, for example, for dataset 102, it can be concluded that the computational results from PPA showed better solution in terms of total travel distance, total fuel consumption, and average working time for drivers when compared to RIC. The total travel distance and total fuel consumption for this dataset decreased by 1.86% (((184.31-180.89) /184.31) x100) and 1.86% (((68.84-67.56) /68.84) x100) over RIC, respectively. Meanwhile, the drivers' average working time is reduced by two hours when compared to RIC. In other words, PPA can improve RIC initial solution even with small changes. The higher the value of the reduction on the RIC, better solution is produced. Meanwhile, the number of vehicles required for waste collection is similar for all datasets.

Table 5.17

Comparison on computational results on WCVRP using RIC and PPA

Dataset	**Start node**	**Total travel distance (miles)**		**Total fuel consumption (litre/mile)**		**Total travel time (secs)**		**Total number of vehicle**		**Average working hour per driver**		**Total computational time (secs)**	
		RIC	**PPA**	**RIC**	**PPA**	**RIC**	**PPA**	**RIC**	**PPA**	**RIC**	**PPA**	**RIC**	**PPA**
102	97	184.31	180.89	68.84	67.56	16587.7	22988.22	3	3	5	3	2.30	686.10
277	224	474.02	472.32	177.05	176.41	42661.8	60659.25	3	3	7	7	0.58	1715.16
335	332	200.25	199.15	74.79	74.38	18022.8	29712.23	6	6	4	4	9.88	1616.6
444	67	89.12	88.67	33.29	33.12	8020.58	32019.29	11	11	1	1	23.61	2016.38
804	259	723.50	716.09	270.23	267.46	65115.3	64976.1	5	5	9	8	34.95	3582.05
1051	505	2550.92	2531.96	952.77	945.69	229583	287302.7	17	17	6	7	41.73	3835.84
1351	749	914.91	913.79	341.72	341.30	82341.9	82341.9	8	8	6	6	67.69	7307.91
1599	1041	1378.01	1372.54	514.69	512.64	124021	126060.6	13	13	10	10	158.31	8134.58
1932	1875	1282.32	1278.52	478.95	477.53	115409	132086.1	16	16	12	12	477.69	11662.2
2100	638	1773.53	1770.29	662.41	661.20	159618	160397.5	16	16	10	10	632.40	12437.3
Total	-	9570.90	9524.21	3574.73	3557.29	861381.08	998543.89	98	98	70	68	1449.13	52994.12

Upon using RIC and PPA to complete the collection for all problem sets, the total distances required for all vehicles are 9570.90 miles and 9524.21 miles, respectively. The total fuel consumption values of all vehicles are 3574.73 liters/miles and 3557.29 liters/miles, respectively. The total travelling time values of all vehicles are 861381.08 secs and 998543.89 secs, respectively. The total number of vehicles needed to solve the benchmark problem is 98 vehicles for both algorithms. The average working hours are 70 and 68 hours, respectively. The average computational time values are 14.4913 secs and 5299.412 secs (52994.12/10), respectively. This section has achieved the fifth sub-objective of the study, which is to evaluate the quality of PPA solution in terms of improving the initial solution and comparing with other metaheuristic technique.

5.3.2 Comparative Results of WCVRP Benchmark Problem proposed by Kim et al. (2006)

The comparison between results of WCVRP benchmark problem from previous studies is summarized in Table 5.18.

Table 5.18

Comparative results of WCVRP benchmark problem proposed by Kim et al. (2006)

Problem set	**Result from PPA**		**Best known result**												**% Impr over dista**
	Distance (miles)	**Vehicle**	**Distance (miles)**	**Vehicle**	**Distance (miles)**	**Vehicle**	**Distance (mile)**	**Vehicle**	**Distance (miles)**	**Vehicle**	**Distance (miles)**	**Vehicle**	**Distance (miles)**	**Vehicle**	
			Kim et al. (2006)		**Benjamin & Beasley (2013)**		**Burkhal et al. (2012)**		**Islam & Rahman (2012)**		**Campos & Arroyo (2017)**		**Gruler et al. (2018)**		
Techniques			***CBSA**		***VNTS**		***ALNS**		***ACO**		***ILS**		***BRSB**		
102	180.8852	3	205.1	3	**156.9**	3	174.5	3	191.613	3	240.5	3	158	4	-13.2
277	472.3201	3	527.3	3	454.7	3	447.6	3	**373.667**	2	394.0	2	463.3	3	-20.8
335	199.1531	6	205.0	6	186.7	6	182.1	6	**173.236**	6	194.8	6	193.1	6	-13.01
444	88.6659	11	87.0	11	79.7	11	78.3	11	**66.4472**	11	72.8	10	85.3	11	-25.0
804	716.089	6	769.5	5	641.8	5	**604.1**	5	610.496	5	634.5	4	621.4	6	-15.6
1051	2531.959	17	2370.4	18	2123.8	17	2325.7	17	1970.15	17	**1876.8**	17	2238.9	16	-25.8
1351	913.7868	8	1039.7	7	874.7	8	871.9	8	834.871	7	**656.8**	8	970.6	7	-28.1
1599	1372.539	14	1459.2	13	**1206.1**	13	1337.5	13	-	-	1338.3	12	1225.2	15	-12.1
1932	1278.522	16	1395.3	17	1127.7	16	1162.5	16	-	-	**1037.5**	16	1178.5	23	-18.8
2100	1770.291	16	1833.8	16	1558.1	16	1818.9	17	-	-	**1461.9**	16	1701.4	17	-17.4
Total	9524.211	100	9892.3	99	8410.2	98	9003.1	99	-	-	7907.9	94	8835.7	108	-16.9

*CBSA = clustering based simulated annealing, VNTS = variable neighbourhood tabu search, ALNS = adaptive large neighbourhood search, ACO = ant colony optimization, ILS = iterated local search, BRSB = biased randomized saving based algorithm

Table 5.18 shows the comparative results of WCVRP benchmark problem proposed by Kim et al. (2006). This comparison was conducted in terms of the total distance travelled and the number of vehicles required to complete the waste collection process. The metaheuristic technique utilized by previous studies to analyze the benchmark data is shown in the fifth row of Table 5.16. The algorithm proposed in this study is presented in the second column. Meanwhile, the last column represents the percentage improvement in PPA over the best solution.

In terms of travel distance, the best solutions for datasets 102 and 1599 are from Benjamin and Beasley (2013); datasets 277, 335, and 444 are from Islam and Rahman (2012); dataset 804 is from Burkhal et al. (2012); and datasets 1051, 1351, 1932, and 2100 are from Campos and Arroyo (2017).

In terms of the number of vehicle used, for dataset 102, all previous studies used three vehicles to complete the waste collection process. For dataset 277, Islam and Rahman (2012) revealed the lowest value - two vehicles. Meanwhile, for dataset 444, Campos and Arroyo (2017) found the lowest number of vehicle used but the total distance was higher.

CHAPTER SIX

CONCLUSIONS AND RECOMMENDATIONS

6.1 Introduction

The main purpose of this chapter is to discuss the overall conclusions drawn from this research based on the main objective, which is to develop greedy heuristics and PPA that can minimize the total operational costs associated with resources for LSSP and WCVRP. Hence, Section 6.2 is devoted to provide a summary of this research. Next, Section 6.3 presents the accomplishment of the research objectives, while Section 6.4 presents the limitation of the research. While, Section 6.5 discusses the importance of implementing the proposed algorithms in SWM, which is a major contribution of this research. Nonetheless, several limitations must be considered for future improvement. The future research directions are discussed in Section 6.6.

6.2 Summary of the Research Work

This research began with a rigorous exploration of SWM. In a nutshell, SWM is a government-provided service to the citizens of a country. This service is divided into six operational phases, starting when solid waste is generated until the waste is disposed of in a safe and effective manner. However, various issues have arisen, including issues with WCVRP and LSSP, which are the focus of this research.

In this research, two models were developed to address the SWM problems, namely a LSSP model and a WCVRP model. In the first proposed model, 33 criteria were identified and broken down into three major clusters: environmental, economical, and social. In addition to that, the new criterion, which is operational cost associated with resources, is proposed under the economical cluster. The Modified AHP technique was deployed to analyze the selected criteria in terms of their relative importance and to rank the weights of the criteria. Using the pairwise comparison procedure, all criteria from each group were weighted and ranked. The greedy heuristic was then applied to evaluate and select the best suitable location of landfill siting in terms of operational cost associated with resources. Finally, the best suitable location for the landfill facility was determined. Herein, two options are offered; single or multiple landfill site(s). The proposed model was tested on the WCVRP benchmark problem and a case-based scenario in Kubang Pasu district, Kedah.

As for the second proposed model, the WCVRP model determined a set of feasible vehicle routes that minimized the total cost, the number of vehicles needed, the total travel time, and the total travel distance. Each vehicle starts and finishes at the depot, while each customer is served by a single vehicle, and the total waste collected by any vehicle must not exceed the vehicle capacity and, if required, must be completed within their time frames.

The greedy heuristic algorithm is often used to solve WCVRP. The capability of the heuristic algorithm to handle large-scale data has led to its selection in many studies. In order to tackle the waste collection problem in this research, both heuristic and metaheuristic algorithms were chosen. The initial solution was created by using the RIC-based greedy algorithm. Second, the PPA was used to enhance the initial solution. The proposed model was tested on a real-life WCVRP benchmark problem.

