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An Integrated Approach for Sustainable Site Selection and Operations Management for Infectious Waste Disposal

by

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This thesis is dedicated to my mother, father, and friends for their continuous support, guidance, and advice.

CERTIFICATE OF APPROVAL

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Abstract

Ever increasing environmental and social concerns have directed organizations to select and manage Infectious Waste Disposal Sites (IWDS) based on a holistic sustainable criterion that involves economic, environmental, and social aspects. The selection of infectious waste disposal site is particularly challenging because of the possibility of risks both to nature and to human health. Additionally, the complexity of managing the operations of infectious waste disposal sites becomes increasingly complex when environmental and social aspects are added along with omnipresent economic aspects. The research work done in this thesis presents a novel framework that integrates sustainable site selection with sustainable operations management for infectious waste disposal. The proposed integrated framework consists of four phases. In the first phase, different criterion and sub-criterion have been short listed based on an extensive literature review and opinions of decision makers involved in the selection of IWDS. Then, fuzzy extended analytical hierarchy (fuzzy E-AHP) and TOPSIS method have been employed to determine the relative importance of selected criteria and to rank different candidate sites. In the second phase, a Mixed Integer Non-Linear Programming (MINLP) mathematical model has been developed, which aimed to simultaneously optimize various objective functions such as total cost, vehicle travel time, environmental impact, and overall sustainability value for the selected site. In the third phase, Augmented Epsilon Constraint-2 algorithm has been used to simultaneously optimize all objective functions to obtain the Pareto optimum solutions. In the fourth and the final phase, TOPSIS augmented with CRITIC method has been used to obtain the final Pareto optimal solution. The proposed integrated framework has been evaluated through a real-time case study. In this regard, thirty-eight hospitals and three prospective candidate sites in Islamabad Pakistan were chosen. The overall objective was to select most sustainable IWDS with optimized operations management. The result of the fuzzy Extended-AHP analysis revealed that the Economic criterion holds the highest weightage as compared to the remaining two sustainability pillars (environment, and social). The three candidate sites were ranked using TOPSIS method aided by decision makers opinion and site

Tarnol(A3) was ranked highest. The developed mathematical model was solved using AUGMECON2 algorithm. The results for the selected sites indicates that the total cost value is $7447. Similarly the total time of vehicle traveled is 7.64 hrs. The environmental impact value is 34359 grams, and the total sustainability value of selected site is 25.83. Furthermore the study presents managerial implications of the suggested techniques and future scenarios for further research.

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Abbreviations

AHP	Analytic hierarchy process
AUGMECON2	Augmented Epsilon Constraint 2
CC	Closeness Coefficient
CFLP	Capacitated Facility Location Problem
CI	Consistency Index
CR	Consistency Ratio
CRITIC	Criteria Importance Through Inter-criteria Correlation
DFW	Distance from Waters
DFS	Distance from Society
E-AHP	Extended Analytic Hierarchy Process
EHS	Employee Health and Safety
EI	Environmental Impact
FLC	Facility Location Cost
FST	Fuzzy Set Theory
GHGE	Green House Gas Emission
IOS	Impact on Society
IWD	Infectious Waste Disposal
IWDS	Infectious Waste Disposal Site
MCDM	Multi-Criteria Decision Making
MINLP	Mixed Integer Non-Linear Programming
MODM	Multi-Objective Decision Making
MOGA	Multi-Objective Genetic Algorithm
NDM	Normalized Decision Matrix

NSGA	Non-dominated Sorting Genetic Algorithm
OC	Operating Cost
RC	Relative Closeness
RC	Resource Consumption
SCM	Supply Chain Management
SCND	Supply Chain Network Design
SI	Social Impact
SSCM	Sustainable Supply Chain Management
SPTD	Staff Personal & Technical Development
SIWDSS	Sustainable Infectious Waste Disposal Site Selection
SOM	Sustainable Operations Management
TC	Total Cost
TOPSIS	Technique of Order Preference Similarity to the Ideal Solution
TRC	Transportation Cost
TSVSS	Total Sustainable Value of Selected Site
TTT	Total Time Travel
UFLP	Uncapacitated Facility Location Problem
WNDM	Weighted Normalized Decision Matrix

Chapter 1

Introduction

Selection of site for infectious waste disposal is a critical issue that poses substantial risks to public health and environment. Infectious waste can be generally classified as biological laboratory waste (e.g., cultures, stocks, and growth media), pathological waste (e.g., human tissue, organs, or body fluids), and contaminated sharp objects (like needles, syringes, and surgical blades). Additionally, single-use disposable equipment, utensils, and instruments that may carry potentially infectious agents are also classified as infectious waste. Research has indicated that tertiary care hospitals in Pakistan generate approximately 1.35 kilograms of medical waste per bed. More specifically, the public sector tertiary care hospitals in Pakistan produce approximately 0.8 million tons of waste daily, collectively operating at a capacity of around 92,000 beds [1].

The infectious waste generated from treating diseases or administering medical procedures to humans or animals should be handled with care to avoid disease transmission and to safeguard environmental health [2]. Medical professionals need to possess exceptional skills, a positive attitude, and follow safe protocols while managing this infectious waste [3]. A significant number of healthcare professionals get infected and sustain sharp injuries due to their failure to follow a proper waste management guidelines [4]. According to a WHO survey, two-third of hospitals across the developing countries do not adhere to the recommended infectious waste management practices [5]. To address the risk of infectious diseases that could jeopardize patients, caregivers, hospital staff, and nearby community members, it has been recommended that healthcare workers (HCWs) receive continuous training in handling hazardous waste [6].

In contrast to industrialized nations, developing countries have often not prioritized infectious waste management adequately. However, there is a growing awareness among people about the importance of implementing stricter regulations for the proper handling and disposal of waste produced by healthcare facilities [7]. Infectious waste management broadly comprises four main procedures: segregation, collection and transportation, storage, and disposal. Before undergoing final disposal methods such as incineration or autoclave, the waste must undergo processing. Hospital waste is typically disposed of in Pakistan using two methods: landfills and incineration. Hospital trash is buried underground using the landfill method, however no landfill, in the opinion of health professionals, is built using scientific principles. When hospital waste is burned, it releases harmful substances such as dioxins and chemicals into the air. These substances can be cancer-causing because the incinerators used in various locations don't have proper filters and scrubbers to remove them effectively [8].

In Pakistan, only big hospitals tend to have their incinerators located within the hospital premises. Generally, many medium-sized or small hospitals lack this dedicated facility. As a result, these hospitals often enter into contracts with third-party agencies to manage their infectious waste. These agencies are responsible for collecting and appropriately disposing of infectious waste on behalf of these hospitals. However, the agencies dealing with infectious waste are not able to do the treatment of waste effectively. As a result, a number of reports have emerged over the years that claim that hospital waste is often found mixed with municipal waste and even with water streams [9]. The improper management of Infectious Waste Disposal Sites (IWDS) in recent decades has led to several issues, including illegal waste dumping and contamination of environment by fly ash. and harmful metals in the cremated. In Pakistan, there is a lack of information about the production of heavy metals during the incineration of medical waste [10]. The environment becomes contaminated with heavy metals as a result of the combustion of hospital wastes, which also emits harmful gases (CO, CO2, NO2, SO2, etc.) into the environment [11].

This alarming situation warrants exploring better ways to build new and suitable IWDS. The selection of an IWDS is a challenging task that involves considering a range of factors, which include social, environmental, financial, and geological criteria. The biophysical environment and ecology of the surrounding region must not be harmed by the disposal site. The minimization of environmental and social impact is just as important as minimization of overall total cost [12]. The environmental and social impact can be analyzed through qualitative and quantitative aspects, lowering the impact value of environmental and social factors will reduce the chances that the selected site may cause damage to the biophysical environment and ecology of the surrounding area. When choosing a location for IWDS, its operations management must also be considered. This includes a variety of tactics and guidelines that guarantee successful and efficient choice-making, resource distribution, and general administration of the selected site.

Researchers and professionals, in operations management are encountering challenges when it comes to incorporating sustainability concerns into their areas of focus. Over the last two decades, businesses have faced increasing demands to consider the resource impacts of their products, services, and operational procedures. One notable response, to this pressure is the growing trend of adopting triple bottom line reporting (3BL) Sustainability approach. 3BL focuses on balancing profit, people, and the planet. This approach presents challenges such as incorporating health and safety considerations, into green product design, efficient and sustainable operations, and closed-loop supply chains [13]. In past years there has been a growing interest, among researchers in both operations management and management science, toward Sustainable Operations Management (SOM). As the majority of SOM research has focused on conducting literature reviews but there remains much to explore in the field of operations management [14], [15]. SOM encompasses areas, including the concept of supply chain [14]. Significance of sustainability is on the rise, prompting organizations to prioritize sustainability management strategies and practices as an increasingly crucial aspect of their operations. As operational decisions greatly impact sustainability outcomes it is crucial for the operations management function to fully embrace the principles of sustainability management. To ensure effective management it is crucial to integrate environmental and social performance objectives, targets, and indicators with quality, cost, and other conventional performance measures [16]. Operations management acts as a guiding framework to help decision-makers to get well-informed about strategic choices when choosing appropriate sites for the disposal of infectious waste.

Dealing with infectious waste challenges requires a systematic approach that balances environmental concerns, legal obligations, efficient resource utilization, and public health considerations. Different sustainable criteria should be considered in the selection and operations of IWDS, thus making it a multi-criteria decision making (MCDM) problem. Many studies have shown fuzzy logic plays an important role in solving MCDM problem [17–19]. Fuzzy Set Theory (FST) is introduced in MCDM problem to convert crisp numerical data for more accurate evaluation of real-world systems [20]. FST is employed in the fuzzy MCDM's performance rating and weights to imitate the uncertainty of human assessments [21].

1.1 Motivation

Based on the above discussion it can be concluded that sustainable selection and operations management of IWDS is critical. Sustainability in Operations management and Site selection is a field of study that's gaining prominence. Researcher and practitioners acknowledge that the goal of minimizing costs is closely tied to factors like minimum delivery time, environmental impact, and maximum sustainability value of the site and social impact. By incorporating sustainable practices into the assessment of operations management and potential sites, businesses can gain a competitive advantage. Considering sustainability in operations management is complex task. The increasing complexity of operations management in infectious waste site selection arises from stricter global regulations, necessitating careful adherence to international standards. Additionally, the interconnections of regions magnifies the potential consequences of poor site choices. Balancing sustainability demands further complicates decision-making by requiring consideration of various factors beyond cost. Attempts were made to analyze the environmental and budget performance of operations management networks at the same time. However, studies that aim to optimize the site selection process in terms of economics, environmental criteria, and social effects for sustainable site selection along with operations management are rare.

1.2 Problem Statement

A limited number of research studies have analyzed all three aspects of sustainability (economic, environment, and social) when choosing sites. Additionally, no studies have simultaneously investigated both operations management and sustainable site selection together. In the context of infectious waste this is the first study to develop an integrated framework for Sustainable Site Selection along with its Operations Management. The proposed integrated framework also take into account type of costs, total time of travel, and hazardous emission of gases.

1.3 Research Objective

This study aimed to develop an integrated framework for Sustainable Site Selection along with its Operations Management. It emphasizes the significant role of operations management in the selection of infectious waste disposal sites, particularly when it comes to sustainability, which involves environmental and social aspects along with cost. The strategic selection of sites not only impacts operational efficiency but also influences environmental and social sustainability within the context of infectious waste management. The developed framework includes the following steps:

1. Selection of criteria from extensive review of existing literature and opinions of the decision makers.
2. The ranking of selected sustainable criteria using Fuzzy E-AHP method.
3. The ranking of candidate sites using Fuzzy TOPSIS method.
4. Development of MINLP mathematical model of a multi-echelon hospital infectious waste network.
5. Optimization of the developed mathematical model using enhanced AUGMECON2 method, leading to the identification of Pareto optimal solutions.
6. Selection of the best Pareto optimum solution using TOPSIS along with CRITIC method.

1.4 Thesis Outline

The remaining report is organized in the following manner to provide a comprehensive exploration of the integrated framework for Sustainable Site Selection and its Operations Management:

Chapter 2

This chapter will extensively cover the literature concerning sustainable operations management, and sustainable infectious waste disposal site selection along with strategies, problem-solving approaches and criteria for site selection.

Chapter 3

This chapter firstly explains the developed integrated approach and MCDM approaches. Secondly, the optimization of objective functions using proposed integrated framework is presented. After that, solution techniques for solving the mathematical model is presented.

Chapter 4

This chapter thoroughly examines the outcomes achieved through implementation of the proposed integrated framework in a case study involving infectious waste disposal sites.

Chapter 5

The presented work is concluded in this chapter, additionally it also discusses the management implications and offers directions for further research.

Chapter 2

Literature Review

The problem regarding the facility location selection has been in discussion for over a century, however, most scholars believe that the primary basis for the concept is a 1909 publication by Alfred Weber [22]. Conventional Facility Location Problems (FLP) comprise taking cost reduction as a single criterion and utilizing a mathematical approach to solve an area network or transportation system (depots, customers, and arcs) problems. The best option is to place the system with the lowest distance in general or the least expensive overall price. Many traditional FLP studies have regularly advocated cost and distance minimization as the only criterion for solving these problems using mathematical methodologies (heuristic and optimization techniques). Nevertheless, for some unique challenges, such as dangerous waste disposal, nuclear power plant location, waste disposal site selection, and IWDS selection, location selection is crucial since it is expensive and implication are of paramount importance. The selection of location problems in the above mentioned cases is multi-criteria decision making choices (MCDM) problems, especially multi-criteria facility location problems (MCFLPs/MOFLPs). The selection must consider the significance of pertinent variables like ethical behavior and awareness of the environment at the same time. As a consequence, developing a suitable approach for analyzing these criteria is one of the most difficult components of addressing these problems.

2.1 Facility Location Selection and Techniques

Within Operations Research (OR), the placement of a facility has always been a well-established research issue. A significant number of research and books support this facility location problem [23]. Even specialized codes for location issues have been developed by the American Mathematical Society (AMS): Use 90B80 for discontinuous placement and assignment and 90B85 for continuous placement. In an isolated facility placement issue, the number of potential candidate locations for a fresh facility is restricted to a finite number. The most basic definition of such a problem is choosing p facilities to reduce overall (weighted) distance or expenses related to meeting customer requests. The p-median dilemma has been extensively discuss in the literature [23],[24],[25].

2.1.1 Facility Location Selection

When the costs associated with establishing a waste disposal facility at different potential locations exhibit variations, the objective function can be adjusted to incorporate fixed infrastructure installation costs. As a consequence, the determination of how many facilities to construct is often made internally, considering endogenous factors. In both scenarios, namely the p-median problem and the Un-Capacitated Facility Location Problem (UFLP), each customer is allocated to the open facilities with the smallest allocation cost. One of the most notable advancements to the UFLP is the capacitated facility location problem (CFLP), which takes endogenous values under consideration to determine the maximum demand that can be delivered from each viable site [26]. Another notable advancement is the addition of unpredictable elements in facility placement models [27]. This is because some of the features, such as potential costs and future client expectations, are frequently connected with uncertainty Owen and Daskin [28], Taking time and uncertainty into consideration, facility placement research has resulted in more accurate models. Many practical location challenges arise from the presence of multiple facility types, each serving distinct functions, and the existence between them, there is an inevitable flow of materials hierarchy. A layer or an echelon is a set of facilities that have the same kind and purpose and constitute a given level in the facility's structure. There are various publications in the literature on this subject [29]. Intra-layer material fluxes have received little attention in core location studies.