The computational results achieved on a benchmark problem from the literature appear to be extremely competitive. Based on the computational results, the waste collection problem may be enhanced in future work, which is discussed in Section 6.6.

6.3 Accomplishment of Research Objectives

This research has met all the specified research objectives, as outlined in the first chapter. The major goal of this research is to develop a greedy heuristic for multiple landfill site selection and to improve waste collection vehicle routing solutions by using PPA. The five specific objectives are listed in Table 6.1.

Table 6.1

Research achievements based on research objectives

Numbers	Research objectives	Writing chapter	Achievement status
First sub-objective	To identify the criteria that must be considered in selecting new landfill sites in Malaysia.	Chapter 5 (sub-section 5.2.2)	Achieved
Second sub-objective	To determine the level of importance of landfill site selection including the new criterion, operational cost by using Modified AHP.	Chapter 5 (sub-section 5.2.3)	Achieved
Third sub-objective	To propose multiple landfill sites with the minimum total operational costs by using the greedy heuristic.	Chapter 5 (sub-section 5.2.4)	Achieved
Forth sub-objective	To develop PPA for improving WCVRP solutions.	Chapter 4 (sub-section 4.3.3)	Achieved
Fifth sub-objective	To evaluate the quality of the WCVRP solution using PPA in terms of total travel distance, number of vehicles/drivers required, total working hours of drivers, and total fuel consumption using a case-based scenario and benchmark problem set by Kim et al. (2006).	Chapter 5 (sub-section 5.3)	Achieved

The main objective of this research is to develop a greedy heuristic and PPA that can minimize the total operational costs related to LSSP and WCVRP. This main objective is accomplished by determining the level of importance of LSSP criteria, including the operational costs associated with resources in selecting a new landfill site. Then, single and multiple LSSP solutions for case-based scenarios and waste benchmark problems are obtained by using a greedy heuristic algorithm. Other than that, the WCVRP results of resource-based analysis between RIC and PPA are also determined.

The first sub-objective is to identify the criteria that must be considered in selecting new landfill sites in Malaysia. This objective is met through data collection from a literature review and expert interviews, as described in sub-section 5.2.2. From the data collection, 33 criteria were identified and classified under three main clusters; environmental, economical, and social. The relevant resources related to operational costs are total travel distance, number of vehicles required, total working hours of drivers, and total fuel consumption.

The second sub-objective is to identify the importance of operational costs in selecting new landfill sites. This objective is accomplished by using the MCDM technique. The M-AHP was applied to calculate the weight and rank the criteria.

The third sub-objective is to propose multiple landfill sites with minimum total operational costs by using a greedy heuristic algorithm. This objective is met by proposing two models for LSSP; single and multiple models. The proposed models were tested on a real-life waste benchmark problem set and a case-based scenario in

Kubang Pasu, Kedah. The computational results retrieved from this proposed model are presented in sub-section 5.2.5. Overall, the single model proved to be the better decision based on the results between single- and multi-model. However, if the authorities want to construct more than one landfill (i.e., multi-landfill), the multi-model suggested in this research can be used as a guideline.

The fourth sub-objective is to develop PPA for solving WCVRP. This objective is met by developing a WCVRP model and solving it with PPA, as described in sub-section 4.3.3.

The fifth sub-objective assesses the quality of the PPA solution in terms of total travel distance, number of vehicles/drivers required, and total fuel consumption. The objective is met by testing the proposed model on a real-life waste benchmark problem set introduced by Kim et al. (2006). The computational results obtained for the waste benchmark problem set from the literature appear to be extremely competitive.

6.4 Limitations of the Research Work

Despite the fact that this research offers numerous significant contributions, several limitations were noted. These setbacks may be addressed in future research endeavors.

The first limitation lies in the LSSP. One of the crucial stages in the LSSP, as emphasized in earlier chapters, is identifying potential landfill locations. These locations were identified in this research by using a manual survey aided by Google Earth. According to previous studies, the best approach for identifying locations is based on the GIS technique. As this research did not contribute any new knowledge on GIS or propose a new approach to identify potential locations, the locations used in the case-based scenario were only identified using Google Earth.

The second limitation is regarding the lack of WCVRP benchmark problems in academic journals. Most studies solved real-life applications of WCVRP. Hence, this research only used a benchmark problem from Kim et al. (2006) to test the quality of PPA. With the high constraints involved in the benchmark problem, it is believed that the PPA had been well tested in producing a good solution to solve the problem.

This research has been successfully completed despite having to deal with several shortcomings. Thus, it is hoped that the setbacks noted in this research can be used by other researchers to produce better outcomes in the future, as suggested in the next section.

6.5 Contributions of the Research Work

This research offers some contributions toward understanding the SWM, specifically in LSSP and WCVRP. The discussion of this research contribution is broken into three sections: contribution to the body of knowledge, contribution to practitioners, and contribution to policymakers. Contribution to the body of knowledge focuses on the criteria and techniques used to solve LSSP and WCVRP, while contribution to practitioners focuses on the implementation of LSSP and WCVRP models and who will directly benefit in the waste management sector. Finally, this research aids policymakers by demonstrating how the proposed models can assist SWCorp.

6.5.1 Contribution to the Body of Knowledge

This research proposes that research endeavors in LSSP can utilize both Modified AHP and greedy heuristic algorithms in weighting and ranking the criteria, as well as evaluating possible landfill locations, respectively. Studies on LSSP may consider the resources related to operational costs that impact the problem.

Second, for the WCVRP, a PPA was deployed. This research investigated the application of a PPA in WCVRP owing to its ability to mimic the way strawberry plants propagate by sending short and long runners.

6.5.2 Contribution to Practitioners

In terms of practice, this research provides several advantages for practitioners and those who are directly involved with LSSP and WCVRP. To begin with, there has been very little research work of this type performed in Malaysia. Hence, this research proposes a new criterion within the economical cluster, while simultaneously proposing a solution in the Malaysian context. This criterion denotes the resources related to operational costs. By incorporating these resources into the selection process, it is possible to reduce some costs in the SWM budget. This can assist the waste management team in planning their resources effectively based on the resources-based solution proposed in this research.

6.5.3 Contribution to Policymakers

The LSSP is a challenging task to accomplish since the process is dependent on several environmental, economical, and social criteria. Currently, the SWCorp solely refers to government standards for LSSP procedures, while neglecting resource-related operational costs criteria. However, this criterion is essential for the LSSP process since it allows for early planning in terms of utilizing existing resources, which reduces some costs. As a result of using this criterion, the corporation can effectively save up on its SWM budget.

6.6 Future Research Endeavor

Some suggestions may need to be considered by future scholars to overcome the research limitations. Several suggestions to extend this research work are as follows:

1. The proposed LSSP model can be combined with GIS to solve real-life applications of LSSP. The potential landfill locations identified from the GIS can meet all the LSSP criteria; thus, more beneficial resources-based solutions can be proposed to find new locations for landfills.

2. The LSSP is full of fuzzy elements due to the ambiguities stemming from data and decision-makers. Thus, in future research, the fuzzy concept may be incorporated into the LSSP model. This component could help to improve SWM.

3. Other constructive heuristic algorithms, such as the savings approach, sweep algorithm, insertion algorithm, clustering algorithm, and parallel algorithm, can be used to construct initial solutions for the PPA. The varied quality of the initial solutions may affect the final solution derived from the PPA. Thus, more experiments on the initial solutions can be conducted to improve PPA solutions.

4. Other metaheuristic algorithms such as TS, SA, GA, and PSO may be integrated into the PPA. With hybrid PPA, the process of producing neighbors in searching for good-quality solutions for the WCVRP can be improved.

5. Finally, the proposed resources-based solutions of greedy heuristics and PPA can be tested on other real-life applications of LSSP and WCVRP. The quality of both algorithms can be further evaluated with different parameters and constraints embedded in the problems.

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Appendix A

Questionnaire for Analytical Hierarchy Process Technique

DESCRIPTION

The selection criteria listed in this questionnaire were obtained from interview session with SWCorp and government report entitled *"The Technical Guideline for Sanitary Landfill, Design and Operation"* by Ministry of Urban Wellbeing, Housing and Local Government. The selection criteria are divided into three clusters: environmental, economical and social. We also propose a new criterion under economical cluster which is operational cost associated to resources. We believe that resource requirements such as (1) total travel distance to transport collected waste to the landfill, (2) number of vehicles/drivers required for the collection and (3) total working hours of drivers affect the operating cost. Therefore, this criterion should be considered in the new landfill site selection process. With your knowledge as experts, it is hoped that the feedback given will give us some insights on the importance of landfill site selection criteria.

OBJECTIVE

This questionnaire aims to determine the importance of landfill site selection criteria in Malaysia.

PRIVATE AND CONFIDENTIAL

All responses will be kept strictly confidential and will only be used for academic purposes.

ESTIMATED TIME FRAME

Please take approximately 10 - 15 minutes to complete the questionnaire.

CONTACT

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Phone No.: +60134408138

SECTION 1

EXPERT'S PROFILE

1. Name : ……………………………………………………………………………..
2. Email address : ……………………………………………………………………………
3. Gender : Male ( )
   Female ( )
4. Age : ……………………………………………………………………………
5. Education level : Doctorate degree ( )
   Master degree ( )
   Bachelor degree ( )
   Others ( )
6. Position : ………………………………………………………………………......
7. Company / Organization : ……………………………………………………………………..
8. Experiences - How long have you been involved in landfill site selection process or landfill management ?