2.1.2 Facility Location Selection Techniques

In recent years, many methodologies for MCDM problem solving have been published, integrating mathematical strategies (mathematical computing methods and AI techniques) and a method known as MCDM methods. A bunch of researchers and publishers [30–35] have offered mathematical strategies for dealing with environmental constraints, whereas another group [35–38] have frequently offered MCDM strategies to tackle difficult-to-interpret MCDM challenges. AHP is a popular MCDM strategy for handling these difficult issues since it is both easy and effective [39],[40]. Because each problem is ambiguous and the decision-making environment is complicated, some researchers [41],[42],[43] have recommended employing Analytical hierarchical process-only or mixed Analytical hierarchical process-other strategies to solve Multi-criteria decision-making difficulties, because cost alone will not solve these problems successfully.

Academics and practitioners have frequently utilized the multiple-criteria decision-making process, which involve analytic hierarchy procedure (AHP) [44],[45],[46]. Since the Analytical Hierarchical Method itself cannot address existing atmospheric limitations, several academics have paired it with quantitative methodologies to address the surrounding constraints concurrently. Linear programming, also known as LP, and goal-based programming (GP), both logical programming methodologies, are extensively used in the scientific community with the Analytical hierarchical process. The Linear Programming framework is used to address issues with a single goal in mind, whereas the Goal Programming approach was designed to address problems with several objectives.

In 1955, Charles, Cooper, and Ferguson [47] studied GP to solve unsolvable LPs. Some scholars, for example, have created coupled AHP-mixed LP approaches to handle single-objective choice-making issues and coupled AHP-mixed GP approaches to solve multi-objective decision-making difficulties. Even though AHP is a common technique for MCDM issue-solving, it cannot imitate human cognitive methods. The traditional Analytical Hierarchical Process method is hard because it uses a precise amount to convey one's viewpoints in a comparative analysis of options, and it is frequently criticized for the use of a scale with an imbalance of judgment, and as well as failing to properly address the intrinsic insecurity and inaccuracy in the case of pairs assessment process. Zadeh after some time created the approach known as a fuzzy analytical hierarchy (Fuzzy Analytical Hierarchical Process), which is based on fuzzy set theory [48], this approach is commonly used to substitute standard AHP when dealing with difficult-to-interpret MCDM difficulties to overcome this limitation.

As a result, numerous academics have recently used FAHP rather than the traditional Analytical Hierarchical Process to address MCDM issues [49–53]. Even though F-AHP is commonly utilized to address MCDM issues, A handful of studies have been published that describe the use of mixed Fuzzy Analytical Hierarchical Process mathematical approaches to solve MCDM within present limitations of the environment as explained by He et al. [54]. To maximize customer service while minimizing logistical expenses, a Fuzzy Analytical Hierarchical Process-LP model was proposed for the multi-criteria transshipment issue Kannan and co [55]. Also, Bakeshlou et al. [56] explain employing a hybrid MODM technique to evaluate a green supplier selection problem to properly address current environmental constraints.

Some MCFLPs/MOFLPs researchers have recently proposed using the FAHP to solve Facility Location Problems (FLPs) in a variety of methods, according to Onut et al. [57] relying upon the FAHP and fuzzy TOPSIS techniques, we created an integrated fuzzy MCDM strategy for locating an appropriate retail center location. Nazari et al. [52] the ideal landfill placement was determined using Chang's fuzzy AHP-based multi attributes decision-making (MADM) approach. Shankar and Choudhary [58] the STEEP-fuzzy AHP-TOPSIS system was described for evaluating and selecting thermal power plant sites. Faghih, Safari, and Fathi [59] explains the approach for evaluating desire by similarity to the ideal outcome (TOPSIS) was used to propose a fuzzy approach to selecting facility sites. Ozgen and Gulsun [60] explained that for tackling the multiple goals capacitated multi-facility placement issue, a mixed stochastic linear algorithm and fuzzy AHP approach were presented. Hanine [61] a comparison of the fuzzy TODIM and fuzzy AHP approaches for landfill placement selection was presented.

Although single-criteria location problems have it indicates that despite having an extensive background in location science this concept has only recently been applied to location challenges as the management sciences have embraced multi-criteria decision-making. Given the study's emphasis on multiple-criteria location models, it includes a brief introduction to MCDM ideas. Methods for MCDM are thought to be a hybrid of MADM and MODM techniques. There are often only a few fixed options in the MADM. These options each meet each aim to a certain degree, and the decision maker (DM) chooses the optimal option (or options) depending on the proportional relevance of each aim and how those objectives interact with one another.

The MADM difficulties are addressed using a variety of approaches. The ones that follow are the most often used: prevailing, maxi-min, maxi-max, removal through elements, combinations method, erect duty method, straightforward additive weighting (SAW), placed combined weighting, removal and preference expressing reality (ELECTRE), technique for ordering preference by similarity to perfect the solution) (TOPSIS), placed compromises, and linear programming methods for multiple dimensions all of these are instances of linear programming approaches [62]. Multi-objective decision-making approaches attempt to develop the optimum solution by accounting for the various relationships within the design constraints that best satisfy the needs of decision-makers by reaching certain satisfactory standards of a set of goals. The MODM issues are made up of many different parts, but they always have the following traits:

- A group of quantifiable goals.
- A group of precise restrictions.
- A method for gathering certain trade-off data

The step technique along with associated methods ordered multifaceted problem-solving, the function of usefulness, Goal programming (GP), goal-setting technique, Geoffrion approach, interactively GP, substitute worth compromises, a technique for setting acceptable goals, Zionts-Wallenius technique, the most extensively used approaches are the chronological data producer for problems with multiple objectives and the global criteria method. To tackle the problem without addressing the strategy, the following general procedures must be investigated and difficulties with Multi-Objective Decision Making:

- Objectives that clash: The MODM issues by their very nature include objectives that conflict.
- Effective Solution: An efficient MODM solution provides optimal values for all function objectives at the same time. Any objective function of a practical solution cannot be improved without also impacting the other goals [63].
- Optimum plan of action: A favored solution, referred to as the best solution, is an effective option selected as the best option chosen by the choice maker (DM). To identify a suitable solution, we employed some simple MODM approaches as well as some sensitivity analysis.

Many techniques may be used to address problems with multi-objective optimization. These techniques may be classified into three types:

- The purpose of ”classical approaches” is the process of reducing a multi-objective issue to a singular objective problem, that is then optimized.
- When a problem is solved utilizing ”Pareto optimal procedures,” a collection of solutions is produced.

- In both of the categories mentioned in above bullets, adaptive algorithms can be utilized to solve complex issues. The multi-objective biological algorithm is one of these ways (MOGA), the non-dominate sorting genetic algorithm (NSGA I1), and the quick non-dominate sorting genetic algorithm (NSGA II2). Additional specialized approaches, such as the vector evaluated genetic algorithm (VEGA), are available to solve complex MODM difficulties [64], The lexicographic ordering approach, the weight min-max method, and the distance method are all options. In the last 10 years, multi-objective combinatorial optimization (MOCO) has gained popularity [63],[65] is an effective strategy for dealing with a variety of multi-criteria difficulties.

2.1.2.1 Heuristics Technique

Particularly in some of the publications that were evaluated, the authors used heuristics to tackle their issues. To address the bi-objective competitive location dilemma. Karkazis [66] the initial step was to apply Lagrangian relaxation, followed by the construction of a heuristic along the sub-gradient axes. To identify the best answer to an issue, Maniezzo et al. [67] combined the overall number of viable solutions, and the k-best approaches for single-objective problems were pooled. Brimberg and Juel developed an approach based on quantitative aspects of the issue at hand, including block specifications and branch-and-bound methods [68]. Myung et al. [69] devised a heuristic to solve their un-capacitated bi-objective issue after taking into account weighting and constraint method strategies. For modeling open finite hierarchical queuing networks, Kerbache and Smith [70] proposed it as a heuristic. The generic enlargement method (GEM) was introduced, and then a multi-objective mathematical optimization strategy was used to find the non-inferior (NI) set of paths for their probabilistic network optimization issue. Galvo et al. [71] explains a capacitated bi-criterion model the constraint technique and a Compositional heuristic were used to solve the problem. Leung et al.'s [72] explains that goal programming problem was also efficiently addressed by a heuristic approach. Throughout iterations, they developed a heuristic focused on finding the lexicographic minimum of their two aims.

2.1.2.2 Meta Heuristics Technique

Meta-heuristics are strategies for search that are more effective than heuristics for larger and more complex issues. As can be seen in this subsection, several recent articles have used similar strategies to tackle their significant and challenging challenges. The Scatter Search (SS) is the meta-heuristic technique for resolving MC-location issues explained by Du and Evans [72], along with the restriction strategy, a scatter search method was utilized to deal with the distinct option variables and the combined linear techniques (to seek the best possible outcomes for the continuous variables). Lin and Kwok examined the performance of Tabu Search (TS) and Simulated Annealing (SA), two other forms of meta-heuristics, using a unique statistical approach [73]. Another example is Drezner et al.[74], who used two heuristics method to solve their minimax regret multi-objective issue, including tabu search and a respectable method. To allow decision-makers to explore the answer space interactively and select the most suitable configuration, Stummer et al. [75] constructed a multi-objective variant of the classic tabu In the initial stage of their method, they use a search strategy with a population set. Caballero et al. used an adaptive memory process with the tabu search-based multi-objective meta-heuristic (MOAMP) [76].

2.1.2.3 Criteria Selection for Facility Location

The majority of studies on multi-criteria location issues approach them theoretically, but it is suggested that very few have examined the ”criteria” in these situations. As a consequence, it was decided to research the available literature as well as the applicable criteria. The criteria in location issues with a single criterion have cost or coverage is often considered, but there is at least one more criterion to think about that, given the specifics of these challenges, is in contradiction with the first. The researchers explore the criteria used in bi-/multi-objective location problems while proceeding on to multi-attribute location problems based on the philosophy underpinning their classification.

1. **Decision Criteria with Multi-Objectives**

   The Table 2.1 offers a thorough overview of the objectives employed in the issues and a description of those objectives. In the next subsections, a detailed description of each of these categories of aims is provided.

   - **Cost:** Costs come in a variety of forms. These are classified into two types: fixed and adjustable. Investment and installation expenditures are examples of fixed expenses. Transportation, operations, production, services, distribution, logistics, waste management, maintenance, and environmental expenditures are examples of variable expenses. The most expensive part is transportation, and the second most expensive part is installation [77],[78].

   - **Environmental Risks:** These concerns include, in order of importance, general "unwanted effects," transportation risks, natural hazards, and risks linked with waste disposal or treatment [76],[79]. According to Table 2.4, the percentage of the cost of hazards to the environment in site concerns is much lower than the total amount of the cost.

   - **Coverage:** All location-related challenges include coverage, whether in terms of distance, time, volume, or even coverage fluctuation [76]. Although distance and population coverage are commonly emphasized as challenge variables, time may be just as important in some circumstances. We added the concept of equity in this category since these types of challenges also entail coverage but in a different way [80]. According to a literature assessment, equity has not received the same emphasis as coverage in location concerns. We put dispersion goals in this category since most of the time the difference between coverage and dispersal consists of shifting the coverage function from "minimizing" to "maximizing" or vice versa.

- **Quality of service and Effectiveness:** In this area, service level standards are developed in addition to effectiveness and efficiency requirements [81],[82].
- **Profit:**Some individuals are interested in net earnings, the difference between benefits and expenses, or other consequences of the capital utilized in facility site selection. The profit category was used to create these criteria.
- **Other Criteria:** The factors, such as resource accessibility and social and political hazards that could not be covered in other categories, were applied to location issues [83],[84].

TABLE 2.1: Criteria for bi-/multi-objective location issues.

Criteria	**Bi-Objective**	**Multi-Objective**
Cost	Bhattacharya et al.[85]	Alumur and Kara.[77]
	Blanquero et al.[86]	Badri et al.[78]
		Bhattacharya et al.[87]
Environmental Risks	El-Houssaine[88]	Alumur and Kara[77]
	Melachrinoudis [89]	Badri et al.[78]
	Skriver et al. [90]	Caballero et al.[76]
	Yapicioglu et al.[91]	Erkut et al.[79]
Coverage	Bhattacharya et al.[85]	Araz et al.[80]
	Blanquero and C.[86]	Badri et al.[78]
		Bhattacharya et al.[87]
		Caballero et al.[76]
Service level	Carrano et al.[92]	Badri et al.[78]
	Harewood [93]	Cho [81]
	Klimberg and Ratick [94]	Doerner et al.[82]
	Karkazis [90]	Klimberg [94]
Profit	Johnson [95]	-
	Myung et al.[69]	
Other Criteria	Fernández et al.[96]	Badri et al.[78]
		Caballero et al.[76]

	Doerner et al.[83]
	Farhan and Murray [84]

2. **Decision Criteria with Multi-Attributes**

Due to the enormous number of criteria used in these concerns, only a few of them are evaluated and organized into a few broad categories, as shown in Table 2.4.

- Cost factors include things like land, transportation, and installation [97].
- Revenue, the worth of a piece of land or an asset, or the value of a product are all examples of value and advantages [98].
- Environmental hazards include health implications, noise and light pollution, odors, air or water pollution, rubbish collection, and so on [99].
- There is no need to go into further information regarding the facility to be located considering the resource accessibility or usage factor [100].
- In some situations, having access to public amenities like airports, roads, and trains as well as places to relax, rest, and stay is crucial [101].
- Competition factors include the presence of rivals and the competitive climate [102].

Table 2.2: Summarized Criteria for multi-attribute location difficulties.

Criterion	**References**
Cost	Aras et al.[97]
	Chan and Chung [100]
	Chou et al.[101]
Benefits and Value	Pereira et al.[98]
	Guo and He.[103]
	Lahdelma et al.[102]

Environmental Risks	Aras et al.[97]
	Barda et al.[99]
Access to and use of resources	Aras et al.[97]
	Barda et al.[99]
	Chan and Chung.[100]
Access to public facilities	Aras et al.[97]
	Barda et al.[99]
	Chou et al.[101]
Economic	Badri [154]
	Barda et al.[99]
Population	Pereira et al.[98]
	Lahdelma et al.[102]
Distance	Pereira et al.[98]

2.2 Operations Management

The process of site selection is a strategic decision-making endeavor that has far-reaching implications for organizational success. Effective site selection entails the consideration of various factors, including geographical location, market accessibility, operational efficiency, and environmental sustainability [104–106]. One key factor that significantly influences site selection is operations management. This section delves into the nuanced relationship between operations management and site selection, highlighting the pivotal role that operations management principles play in optimizing site choices for diverse industries. Fitzsimmons and Fitzsimmons [107] emphasize the interconnections of operations management and strategic decisions, underscoring how operations considerations influence site selection decisions in the context of service industries. The seamless alignment of site characteristics and operational capabilities enhances service delivery and customer satisfaction.