   ……........

   ……………………………………………………………………………………

SECTION 2
LANDFILL SITE SELECTION CRITERIA

For each criterion below, please rate the level of its importance in selecting a new location for a landfill facility in Kedah, by ticking (X) the appropriate number.

(Hint: 1 = Not important, 9 = extremely important)

A. Environmental cluster

		Rating								
	Sub-criteria	Not Important			→					Extremely Important
		1	2	3	4	5	6	7	8	9
C1	Slope									
C2	Land use (agriculture, forest)									
C3	Ground water									
C4	Geology									
C5	Surface water									
C6	Topography and geological conditions									
C7	River									
C8	Drinking water sources									
C9	Soil type									
C10	Fault line									
C11	Weather / Climate									
C12	Lakes / Ponds / Dams / Reservoirs									
C13	Pollution (water, air, noise)									
C14	Infrastructures (water pipelines, power pipelines, electricity)									
C15	Floodplain									
C16	Wind direction									

B. Economical cluster

	Sub-criteria	Rating								
		Not Important			→					Extremely Important
		1	2	3	4	5	6	7	8	9
C1	Lifespan									
C2	Land cost / price									
C3	Job opportunity									
C4	Construction cost									
C5	**Operational cost (i.e.: transportation cost, number of drivers/vehicles, drivers working hours)**									

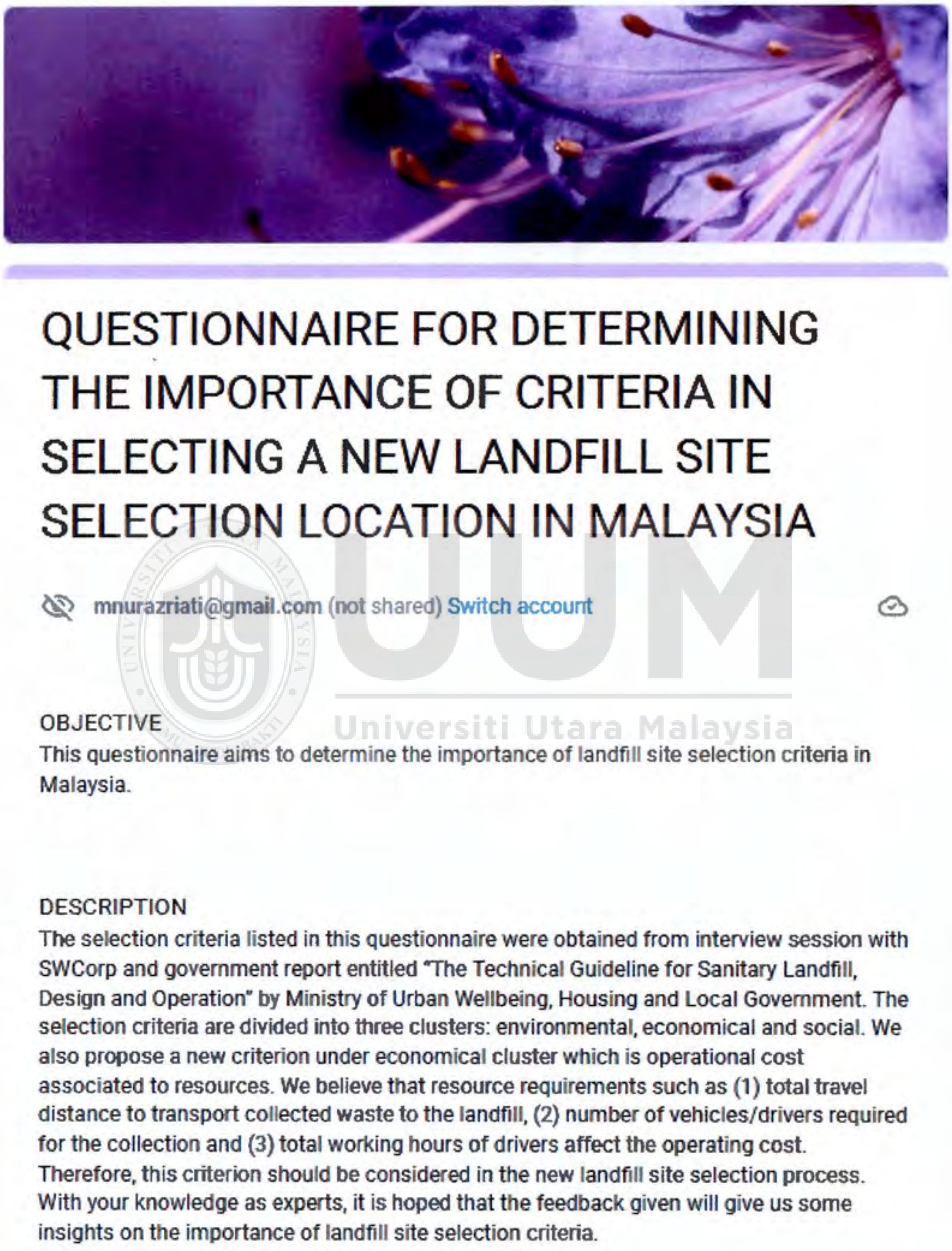
C. Social cluster

	Sub-criteria	Rating								
		Not Important			→					Extremely Important
		1	2	3	4	5	6	7	8	9
C1	Residential / Waste production areas									
C2	Urban / Rural areas									
C3	Historical / Tourism areas									
C4	Park / Recreational areas									
C5	Mining areas									
C6	Airport									
C7	Transport infrastructure and access									
C8	Road access									
C9	Highways									
C10	Railways									
C11	Political influence									
C12	Public acceptance									

YOUR COOPERATION IS HIGHLY APPRECIATED
THANK YOU VERY MUCH
WITHOUT YOUR SUPPORT THIS RESEARCH WILL NEVER BE SUCCESSFUL

Appendix B

Screenshot of Questionnaire in Google Form

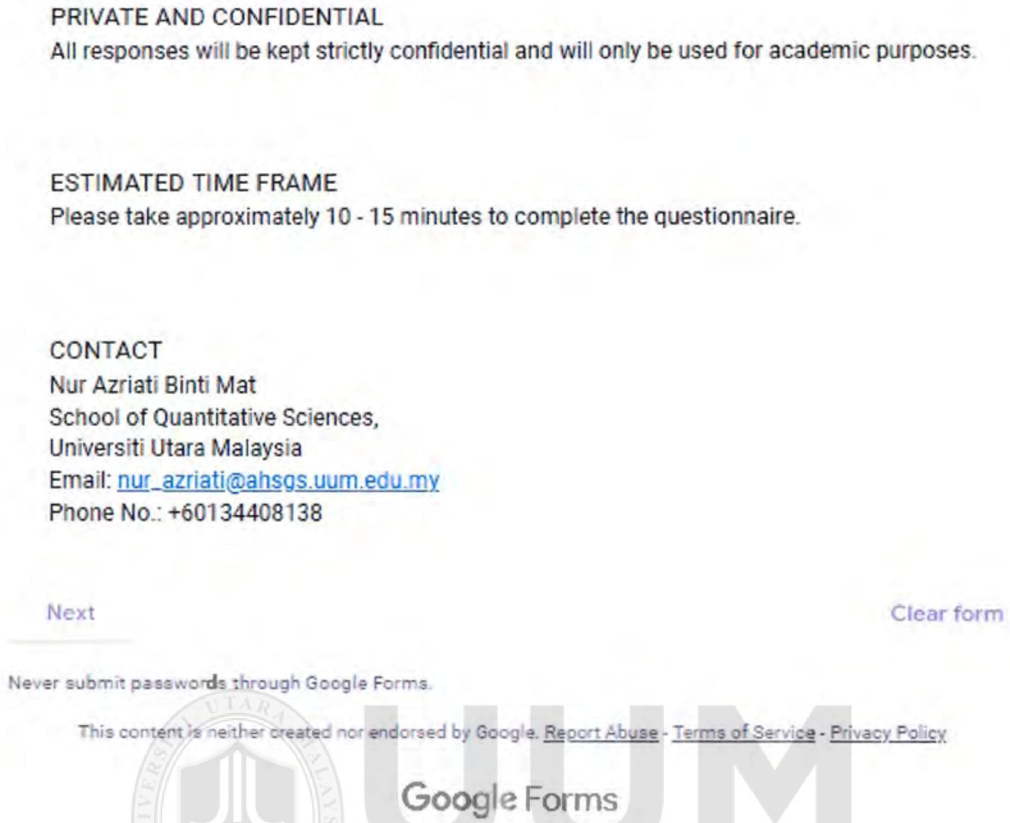


QUESTIONNAIRE FOR DETERMINING THE IMPORTANCE OF CRITERIA IN SELECTING A NEW LANDFILL SITE SELECTION LOCATION IN MALAYSIA

mnurazriati@gmail.com (not shared) Switch account

OBJECTIVE
This questionnaire aims to determine the importance of landfill site selection criteria in Malaysia.