2.2.1 Impact of Operational Factors on Site Selection

Operational factors wield substantial influence over site selection outcomes, encompassing supply chain efficiency, transportation costs, labor availability, and facility layout. These factors are pivotal determinants of strategic decisions that shape an organization's footprint. Operations management principles guide the systematic evaluation of these factors, ensuring chosen sites harmonize seamlessly with operational necessities. Pereira et al. [108] conducted an in-depth study elucidating the profound impact of supply chain efficiency on site selection, particularly within the manufacturing context. Their research illuminated the intricate interplay between supply chain networks and optimal site decisions. By optimizing supply chain networks during site selection, organizations stand to reap multifaceted advantages. One notable gain is the reduction of transportation costs; strategically positioned sites can curtail distances traveled between suppliers, manufacturers, and customers. Additionally, this optimization fosters heightened supply chain responsiveness, empowering organizations to swiftly adapt to ever-evolving market demands.In a parallel vein, Smith and Johnson [109] explored the intricate relationship between labor availability and site selection. Their investigation underscored the crucial role of an available workforce in influencing site choices. Sites endowed with a skilled labor pool can enhance operational efficiency, accelerate production processes, and foster innovation. Meanwhile, the research by Davis et al. [110] unearthed the multifaceted implications of facility layout on site selection. They examined the intricate spatial arrangements of facilities and their subsequent impact on operational workflows. A well-designed facility layout not only optimizes internal processes but also enhances employee productivity and safety.In conclusion, operational factors wield immense influence over site selection endeavors. The above mentioned researchers collectively emphasize the crucial role of supply chain efficiency, labor availability, and facility layout in the site selection process. By integrating operations management principles into site selection evaluations, organizations can align their choices with operational imperatives and drive competitive advantages.

Table 2.3: Comparison of Studies on Impact of Operational Factors on Site Selection

Study	Factors Explored	Key Findings
Pereira et al.[108]	Supply chain efficiency in manufacturing context	Optimizing supply chain networks reduces transportation costs, and enhances supply chain responsiveness.
Smith & Johnson [109]	Labor availability	Sites with skilled labor pools enhance efficiency, production acceleration, and innovation.
Davis et al.[110]	Facility layout	Well-designed facility layouts optimize processes, boost employee productivity, and enhance safety.
Seydanlou et al.[111]	Environmental sustainability	Incorporating environmental considerations in site selection mitigates ecological impacts and enhances corporate image.
Huo et al.[112]	Proximity to suppliers and customers	Choosing sites near suppliers and customers reduces logistics costs and improves supply chain responsiveness.
Lin et al.[113]	Infrastructure quality	Sites with robust infrastructure facilitate efficient operations and reduce operational disruptions.

2.2.2 Sustainability Integration through Operations Management

In contemporary business landscapes, sustainability considerations have risen to the forefront of organizational priorities. The imperative to minimize environmental impact and fulfill social responsibilities has driven companies to integrate sustainable principles into various facets of their operations. One such critical area is site selection, where the strategic placement of facilities can significantly influence an organization's environmental footprint and societal contributions. In this context, operations management emerges as a central enabler for integrating sustainability practices into site selection decisions [114–116]. The integration of sustainability principles into site selection decisions represents a paradigm shift in how businesses approach their growth strategies. Organizations are recognizing that choosing the right location for their facilities goes beyond traditional factors like cost and market access [117],[118]. The consideration of sustainability aspects encompasses environmental factors, social impacts, and long-term viability. Operations management, as a multidisciplinary field, provides the tools and methodologies needed to holistically evaluate these dimensions. A noteworthy study by Ayyub and Angerhofer [119] delves into the intricacies of sustainability integration within site selection processes. The researchers investigate the synergies between operations management principles and sustainability metrics to arrive at site choices aligned with both ecological and social objectives. By quantifying the impact of various factors through operations management techniques, organizations can make informed decisions that strike a balance between economic feasibility and sustainable practices. Moreover, the study conducted by Walker et al.[120] further emphasizes the integral role of operations management in sustainability integration. The researchers elucidate how operations management methods can optimize the allocation of resources, minimize waste generation, and promote environmentally friendly practices [121], [122]. This integration not only contributes to a reduced carbon footprint but also enhances the overall competitiveness of the organization by aligning its operations with evolving environmental regulations and consumer preferences.

2.2.3 Operation Management a Holistic Approach

Operations management, a pivotal aspect of modern business practices, encompasses a wide array of functions, from designing products and optimizing supply chains to ensuring quality control and managing resources. This section elucidates the profound influence of operations management in shaping strategic site selection decisions. By delving into its multifaceted dimensions and showcasing its intersection with sustainability considerations, this discussion underscores the critical role that operations management plays in aligning site selection with operational efficiency and environmental responsibility. Beyond its conventional functions, operations management's reach extends to strategic site selection decisions. By employing techniques from operations research and management science, organizations can make informed choices that balance factors like supply chain efficiency, transportation costs, labor availability, and facility layout. This connection highlights how operations management principles aid in evaluating diverse considerations crucial for site selection outcomes [123]. Operations management plays a pivotal role in both manufacturing and service industries, encompassing a wide spectrum of tasks. These tasks include designing products, acquiring materials, overseeing production, ensuring quality control, managing inventory, handling distribution, and optimizing supply chain operations [123]. There are distinct categories within operations management, each with its own focus and features. Some of these types include:

- **Production Management:** This branch of operations management primarily deals with overseeing the production process, including tasks such as scheduling, resource allocation, and maintaining quality control. It is particularly relevant to industries engaged in manufacturing [107].
- **Service Operations Management:** In service-based industries operations management concentrates on delivering high-quality services. This involves managing customer interactions, service delivery processes, and ensuring service quality [120].
- **Supply Chain Management:** This type of operations management centers around optimizing the supply chain, from suppliers of materials to end customers. It involves streamlining the flow of goods, information, and financial resources across the supply chain [124].

- **Project Management;** Although it encompasses more, than operations management project management is commonly regarded as a component of operations. Its focus lies in the planning, execution, and control of projects to attain objectives while adhering to constraints such as time, cost, and scope [125].
- **Facility Management:** This particular aspect of operations management entails the supervision of facilities and resources. It encompasses responsibilities such, as maintenance, space allocation, and facilities planning [119], [110].

The operations managements of any company is closely connected to supply chain management since the strategic positioning of facilities directly affects the effectiveness of logistics, distribution, and transportation networks. This in turn impacts cost optimization and customer satisfaction within the supply chain.

2.2.3.1 Supply Chain Management

The consideration of operations management as the application of tools and frameworks to enhance business processes that span functional areas then supply chain management (SCM) encompasses coordinating physical, relational, informational, and financial flows to align demand, with supply. This involves utilizing tools and frameworks to improve business processes that extend beyond boundaries. The process of effectively designing, executing, and managing a supply chain is a complex and critical task for businesses and organizations, activities are known as Management of Supply Chain (SCM) and encompass all the activities engaged in the transportation and storage of raw commodities from the place of production to the moment of utilization of raw materials, work-in-process stocks, and completed commodities [124],[126].

The best structure of the supply chain is one of the planning stages in SCM, other elements, including purchasing, manufacturing, stock, shipment, and transportation are a few examples., must be addressed in addition to the overall facility site design [127]. Supply Chain Management is the logistics sector topic that is receiving a lot of attention [124]. In actuality, OR did not initially influence SCM's development; rather, OR was introduced to SCM gradually [128]. Another option is to strike a balance in which tactical/operational choices, such as how to distribute customer needs to facilities, are made early in the planning horizon while strategic location decisions are executed later [29, 129–131].