DESCRIPTION
The selection criteria listed in this questionnaire were obtained from interview session with SWCorp and government report entitled "The Technical Guideline for Sanitary Landfill, Design and Operation" by Ministry of Urban Wellbeing, Housing and Local Government. The selection criteria are divided into three clusters: environmental, economical and social. We also propose a new criterion under economical cluster which is operational cost associated to resources. We believe that resource requirements such as (1) total travel distance to transport collected waste to the landfill, (2) number of vehicles/drivers required for the collection and (3) total working hours of drivers affect the operating cost. Therefore, this criterion should be considered in the new landfill site selection process. With your knowledge as experts, it is hoped that the feedback given will give us some insights on the importance of landfill site selection criteria.



PRIVATE AND CONFIDENTIAL
All responses will be kept strictly confidential and will only be used for academic purposes.

ESTIMATED TIME FRAME
Please take approximately 10 - 15 minutes to complete the questionnaire.

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SECTION 1: EXPERT'S PROFILE

Name:

Your answer

Email address:

Your answer

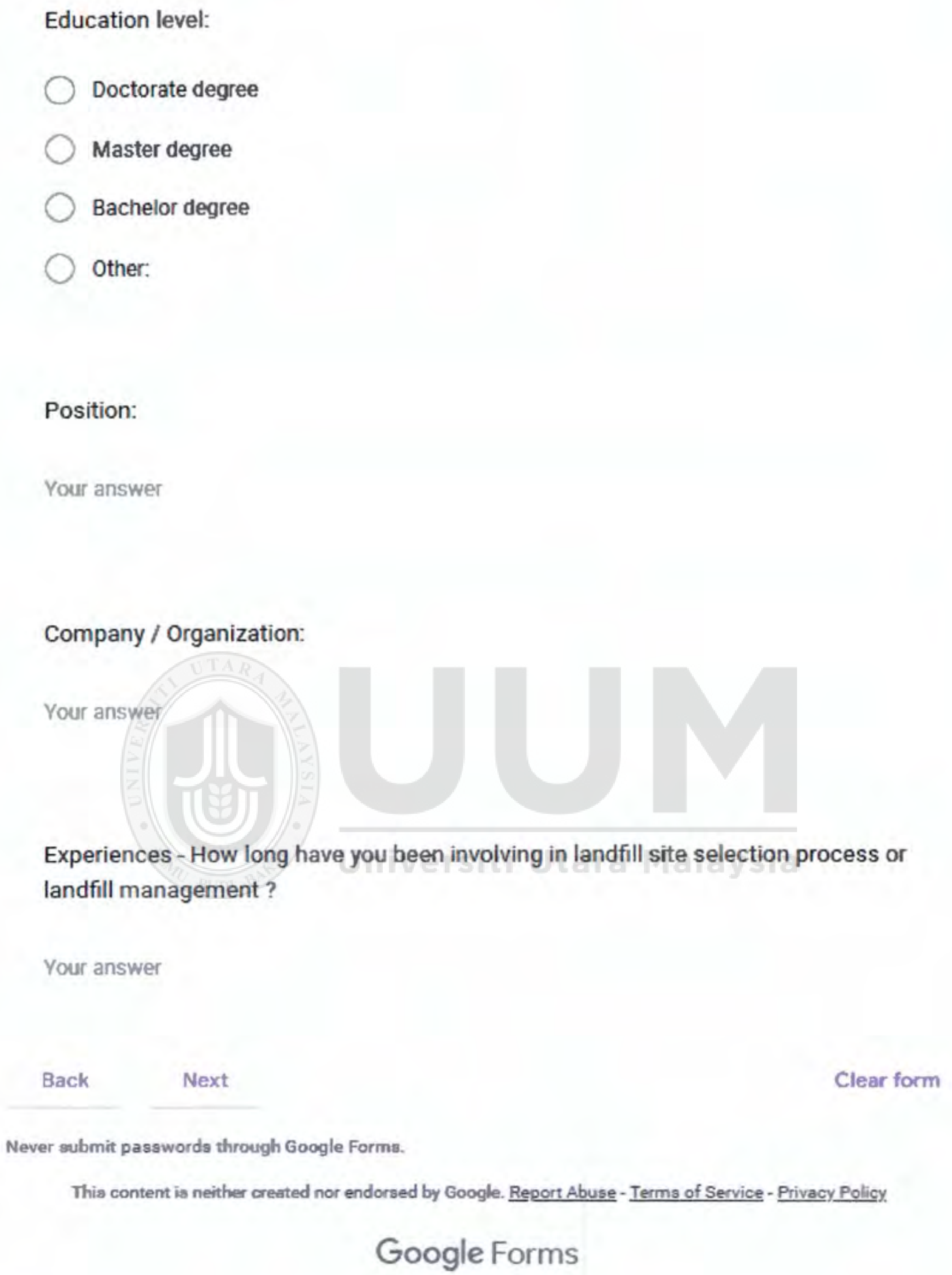
Gender:

○ Male

○ Female

Age:

Your answer



Education level:

○ Doctorate degree
○ Master degree
○ Bachelor degree
○ Other:

Position:

Your answer

Company / Organization:

Your answer

Experiences - How long have you been involving in landfill site selection process or landfill management ?

Your answer

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SECTION 2: LANDFILL SITE SELECTION CRITERIA

For each criterion below, please rate the level of its importance in selecting a new location for a landfill facility in Malaysia, by ticking the appropriate number.

A. Main Criteria (Cluster)

Environmental

	1	2	3	4	5	6	7	8	9	
Not important	○	○	○	○	○	○	○	○	○	Extremely important

Economical

	1	2	3	4	5	6	7	8	9	
Not important	○	○	○	○	○	○	○	○	○	Extremely important

Social

	1	2	3	4	5	6	7	8	9	
Not important	○	○	○	○	○	○	○	○	○	Extremely important

B. Environmental cluster

Slope

	1	2	3	4	5	6	7	8	9	
Not important	○	○	○	○	○	○	○	○	○	Extremely important

Land use (i.e. agricultural, forest)

	1	2	3	4	5	6	7	8	9	
Not important	○	○	○	○	○	○	○	○	○	Extremely important

Ground water

	1	2	3	4	5	6	7	8	9	
Not important	○	○	○	○	○	○	○	○	○	Extremely important

Geology

	1	2	3	4	5	6	7	8	9	
Not important	○	○	○	○	○	○	○	○	○	Extremely important

Surface water

	1	2	3	4	5	6	7	8	9	
Not important	○	○	○	○	○	○	○	○	○	Extremely important

Topography and geological conditions

	1	2	3	4	5	6	7	8	9	
Not important	○	○	○	○	○	○	○	○	○	Extremely important

River

	1	2	3	4	5	6	7	8	9	
Not important	○	○	○	○	○	○	○	○	○	Extremely important

Drinking water sources

	1	2	3	4	5	6	7	8	9	
Not important	○	○	○	○	○	○	○	○	○	Extremely important

Soil type

	1	2	3	4	5	6	7	8	9	
Not important	○	○	○	○	○	○	○	○	○	Extremely important

Fault line

	1	2	3	4	5	6	7	8	9	
Not important	○	○	○	○	○	○	○	○	○	Extremely important

Weather / Climate

	1	2	3	4	5	6	7	8	9	
Not important	○	○	○	○	○	○	○	○	○	Extremely important

Lakes / Ponds / Dams / Reservoirs

	1	2	3	4	5	6	7	8	9	
Not important	○	○	○	○	○	○	○	○	○	Extremely important

Pollution (water, air, noise)

	1	2	3	4	5	6	7	8	9	
Not important	○	○	○	○	○	○	○	○	○	Extremely important

Infrastructures (water pipelines, power pipelines, electricity)

	1	2	3	4	5	6	7	8	9	
Not important	○	○	○	○	○	○	○	○	○	Extremely important

Floodplain

	1	2	3	4	5	6	7	8	9	
Not important	○	○	○	○	○	○	○	○	○	Extremely important

Wind direction

	1	2	3	4	5	6	7	8	9	
Not important	○	○	○	○	○	○	○	○	○	Extremely important

C. Economical cluster

Lifespan

	1	2	3	4	5	6	7	8	9	
Not important	○	○	○	○	○	○	○	○	○	Extremely important

Land cost / price

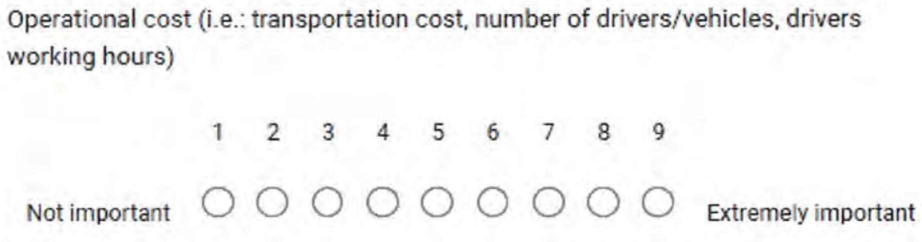
	1	2	3	4	5	6	7	8	9	
Not important	○	○	○	○	○	○	○	○	○	Extremely important

Job opportunity

	1	2	3	4	5	6	7	8	9	
Not important	○	○	○	○	○	○	○	○	○	Extremely important

Construction cost

	1	2	3	4	5	6	7	8	9	
Not important	○	○	○	○	○	○	○	○	○	Extremely important



Operational cost (i.e.: transportation cost, number of drivers/vehicles, drivers working hours)