Considering the reasons mentioned earlier and those outlined in the previous section, to ensure effectiveness in strategic supply chain planning, a facility location model can be enhanced with four fundamental characteristics: fitting deterministic or stochastic characteristics, managing numerous commodities, spanning several periods, and utilizing multi-layer facilities, the reviewed material divided into categories is shown in Table 2.4.

Table 2.4: Structure of the SC based on the quantity of products.

Modes	**Layer**	**Product**	**Single Period**	**Multi Period**
Single layer	Single location	Mono	[132], [133], [134], [135], [136], [137]	[138], [139], [140], [141]
		Multi	[142], [143], [144], [145]	[146]
Two Layers	Single location	Mono	[147], [148], [149]	[150]
		Multi	[151], [152], [153]	
	Two Location	Mono	[129], [154], [155], [156]	
		Multi	[157], [158], [159]	[160], [161], [162]
Three Layers	Single location	Mono	[163]	
		Multi	[164]	
	Two Location	Mono	[164], [165]	
		Multi	[73]	[166], [167]

Three Location	Mono		[127]
	Multi	[168], [29], [169]	[170]

The consideration of various facility levels does not imply that placement decisions are permitted across the board. As a result, Table 2.4 lists the quantity of layers and the number of facility tiers in which choosing a site is done. It is essential to emphasize that when not considering all facility levels, facility placement decisions often concentrate on the layers in between, typically linked with warehouses or distribution hubs. Approximately 80% of the articles found in the study solely focus on several layer locations, and approximately two-thirds of them merely replicate location options in a single layer. In the preceding section, the prevailing assumption is that in core location challenges, customers can only be served from the layer that is closest to them. This assumption is inaccurate in many SCND circumstances, as direct shipping from facilities in the top tier to clients or places other than those in the layer below may be possible (for example, owing to very large deliveries). This information was taken into account in [165],[148],[169] ,[129],[170],[127]. Regarding intra-layer fluxes, many supply chain networks also have key characteristics. This trait was explicitly included in the models of Aghezzaf [88], Carlsson and Rönnqvist [148], Cordeau et al. [169], Melo et al. [170]. This specific feature, as denoted in Table 2.4, is prevalent in approximately 41% of the publications examined. This statistic underscores the noteworthy presence and utilization of this particular feature within the data set, suggesting its significant representation and relevance in the analyzed body of work. The fact that this feature is present in a substantial portion of the publications may indicate its importance, influence, or frequency of occurrence within the context of the research or subject matter under consideration.

2.2.3.2 Supply Chain Network Decision Variables

According to the growing level of complexity in the supply network, numerous planning considerations must be considered alongside the traditional location-allocation variables. Table 2.5 organizes the scientific literature by many common supply chain choices, such as capability, inventory, purchasing, manufacturing, routing, and method of conveyance. In recent research, several scholars, including Aghezzaf [88], Fleischmann et al. [146], Ko and Evans [167], Schultmann et al. [171], and Troncoso and Garrido [127], have explored capacity expansion models for industrial facilities. Most of these studies incorporate the possibility of capacity growth, sometimes coupled with multi-period site selection decisions. For instance, Schultmann et al. [171] consider capacity growth alongside site choices. While some researchers restrict capacity choices to specific tiers, such as in van Ommeren et al. [172] and Aghezzaf [88], where capacity increase is limited to top-tier facilities, others like Lowe et al. [139] simulate capacity decline situations.

Some studies, such as those by Vila et al. [130] and Levén and Segerstedt [156], consider both capacity expansion and reduction concurrently. Melachrinoudis et al. [173] address warehouse consolidation, involving moving all capacity at once between predetermined-sized modules. The choice of equipment or technology often closely relates to capacity decisions, with scholars like Dogan and Goetschalckx [164], Karabakal et al. [158], and Verter and Dasci [145] discussing this connection. Only two of the articles in Table 2.5 have a decision to be made on the mode of transportation. These articles are separated between those that allow a single type of transportation in every connection (the references below) and those that enable numerous modes to be defined for one network link [131],[148].

Table 2.5: Location-allocation Considerations

Research Articles	**Capacity**	**Production**	**Routing**	**Transport Modes**
Aghezzaf [88]	✓			
Asken [147]			✓	
Amiri [157]	✓			

Carlsson [148]		✓		✓
Goetschalckx [164]		✓		
Fleischmann [146]	✓	✓		
Guillén [160]	✓	✓		
Hinojosa [162]		✓		
Jayaraman [154]		✓		
Evans and Ko [167]	✓			
Rosenblatt [158]		✓		
Segerstedt [156]	✓		✓	
Lowe et al. [139]	✓	✓		
Min et al. [141]	✓			
Melachrinoudis [173]	✓	✓		
Melo [170]	✓	✓	✓	
Schultmann [171]	✓			
Teo and Shu [174]			✓	
Tuzun et al. [175]			✓	
Ommeren et al.[172]	✓			
Wilhelm et al. [131]		✓		✓

Different modes of transportation are often a result of the available methods of international travel, which are either via air, sea, or land. five publications are included in Table 2.5 that discuss routing choices. The research literature may also be broken down into publications that presuppose a uniform fleet of vehicles [147] and those who take into account cars with various types or capabilities are mentioned in this article [175]. Another critical issue is the ability to service a customer with several vehicles.

2.3 Summary

In conclusion, the literature claims that the sustainable site selection problem and operations management along with supply chain management problem have been thoroughly researched. It involves doing a multi-dimensional comparison study. Researchers' attention has switched to Sustainable Site Selection and Operations Management as organization's interest in sustainable operations management grows. To choose the best criteria, the researchers performed lengthy and comprehensive surveys including Managers and decision-makers. To choose a sustainable site, a variety of stand-alone and hybrid Multi-Criteria Decision Making (MCDM) strategies have been utilized, but extended Analytic Hierarchy Process (AHP) in combination with Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) emerging as the most commonly favored approach. Exact optimization techniques have been created and used to address a variety of single, bi, and multi-objective models for site selection problems. Fuzzy set theory has recently been used by scholars to account for the haziness and ambiguity of judgment. The bulk of the research focused on choosing traditional and environmentally friendly site locations and fulfilling criteria with the goals of expenses, sustainability, and environment while attempting to figure out the best location for the site. Additional, initiatives are being made to strengthen the suitable sustainable criteria and goals for the Sustainable site selection and operations management problem. There is still space to investigate the issue holistically by offering a clear framework that combines various operations management aspects. Additionally, there is very little usage of meta-heuristics and hybrid exact optimization solution techniques for sustainable site selection problems. Therefore, utilizing fuzzy E-AHP and fuzzy TOPSIS, this study aims to give a comprehensive strategy that takes into account the traditional, environmental, and social factors specified in the literature used to assess the viable sustainable site. The objective functions (TC, TTT, EI, and TSVSS) will be optimized by utilizing two solution algorithms. The Pareto outcomes are then compared using TOPSIS to get the final answer.

Chapter 3

Methodology

3.1 Introduction

The proposed integrated framework is used to optimize the Sustainable Site Selection and Operations Management of Infectious Waste Disposal is presented in this chapter. Multiple MCDM approaches are used in the assessment of criteria and relative weights of candidate sites. After ranking the possible candidate sites, the mathematical model consist of objective functions and constraints is developed for the sustainable site selection and operations management by integrated the weights of each candidate site in the objective functions. The mathematical model was solved using optimization algorithm to get the optimized answer.