	1	2	3	4	5	6	7	8	9	
Not important	○	○	○	○	○	○	○	○	○	Extremely important

D. Social cluster

Residential / Waste production areas

	1	2	3	4	5	6	7	8	9	
Not important	○	○	○	○	○	○	○	○	○	Extremely important

Urban / Rural areas

	1	2	3	4	5	6	7	8	9	
Not important	○	○	○	○	○	○	○	○	○	Extremely important

Historical / Tourism areas

	1	2	3	4	5	6	7	8	9	
Not important	○	○	○	○	○	○	○	○	○	Extremely important

Park / Recreational areas

	1	2	3	4	5	6	7	8	9	
Not important	○	○	○	○	○	○	○	○	○	Extremely important

Mining areas

	1	2	3	4	5	6	7	8	9	
Not important	○	○	○	○	○	○	○	○	○	Extremely important

Airport

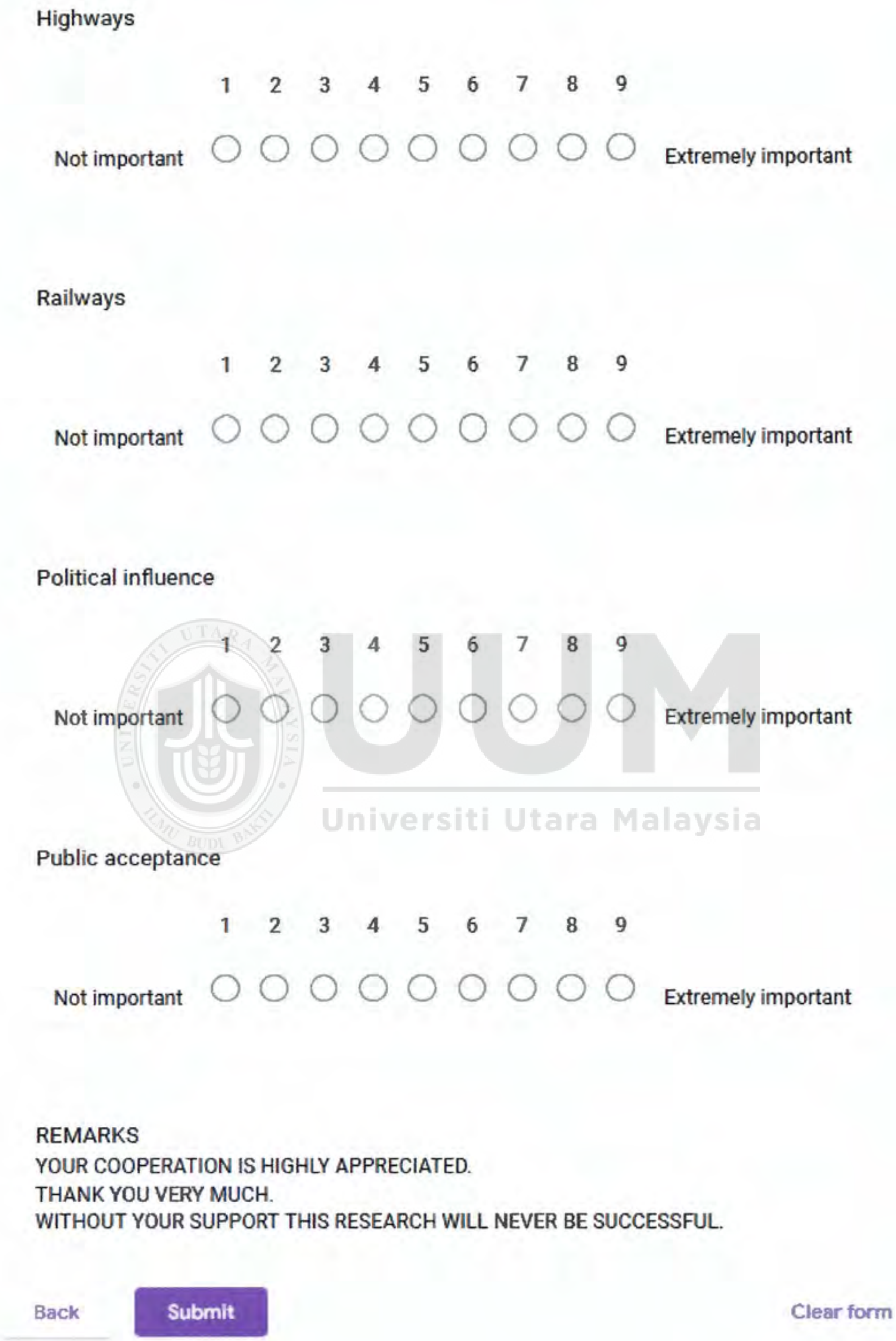
	1	2	3	4	5	6	7	8	9	
Not important	○	○	○	○	○	○	○	○	○	Extremely important

Transport infrastructure and access

	1	2	3	4	5	6	7	8	9	
Not important	○	○	○	○	○	○	○	○	○	Extremely important

Road access

	1	2	3	4	5	6	7	8	9	
Not important	○	○	○	○	○	○	○	○	○	Extremely important



Highways

	1	2	3	4	5	6	7	8	9	
Not important	○	○	○	○	○	○	○	○	○	Extremely important

Railways

	1	2	3	4	5	6	7	8	9	
Not important	○	○	○	○	○	○	○	○	○	Extremely important

Political influence

	1	2	3	4	5	6	7	8	9	
Not important	○	○	○	○	○	○	○	○	○	Extremely important

Public acceptance

	1	2	3	4	5	6	7	8	9	
Not important	○	○	○	○	○	○	○	○	○	Extremely important

REMARKS
YOUR COOPERATION IS HIGHLY APPRECIATED.
THANK YOU VERY MUCH.
WITHOUT YOUR SUPPORT THIS RESEARCH WILL NEVER BE SUCCESSFUL.

Appendix C

Respondents Evaluation using the Modified Analytical Hierarchy Process

Respondent 2

Rating table for the environmental cluster

Criteria	Rating								
	1	2	3	4	5	6	7	8	9
C_1								X	
C_2						X			
C_3								X	
C_4			X						
C_5								X	
C_6							X		
C_7								X	
C_8							X		
C_9						X			
C_{10}							X		
C_{11}						X			
C_{12}							X		
C_{13}								X	
C_{14}						X			
C_{15}						X			
C_{16}				X					

Rating table for the economical cluster

Criteria	Rating								
	1	2	3	4	5	6	7	8	9
C_1						X			
C_2							X		
C_3				X					
C_4				X					
C_5				X					

Rating table for the social cluster

Criteria	Rating								
	1	2	3	4	5	6	7	8	9
C_1							X		
C_2							X		
C_3							X		
C_4							X		
C_5							X		
C_6						X			
C_7								X	
C_8								X	
C_9					X				
C_{10}						X			
C_{11}							X		
C_{12}								X	

Respondent 3

Rating table for the environmental cluster

Criteria	Rating								
	1	2	3	4	5	6	7	8	9
C_1									X
C_2									X
C_3									X
C_4									X
C_5									X
C_6									X
C_7									X
C_8									X
C_9									X
C_{10}									X
C_{11}									X
C_{12}									X
C_{13}									X
C_{14}									X
C_{15}									X
C_{16}									X

Rating table for the economical cluster

Criteria	Rating								
	1	2	3	4	5	6	7	8	9
C_1									X
C_2									X
C_3									X
C_4									X
C_5									X

Rating table for the social cluster

Criteria	Rating								
	1	2	3	4	5	6	7	8	9
C_1									X
C_2									X
C_3									X
C_4									X
C_5									X
C_6									X
C_7									X
C_8									X
C_9									X
C_{10}									X
C_{11}									X
C_{12}									X

Respondent 4

Rating table for the environmental cluster

Criteria	Rating								
	1	2	3	4	5	6	7	8	9
C_1								X	
C_2								X	
C_3								X	
C_4								X	
C_5								X	
C_6								X	
C_7								X	
C_8								X	
C_9								X	
C_{10}								X	
C_{11}							X		

C_{12}								X	
C_{13}								X	
C_{14}								X	
C_{15}								X	
C_{16}				X					

Rating table for the economical cluster

Criteria	**Rating**								
	1	2	3	4	5	6	7	8	9
C_1								X	
C_2								X	
C_3								X	
C_4								X	
C_5								X	

Rating table for the social cluster

Criteria	**Rating**								
	1	2	3	4	5	6	7	8	9
C_1								X	
C_2								X	
C_3								X	
C_4								X	
C_5						X			
C_6							X		
C_7							X		
C_8								X	
C_9							X		
C_{10}					X				
C_{11}					X				
C_{12}								X	

Respondent 5

Rating table for the environmental cluster

Criteria	**Rating**								
	1	2	3	4	5	6	7	8	9
C_1						X			
C_2									X
C_3									X
C_4							X		

C_5							X		
C_6								X	
C_7									X
C_8									X
C_9			X						
C_{10}					X				
C_{11}			X						
C_{12}									X
C_{13}									X
C_{14}							X		
C_{15}							X		
C_{16}			X						

Rating table for the economical cluster

Criteria	**Rating**								
	1	2	3	4	5	6	7	8	9
C_1								X	
C_2						X			
C_3				X					
C_4							X		
C_5							X		

Rating table for the social cluster

Criteria	**Rating**								
	1	2	3	4	5	6	7	8	9
C_1								X	
C_2							X		
C_3							X		
C_4							X		
C_5						X			
C_6								X	
C_7							X		
C_8							X		
C_9					X				
C_{10}					X				
C_{11}			X						
C_{12}						X			

Respondent 6

Rating table for the environmental cluster

Criteria	Rating								
	1	2	3	4	5	6	7	8	9
C_1									X
C_2					X				
C_3									X
C_4								X	
C_5									X
C_6							X		
C_7									X
C_8									X
C_9								X	
C_{10}								X	
C_{11}							X		
C_{12}								X	
C_{13}								X	
C_{14}								X	
C_{15}									X
C_{16}								X	

Rating table for the economical cluster

Criteria	Rating								
	1	2	3	4	5	6	7	8	9
C_1									X
C_2								X	
C_3							X		
C_4							X		
C_5								X	

Rating table for the social cluster

Criteria	Rating								
	1	2	3	4	5	6	7	8	9
C_1								X	
C_2								X	
C_3							X		
C_4								X	
C_5								X	

C_6								X	
C_7									X
C_8									X
C_9						X			
C_{10}						X			
C_{11}					X				
C_{12}						X			

Respondent 7

Rating table for the environmental cluster

Criteria	Rating								
	1	2	3	4	5	6	7	8	9
C_1								X	
C_2									X
C_3									X
C_4								X	
C_5									X
C_6									X
C_7									X
C_8									X
C_9							X		
C_{10}							X		
C_{11}								X	
C_{12}								X	
C_{13}									X
C_{14}								X	
C_{15}									X
C_{16}								X	

Rating table for the economical cluster

Criteria	Rating								
	1	2	3	4	5	6	7	8	9
C_1									X
C_2					X				
C_3						X			
C_4							X		
C_5								X	

Rating table for the social cluster

Criteria	Rating								
	1	2	3	4	5	6	7	8	9
C_1									X
C_2									X
C_3									X
C_4									X
C_5					X				
C_6						X			
C_7					X				
C_8						X			
C_9						X			
C_{10}				X					
C_{11}									X
C_{12}									X

Respondent 8

Rating table for the environmental cluster

Criteria	Rating								
	1	2	3	4	5	6	7	8	9
C_1							X		
C_2								X	
C_3							X		
C_4								X	
C_5							X		
C_6								X	
C_7								X	
C_8						X			
C_9							X		
C_{10}							X		
C_{11}								X	
C_{12}							X		
C_{13}									X
C_{14}								X	
C_{15}								X	
C_{16}							X		

Rating table for the economical cluster

Criteria	Rating								
	1	2	3	4	5	6	7	8	9
C_1								X	
C_2									X
C_3							X		
C_4								X	
C_5						X			

Rating table for the social cluster

Criteria	Rating								
	1	2	3	4	5	6	7	8	9
C_1						X			
C_2								X	
C_3							X		
C_4						X			
C_5						X			
C_6				X					
C_7							X		
C_8							X		
C_9					X				
C_{10}			X						
C_{11}								X	
C_{12}							X		

Respondent 9

Rating table for the environmental cluster

Criteria	Rating								
	1	2	3	4	5	6	7	8	9
C_1									X
C_2									X
C_3									X
C_4									X
C_5									X
C_6									X
C_7									X
C_8									X
C_9									X
C_{10}									X
C_{11}							X		
C_{12}									X

C_{13}									X
C_{14}							X		
C_{15}							X		
C_{16}								X	

Rating table for the economical cluster

Criteria	Rating								
	1	2	3	4	5	6	7	8	9
C_1									X
C_2								X	
C_3								X	
C_4								X	
C_5								X	

Rating table for the social cluster

Criteria	Rating								
	1	2	3	4	5	6	7	8	9
C_1								X	
C_2								X	
C_3							X		
C_4							X		
C_5								X	
C_6							X		
C_7								X	
C_8								X	
C_9				X					
C_{10}	X								
C_{11}				X					
C_{12}								X	

Respondent 10

Rating table for the environmental cluster

Criteria	Rating								
	1	2	3	4	5	6	7	8	9
C_1						X			
C_2							X		
C_3								X	
C_4							X		
C_5								X	
C_6								X	

C_7								X	
C_8								X	
C_9								X	
C_{10}								X	
C_{11}								X	
C_{12}							X		
C_{13}								X	
C_{14}								X	
C_{15}							X		
C_{16}							X		

Rating table for the economical cluster

Criteria	**Rating**								
	1	2	3	4	5	6	7	8	9
C_1								X	
C_2								X	
C_3						X			
C_4								X	
C_5								X	

Rating table for the social cluster

Criteria	**Rating**								
	1	2	3	4	5	6	7	8	9
C_1								X	
C_2							X		
C_3							X		
C_4							X		
C_5							X		
C_6							X		
C_7								X	
C_8								X	
C_9							X		
C_{10}							X		
C_{11}								X	
C_{12}								X	

Respondent 11

Rating table for the environmental cluster

Criteria	Rating								
	1	2	3	4	5	6	7	8	9
C_1							X		
C_2						X			
C_3								X	
C_4							X		
C_5								X	
C_6							X		
C_7								X	
C_8									X
C_9							X		
C_{10}							X		
C_{11}								X	
C_{12}									X
C_{13}									X
C_{14}								X	
C_{15}								X	
C_{16}						X			

Rating table for the economical cluster

Criteria	Rating								
	1	2	3	4	5	6	7	8	9
C_1								X	
C_2								X	
C_3							X		
C_4								X	
C_5								X	

Rating table for the social cluster

Criteria	Rating								
	1	2	3	4	5	6	7	8	9
C_1							X		
C_2							X		
C_3							X		
C_4							X		
C_5							X		
C_6							X		
C_7							X		
C_8							X		
C_9							X		
C_{10}							X		
C_{11}						X			
C_{12}								X	

Respondent 12

Rating table for the environmental cluster

Criteria	Rating								
	1	2	3	4	5	6	7	8	9
C_1							X		
C_2									X
C_3								X	
C_4								X	
C_5									X
C_6							X		
C_7									X
C_8									X
C_9							X		
C_{10}							X		
C_{11}							X		
C_{12}							X		
C_{13}								X	
C_{14}						X			
C_{15}								X	
C_{16}							X		

Rating table for the economical cluster

Criteria	**Rating**								
	1	2	3	4	5	6	7	8	9
C_1									X
C_2									X
C_3						X			
C_4								X	
C_5								X	

Rating table for the social cluster

Criteria	**Rating**								
	1	2	3	4	5	6	7	8	9
C_1									X
C_2								X	
C_3								X	
C_4							X		
C_5							X		
C_6							X		
C_7							X		
C_8							X		
C_9					X				
C_{10}	X								
C_{11}				X					
C_{12}								X	

Appendix D
First Respondent Weight Evaluation using The Modified Analytical Hierarchy Process

Environmental cluster

The pairwise comparison matrix and the summed of each column for the environmental cluster

	C_{1}	C_{2}	C_{3}	C_{4}	C_{5}	C_{6}	C_{7}	C_{8}	C_{9}	C_{10}	C_{11}	C_{12}	C_{13}	C_{14}	C_{15}	C_{16}
C_{1}	1	1/2	1/3	1	1/3	1	1/3	1/3	1/3	1	1/3	1	1/3	1	1	2
C_{2}	2	1	1/2	2	1/2	2	1/2	1/2	1/2	2	1/2	2	1/2	2	2	3
C_{3}	3	2	1	3	1	3	1	1	1	3	1	3	1	3	3	4
C_{4}	1	1/2	1/3	1	1/3	1	1/3	1/3	1/3	1	1/3	1	1/3	1	1	2
C_{5}	3	2	1	3	1	3	1	1	1	3	1	3	1	3	3	4
C_{6}	1	½	1/3	1	1/3	1	1/3	1/3	1/3	1	1/3	1	1/3	1	1	2
C_{7}	3	2	1	3	1	3	1	1	1	3	1	3	1	3	3	4
C_{8}	3	2	1	3	1	3	1	1	1	3	1	3	1	3	3	4
C_{9}	3	2	1	3	1	3	1	1	1	3	1	3	1	3	3	4
C_{10}	1	1/2	1/3	1	1/3	1	1/3	1/3	1/3	1	1/3	1	1/3	1	1	2
C_{11}	3	2	1	3	1	3	1	1	1	3	1	3	1	3	3	4
C_{12}	1	1/2	1/3	1	1/3	1	1/3	1/3	1/3	1	1/3	1	1/3	1	1	2
C_{13}	3	2	1	3	1	3	1	1	1	3	1	3	1	3	3	4
C_{14}	1	1/2	1/3	1	1/3	1	1/3	1/3	1/3	1	1/3	1	1/3	1	1	2
C_{15}	1	1/2	1/3	1	1/3	1	1/3	1/3	1/3	1	1/3	1	1/3	1	1	2
C_{16}	1/2	1/3	1/4	1/2	1/4	½	1/4	1/4	1/4	1/2	1/4	1/2	1/4	1/2	1/2	1
Σ	30.5	18.8	10.1	30.5	10.1	30.5	10.1	10.1	10.1	30.5	10.1	30.5	10.1	30.5	30.5	46

C_{1} = Slope, C_{2} = Land use, C_{3} = Groundwater, C_{4} = Geology, C_{5} = Surface water, C_{6} = Topography and geological condition, C_{7} = River, C_{8} = Drinking water sources, C_{9} = Soil type, C_{10} = Faultline, C_{11} = Weather/Climate, C_{12} = Lakes/Ponds/Dams/Reservoirs, C_{13} = Pollution, C_{14} = Infrastructures, C_{15} = Floodplain, C_{16} = Wind direction

Divide each element in the pairwise comparison matrix by column total.