Figure 3.1 shows a multi-echelon hospitals infectious waste network problem. It involves multiple hospitals, municipalities/candidate site, incinerator of different sizes, and distances of hospitals from the candidate sites. The multi-echelon network was evaluated in order to get the optimize allocation of hospitals to municipalities while considering waste demands, incinerator sizes, distances, and other relevant factors. Hospital j waste Qj is transferred to Municipality i and treated by using the k size incinerators present at each Municipality.

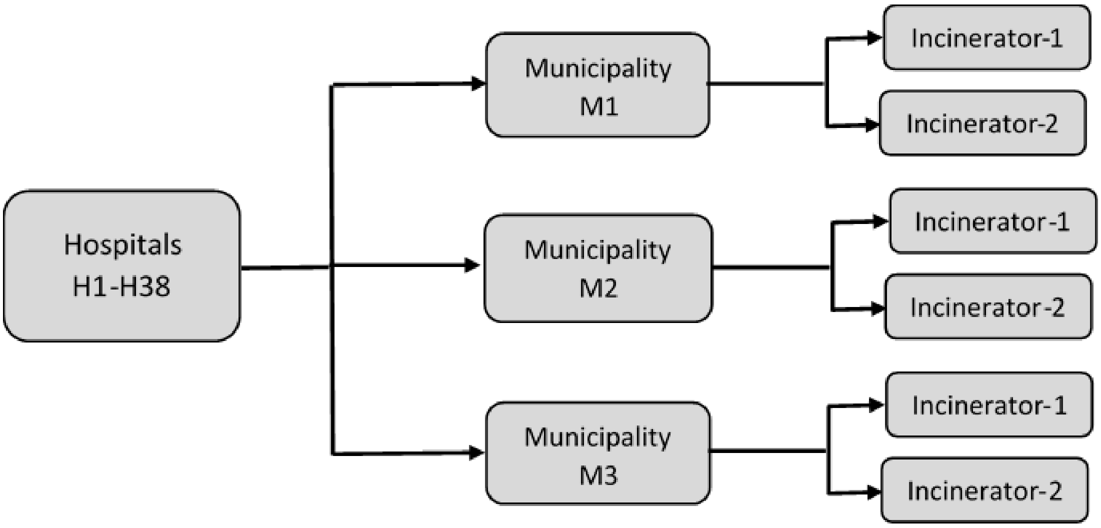

FIGURE 3.1: Multi-Echelon Network of Infectious Waste Site.

3.2 Proposed Methodology Framework

The following subsection includes a thorough methodological structure for addressing the multi-layer networks as shown in Figure 3.1. The proposed framework is divided into four stages. The experts will describe relevant criteria that influence location selection for IWDS in the first phase, and then they will choose candidate venues. There are crucial or general elements that influence the selection of new appropriate places in Pakistan and other countries. MCDM algorithms were used to assess Municipality/candidate locations against sustainable criteria specified by experts. A high-priority weight is preferable to a low-priority weight. The mixed integer non-linear programming (MINLP) mathematical model is used in the second phase to discover the sustainable optimum quantity for the optimal solution. In the third stage, the MCDM methodologies are utilized to analyze the previous phase's data to achieve the desired outcomes. The following are the steps to take for every stage:

Phase 1

Step 1: Decision maker recommended three candidate sites for infectious waste disposal based on three sustainable factors.

Step 2: After reviewing the literature, specific sub-criteria were selected for each sustainable criterion. A total of ten sub-criteria were chosen to align with the three main criteria: economic, social, and environmental.

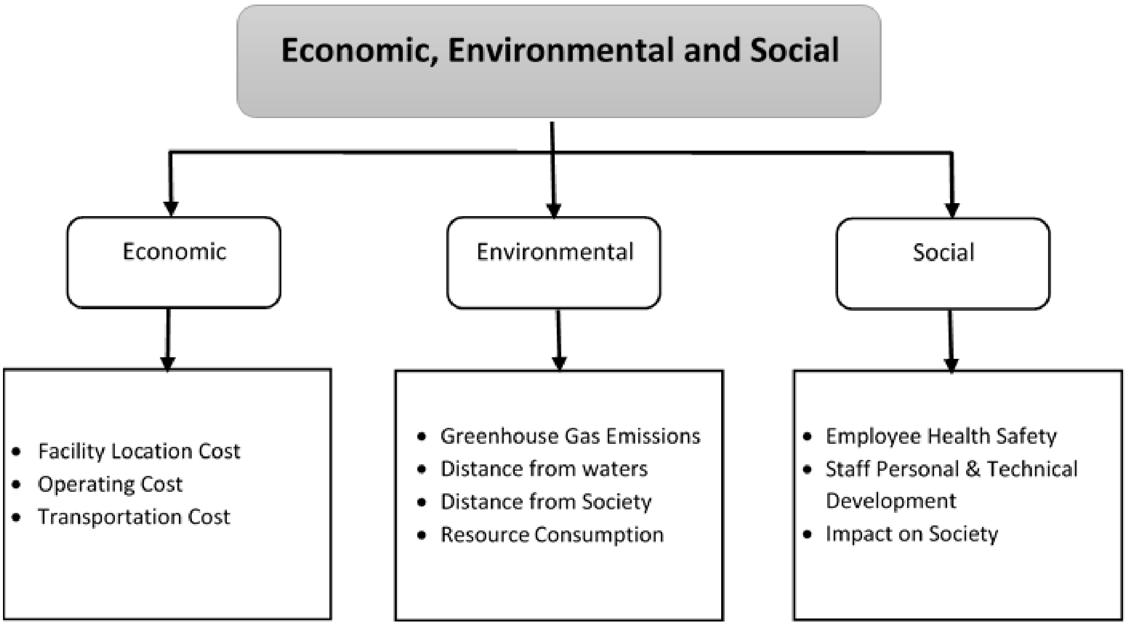

Figure 3.2: Criteria and Sub-criteria Of Infectious Waste Site Selection.

Figure 3.2 depicts the breakdown of three important sustainable criteria. It can seen that Economic criteria are divided into three sub-criteria and the environmental criteria are broken down into four different sub-criteria, whereas social criteria are broken down into three.

Table 3.1: Criteria and Study Synopsis

Major Criteria	Sub Criteria	Description	Studies
Economic Criteria	Facility Location Cost	Facility location costs refer to the expenses associated with selecting and establishing an infectious waste disposal site in a particular location. These costs can vary depending on several factors.	[176],[177],[178],[179],[43]

	Operating Costs	The operating costs refer to the ongoing expenses incurred to operate and maintain the facility. These expenses are related to the site's day-to-day operations and enable the proper and safe handling of infectious waste.	
	Transportation Cost	Transportation costs are a crucial consideration when selecting an infectious waste disposal site. These costs pertain to the expenses associated with transporting infectious waste from its generation sources to the disposal facility.	
Environmental Criteria	Greenhouse Gas Emission	GHGs are gases that hold heat in the planet's environment, leading to climate change and global warming. The following are the most frequent greenhouse gases • CO2. • Dioxin. • N2O.	[43],[61], [176],[177], [180],[181], [182]

Distance from Waters	Locating the waste disposal site away from water bodies, such as rivers, lakes, or aquifers, helps protect these valuable resources from potential contamination. By maintaining a safe distance, the risk of pollutants leaching into water sources and causing ecological damage is reduced.
Distance from Society	Selecting a site that is at a sufficient distance from populated areas helps protect public health by minimizing potential exposure to hazardous materials and reducing the risk of disease transmission. It helps to ensure that it does not pose a direct threat to nearby communities.
Resource Consumption	Resource consumption refers to the use of various resources during the establishment, operation, and maintenance of the facility.