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}	C_{11}	C_{12}	C_{13}	C_{14}	C_{15}	C_{16}
C_1	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.04
C_2	0.07	0.05	0.05	0.07	0.05	0.07	0.05	0.05	0.05	0.07	0.05	0.07	0.05	0.07	0.07	0.07
C_3	0.10	0.11	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.09
C_4	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.04
C_5	0.10	0.11	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.09
C_6	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.04
C_7	0.10	0.11	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.09
C_8	0.10	0.11	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.09
C_9	0.10	0.11	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.09
C_{10}	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.04
C_{11}	0.10	0.11	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.09
C_{12}	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.04
C_{13}	0.10	0.11	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.09
C_{14}	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.04
C_{15}	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.04
C_{16}	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02

Calculate the element's average in each row to determine the priority for each criterion.

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}	C_{11}	C_{12}	C_{13}	C_{14}	C_{15}	C_{16}	TOTAL	PRIORITIES
C_1	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.04	0.53	0.03
C_2	0.07	0.05	0.05	0.07	0.05	0.07	0.05	0.05	0.05	0.07	0.05	0.07	0.05	0.07	0.07	0.07	0.92	0.06
C_3	0.10	0.11	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.09	1.58	0.10
C_4	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.04	0.53	0.03
C_5	0.10	0.11	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.09	1.58	0.10
C_6	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.04	0.53	0.03
C_7	0.10	0.11	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.09	1.58	0.10
C_8	0.10	0.11	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.09	1.58	0.10
C_9	0.10	0.11	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.09	1.58	0.10
C_{10}	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.04	0.53	0.03
C_{11}	0.10	0.11	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.09	1.58	0.10
C_{12}	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.04	0.53	0.03
C_{13}	0.10	0.11	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.09	1.58	0.10
C_{14}	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.04	0.53	0.03
C_{15}	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.04	0.53	0.03
C_{16}	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.33	0.02

C_1 0.53 / 0.03 = 16.03
C_2 0.93 / 0.06 = 16.07
C_3 1.58 / 0.10 = 16.08
C_4 0.53 / 0.03 = 16.03
C_5 1.58 / 0.10 = 16.08
C_6 0.53 / 0.03 = 16.03
C_7 1.58 / 0.10 = 16.08
C_8 1.58 / 0.10 = 16.08

C_9 1.58 / 0.10 = 16.08
C_{10} 0.53 / 0.03 = 16.03
C_{11} 1.58 / 0.10 = 16.08
C_{12} 0.53 / 0.03 = 16.03
C_{13} 1.58 / 0.10 = 16.08
C_{14} 0.53 / 0.03 = 16.03
C_{15} 0.53 / 0.03 = 16.03
C_{16} 0.33 / 0.02 = 16.02

$$\lambda_{\max} = \frac{16.03+16.07+16.08+16.03+16.08+16.03+16.08+16.08+16.08+16.03+16.08+16.03+16.08+16.03+16.03+16.02}{16} = 16.05$$

$$CI = \frac{16.05 - 16}{16 - 1} = 0.0036$$

The value of *RI* for dimension greater than 16

M	16	17	18	19	20	21	22	23
RI	1.5978	1.6086	1.6181	1.6265	1.6341	1.6409	1.6470	1.6526
M	24	25	26	27	28	29	30	31
RI	1.6577	1.6624	1.6667	1.6706	1.6743	1.6777	1.6809	1.6839
M	32	33	34	35	36	37	38	39
RI	1.6867	1.6893	1.6917	1.6940	1.6962	1.6982	1.7002	1.7020

Sources: Alonso & Lamata (2006)

$$CR = \frac{0.0036}{1.5978} = 0.0023$$

Economical cluster

The pairwise comparison matrix and the summed of each column

	C_1	**C_2**	**C_3**	**C_4**	**C_5**
C_1	1	1	3	1	2
C_2	1	1	3	1	2
C_3	1/3	1/3	1	1/3	½
C_4	1	1	3	1	2
C_5	1/2	1/2	2	1/2	1
Σ	3.83	3.83	12	3.83	7.5

C_1 = Lifespan, C_2 = Land cost/price, C_3 = Job opportunity, C_4 = Construction cost, C_5 = Operational cost

Divide each element in the pairwise comparison matrix by column total.

	C_1	**C_2**	**C_3**	**C_4**	**C_5**
C_1	0.26	0.26	0.25	0.26	0.27
C_2	0.26	0.26	0.25	0.26	0.27
C_3	0.09	0.09	0.08	0.09	0.07
C_4	0.26	0.26	0.25	0.26	0.27
C_5	0.13	0.13	0.17	0.13	0.13

Calculate the element's average in each row to determine the priority for each criterion.

	C_1	**C_2**	**C_3**	**C_4**	**C_5**	**TOTAL**	**PRIORITIES**
C_1	0.26	0.26	0.25	0.26	0.27	1.30	0.26
C_2	0.26	0.26	0.25	0.26	0.27	1.30	0.26
C_3	0.09	0.09	0.08	0.09	0.07	0.41	0.08
C_4	0.26	0.26	0.25	0.26	0.27	1.30	0.26
C_5	0.13	0.13	0.17	0.13	0.13	0.69	0.14

C_1 1.30 / 0.26 = 5.01
C_2 1.30 / 0.26 = 5.01
C_3 0.41 / 0.08 = 5.00
C_4 1.30 / 0.26 = 5.01
C_5 0.69 / 0.14 = 5.01

$$\lambda_{max} = \frac{5.01 + 5.01 + 5.00 + 5.01 + 5.01}{5} = 5.0100$$

$$CI = \frac{5.0100 - 5}{5 - 1} = 0.0025$$

The value of RI

M	3	4	5	6	7	8	9	10	11	12	13
RI	0.525	0.882	1.115	1.252	1.341	1.404	1.452	1.484	1.513	1.535	1.555

Source: Saaty (1980)

$$CR = \frac{0.0025}{1.115} = 0.0022$$

Social cluster

The pairwise comparison matrix and the summed of each column

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}	C_{11}	C_{12}
C_1	1	1	1	1	3	1	2	3	3	3	1	1
C_2	1	1	1	1	3	1	2	3	3	3	1	1
C_3	1	1	1	1	3	1	2	3	3	3	1	1
C_4	1	1	1	1	3	1	2	3	3	3	1	1
C_5	1/3	1/3	1/3	1/3	1	1/3	1/2	1	1	1	1/3	1/3
C_6	1	1	1	1	3	1	2	3	3	3	1	1
C_7	1/2	1/2	1/2	½	2	1/2	1	2	2	2	1/2	1/2
C_8	1/3	1/3	1/3	1/3	1	1/3	1/2	1	1	1	1/3	1/3
C_9	1/3	1/3	1/3	1/3	1	1/3	1/2	1	1	1	1/3	1/3
C_{10}	1/3	1/3	1/3	1/3	1	1/3	1/2	1	1	1	1/3	1/3
C_{11}	1	1	1	1	3	1	2	3	3	3	1	1
C_{12}	1	1	1	1	3	1	2	3	3	3	1	1
Σ	8.83	8.83	8.83	8.83	27.00	8.83	17.00	27.00	27.00	27.00	8.83	8.83

C_1 = Residential/Waste production areas, C_2 = Urban/Rural areas, C_3 = Historical/Tourism areas, C_4 = Park/Recreational areas, C_5 = Mining areas, C_6 = Airport, C_7 = Transport infrastructure and access, C_8 = Road access, C_9 = Highways, C_{10} = Railways, C_{11} = Political influence C_{12} = Public acceptance

Divide each element in the pairwise comparison matrix by column total.

	C_1	**C_2**	**C_3**	**C_4**	**C_5**	**C_6**	**C_7**	**C_8**	**C_9**	**C_{10}**	**C_{11}**	**C_{12}**
C_1	0.11	0.11	0.11	0.11	0.11	0.11	0.12	0.11	0.11	0.11	0.11	0.11
C_2	0.11	0.11	0.11	0.11	0.11	0.11	0.12	0.11	0.11	0.11	0.11	0.11
C_3	0.11	0.11	0.11	0.11	0.11	0.11	0.12	0.11	0.11	0.11	0.11	0.11
C_4	0.11	0.11	0.11	0.11	0.11	0.11	0.12	0.11	0.11	0.11	0.11	0.11
C_5	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.04	0.04	0.04	0.04	0.04
C_6	0.11	0.11	0.11	0.11	0.11	0.11	0.12	0.11	0.11	0.11	0.11	0.11
C_7	0.06	0.06	0.06	0.06	0.07	0.06	0.06	0.07	0.07	0.07	0.06	0.06
C_8	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.04	0.04	0.04	0.04	0.04
C_9	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.04	0.04	0.04	0.04	0.04
C_{10}	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.04	0.04	0.04	0.04	0.04
C_{11}	0.11	0.11	0.11	0.11	0.11	0.11	0.12	0.11	0.11	0.11	0.11	0.11
C_{12}	0.11	0.11	0.11	0.11	0.11	0.11	0.12	0.11	0.11	0.11	0.11	0.11

Calculate the element's average in each row to determine the priority for each criterion.

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}	C_{11}	C_{12}	TOTAL	PRIORITIES
C_1	0.11	0.11	0.11	0.11	0.11	0.11	0.12	0.11	0.11	0.11	0.11	0.11	1.35	0.11
C_2	0.11	0.11	0.11	0.11	0.11	0.11	0.12	0.11	0.11	0.11	0.11	0.11	1.35	0.11
C_3	0.11	0.11	0.11	0.11	0.11	0.11	0.12	0.11	0.11	0.11	0.11	0.11	1.35	0.11
C_4	0.11	0.11	0.11	0.11	0.11	0.11	0.12	0.11	0.11	0.11	0.11	0.11	1.35	0.11
C_5	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.04	0.04	0.04	0.04	0.04	0.44	0.04
C_6	0.11	0.11	0.11	0.11	0.11	0.11	0.12	0.11	0.11	0.11	0.11	0.11	1.35	0.11
C_7	0.06	0.06	0.06	0.06	0.07	0.06	0.06	0.07	0.07	0.07	0.06	0.06	0.75	0.06
C_8	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.04	0.04	0.04	0.04	0.04	0.44	0.04
C_9	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.04	0.04	0.04	0.04	0.04	0.44	0.04
C_{10}	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.04	0.04	0.04	0.04	0.04	0.44	0.04
C_{11}	0.11	0.11	0.11	0.11	0.11	0.11	0.12	0.11	0.11	0.11	0.11	0.11	1.35	0.11
C_{12}	0.11	0.11	0.11	0.11	0.11	0.11	0.12	0.11	0.11	0.11	0.11	0.11	1.35	0.11

C_1 1.36 / 0.11 = 12.02
C_2 1.36 / 0.11 = 12.02
C_3 1.36 / 0.11 = 12.02
C_4 1.36 / 0.11 = 12.02
C_5 0.44 / 0.04 = 12.01
C_6 1.36 / 0.11 = 12.02
C_7 0.75 / 0.06 = 12.01
C_8 0.44 / 0.04 = 12.01
C_9 0.44 / 0.04 = 12.01
C_{10} 0.44 / 0.04 = 12.01
C_{11} 1.36 / 0.11 = 12.02
C_{12} 1.36 / 0.11 = 12.02

$$\lambda_{max} = \frac{12.02 + 12.02 + 12.02 + 12.02 + 12.01 + 12.02 + 12.01 + 12.01 + 12.01 + 12.01 + 12.02 + 12.02}{12} = 12.0162$$

$$CI = \frac{12.0162 - 12}{12 - 1} = 0.0015$$

The value of RI

M	3	4	5	6	7	8	9	10	11	12	13
RI	0.525	0.882	1.115	1.252	1.341	1.404	1.452	1.484	1.513	1.535	1.555

Source: Saaty (1980)

$$CR = \frac{0.0015}{1.535} = 0.0010$$

Appendix E

Final weights and ranks of all respondents for the criteria and the consistency

Environmental cluster

	DM1	**DM2**	**DM3**	**DM4**	**DM5**	**DM6**	**DM7**	**DM8**	**DM9**	**DM10**	**DM11**	**DM12**	**TOTAL**	**RANK**
C_1	0.03	0.11	0.06	0.02	0.04	0.10	0.04	0.04	0.04	0.07	0.07	0.03	0.66	14
C_2	0.06	0.04	0.06	0.04	0.02	0.01	0.09	0.08	0.11	0.07	0.07	0.11	0.76	6
C_3	0.10	0.11	0.06	0.08	0.07	0.10	0.09	0.04	0.07	0.07	0.07	0.11	0.95	4
C_4	0.03	0.01	0.06	0.04	0.04	0.05	0.04	0.08	0.07	0.07	0.07	0.05	0.61	11
C_5	0.10	0.11	0.06	0.08	0.07	0.10	0.09	0.04	0.11	0.07	0.07	0.05	0.93	5
C_6	0.03	0.06	0.06	0.08	0.04	0.03	0.09	0.08	0.04	0.07	0.07	0.07	0.71	8
C_7	0.10	0.11	0.06	0.08	0.07	0.10	0.09	0.08	0.11	0.07	0.07	0.11	1.04	2
C_8	0.10	0.06	0.06	0.08	0.12	0.10	0.09	0.02	0.11	0.07	0.07	0.11	0.99	3
C_9	0.10	0.04	0.06	0.08	0.04	0.05	0.03	0.04	0.04	0.07	0.07	0.01	0.62	10
C_{10}	0.03	0.06	0.06	0.08	0.04	0.05	0.03	0.04	0.04	0.07	0.07	0.02	0.59	15
C_{11}	0.10	0.04	0.06	0.08	0.07	0.03	0.04	0.08	0.04	0.04	0.02	0.01	0.60	13
C_{12}	0.03	0.06	0.06	0.04	0.12	0.05	0.04	0.04	0.04	0.07	0.07	0.11	0.74	7
C_{13}	0.10	0.11	0.06	0.08	0.15	0.05	0.09	0.14	0.07	0.07	0.07	0.11	1.09	1
C_{14}	0.03	0.04	0.06	0.08	0.07	0.05	0.04	0.08	0.02	0.07	0.02	0.05	0.61	12
C_{15}	0.03	0.04	0.06	0.04	0.07	0.10	0.09	0.08	0.07	0.07	0.02	0.05	0.70	9
C_{16}	0.02	0.02	0.06	0.04	0.02	0.05	0.04	0.04	0.04	0.01	0.04	0.01	0.40	16
CONSISTENCY	0.0023	0.0082	0.0000	0.0007	0.0165	0.0038	0.0013	0.0017	0.0058	0.0005	0.0005	0.0173		

Consistency for 12 experts = (0.0023+0.0082+0.0000+0.0007+0.00165+0.0038+0.0013+0.0017+0.0058+0.0005+0.0005+0.0173)/12
= 0.0049

Economical cluster

	DM1	DM2	DM3	DM4	DM5	DM6	DM7	DM8	DM9	DM10	DM11	DM12	TOTAL	RANK
C_1	0.26	0.27	0.20	0.23	0.22	0.37	0.42	0.21	0.30	0.20	0.33	0.38	3.40	1
C_2	0.26	0.43	0.20	0.23	0.22	0.21	0.06	0.38	0.30	0.20	0.17	0.13	2.78	2
C_3	0.08	0.10	0.20	0.08	0.11	0.11	0.10	0.12	0.07	0.20	0.17	0.06	1.39	5
C_4	0.26	0.10	0.20	0.23	0.22	0.11	0.16	0.21	0.16	0.20	0.17	0.22	2.25	3
C_5	0.14	0.10	0.20	0.23	0.22	0.21	0.26	0.07	0.16	0.20	0.17	0.22	2.18	4
CONSISTENCY	0.0022	0.0045	0.0000	0.0000	0.0001	0.0030	0.0153	0.0074	0.0059	0.0000	0.0000	0.0116		

Consistency for 12 experts = (0.0022+0.0045+0.0000+0.0000+0.0001+0.0030+0.0153+0.0074+0.0059+0.0000+0.0000+0.0116) / 12
= 0.0042

Social cluster

	DM1	DM2	DM3	DM4	DM5	DM6	DM7	DM8	DM9	DM10	DM11	DM12	TOTAL	RANK
C_1	0.11	0.08	0.08	0.12	0.08	0.10	0.14	0.06	0.20	0.12	0.12	0.16	1.36	1
C_2	0.11	0.08	0.08	0.06	0.08	0.10	0.14	0.17	0.12	0.12	0.12	0.10	1.27	3
C_3	0.11	0.08	0.08	0.06	0.08	0.06	0.14	0.10	0.12	0.12	0.07	0.10	1.11	6
C_4	0.11	0.08	0.08	0.06	0.08	0.10	0.14	0.06	0.07	0.12	0.07	0.10	1.06	7
C_5	0.04	0.08	0.08	0.06	0.08	0.10	0.03	0.06	0.07	0.04	0.12	0.06	0.81	10
C_6	0.11	0.04	0.08	0.06	0.08	0.10	0.04	0.03	0.07	0.07	0.07	0.16	0.91	8
C_7	0.06	0.14	0.08	0.12	0.08	0.17	0.03	0.10	0.07	0.07	0.12	0.10	1.13	5
C_8	0.04	0.14	0.08	0.12	0.08	0.17	0.04	0.10	0.07	0.12	0.12	0.10	1.17	4
C_9	0.04	0.03	0.08	0.06	0.08	0.04	0.04	0.04	0.03	0.07	0.02	0.03	0.56	11
C_{10}	0.04	0.04	0.08	0.06	0.08	0.04	0.02	0.02	0.01	0.03	0.01	0.03	0.46	12
C_{11}	0.11	0.08	0.08	0.12	0.04	0.02	0.14	0.17	0.02	0.03	0.02	0.02	0.85	9
C_{12}	0.11	0.14	0.08	0.12	0.16	0.04	0.14	0.10	0.12	0.12	0.12	0.06	1.30	2
CONSISTENCY	0.0010	0.0033	0.0000	0.0023	0.0000	0.0066	0.0085	0.0104	0.0161	0.0041	0.0120	0.0087		

Consistency for 12 experts = (0.0010+0.0033+0.0000+0.0023+0.0000+0.0066+0.0085+0.0104+0.0161+0.0041+0.0120+0.0087) / 12
= 0.0061