Social Criteria	Employee Health Safety	Employee health and safety considerations are crucial when selecting an infectious waste disposal site. Given the potential hazards, it's important to prioritize the well-being of employees involved in waste collection, transportation, treatment, and disposal.	[181],[182], [183]
	Staff Personnel & Technical Development	Staff personnel and technical development are important considerations when selecting an infectious waste disposal site. These factors focus on the recruitment and training of personnel involved in waste management operations.	
	Impact on Society	Selecting an infectious waste disposal site can have various impacts on society. It is essential to consider the impacts on the well-being, acceptance, and needs of the local community.	

Step 3: The fuzzy extended-AHP method is employed to analyze the relative importance of each site selection criterion.

Step 4: The Fuzzy TOPSIS method was utilized to rank the candidate sites based on economic, environmental, and social criteria.

Step 5: The Closeness Coefficient matrix, considering economic, environmental, and social variables, is computed using the Fuzzy TOPSIS method as well.

Step 6: The best candidate site was chosen based on a Closeness Coefficient set to the threshold.

Phase 2

Step 7: A Mixed Integer Non-Linear Programming (MINLP) mathematical model has been developed.

Step 8: The objective functions selected based on the literature for the sustainable IWDS selection include Total Cost (TC), Total Travel Time (TTT), Environmental Impact (EI), and Total Sustainability Value of Selected Site (TSVSS).

Phase 3

Step 8: To analyze the sustainable operations management of IWDS, a multi-objective mixed integer nonlinear mathematical model incorporating constraints like hospital waste generation, and capacities of incinerator was developed. The AUGMECON2 method is then applied to proposed model, which simultaneously minimizes TC, TTT, and EI while maximizing TSVSS.

Phase 4

Step 9: The CRITIC Weighted Technique is used to assign weights to AUGMECON2 Pareto solution.

Step 10: TOPSIS was used to choose the best optimum solution from the Pareto solution generated from AUGMECON2 and weighted by CRITIC.

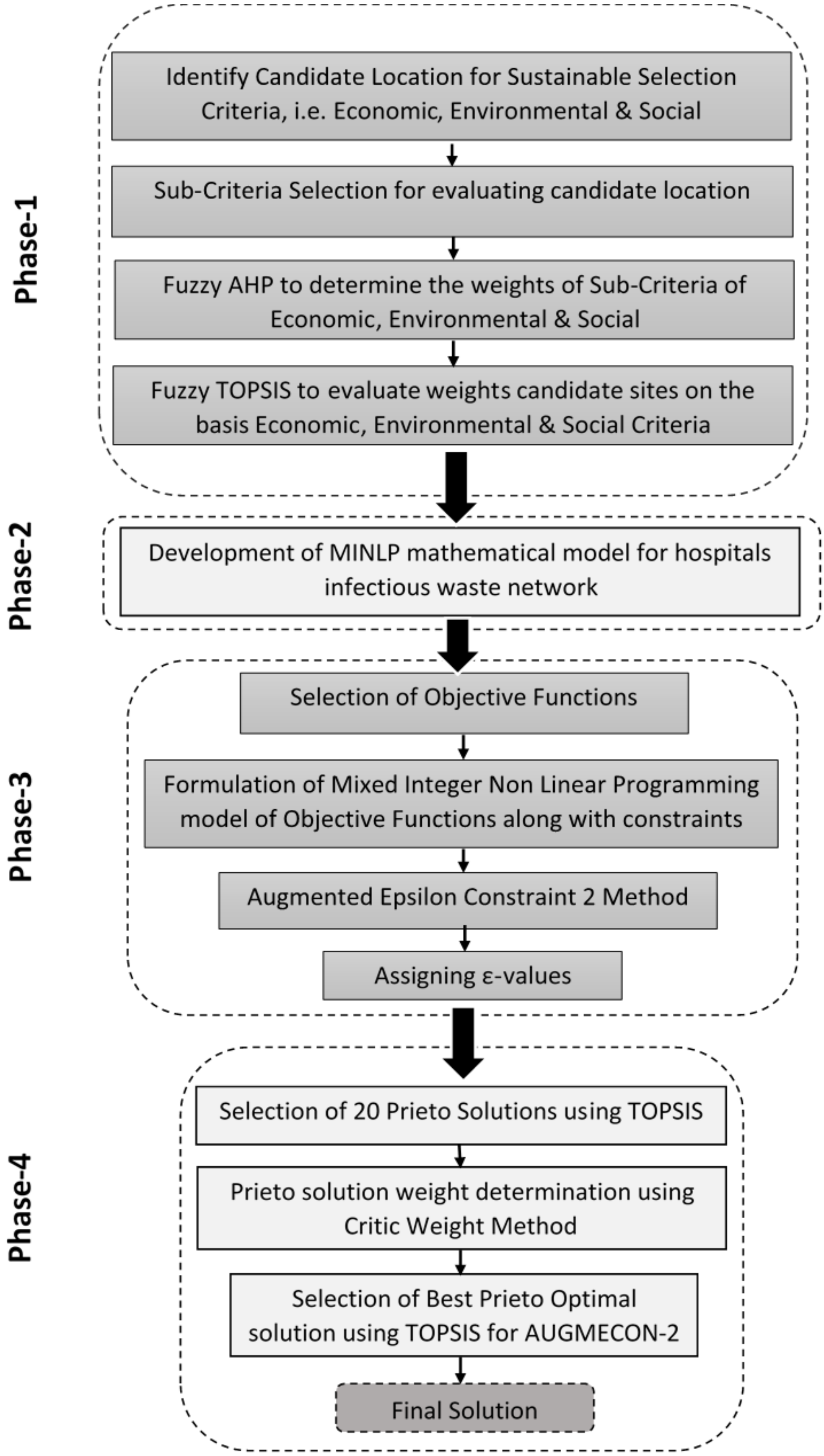

Figure 3.3: Proposed Methodology Flow Chart

3.3 Facility Location Selection Technique (Phase-1)

The selection of a sustainable site is separated into the following steps: ranking of criteria and candidate location rating. The factors which are for candidate location are initially sorted using weights determined from their relative relevance. Criteria rankings are the key parameters used to select the best candidate locations. The number of potential sites that were evaluated for optimal candidate location ranking. Fuzzy AHP weights are then utilized in Fuzzy TOPSIS to rank candidate sites. Linguistic traits are used in this study to include incoherence in decision-making. Dubois and Prade found a direction for translating verbal factors into numerical form (i.e. x (a, n, m)) [184]. While ”a” stands for the greatest probable scenario, ”n” for the utmost dismal scenario, and ”m” for the hopeful one. The following sections detail the specific techniques and methodologies used for the facility's selection.

3.3.1 Fuzzy Set Theory

To eliminate uncertainty in decision-making, Zadeh [185] FST was introduced in Multi-Criteria Decision Making to modify precise numerical data for more exact evaluation of systems in reality [186]. In the fuzzy MCDM. FST was employed to simulate the unpredictability of human evaluations when evaluations of performance and scores were applied. Various research have claimed that fuzzy MCDM improves the comprehensiveness of decision-making processes. Because of their simplicity, triangular fuzzy numbers a, n, and m were used within the current study to gain entry to desire [187],[188],[189],[190]. While a, n, and m denote the lowest, average, and highest values, respectively. Chang's study was used to alter the membership function used in the analysis [191] and is as follows.

$$M_1 = (a_1, n_1, m_1), \quad M_2 = (a_2, n_2, m_2)$$

$$\text{Membership Function} : (M_i \geq M_j) = \begin{cases} 1, & \text{if } n_2 < n_1 \\ \dfrac{a_1 - m_2}{(n_2 - m_2) - (n_1 - a_1)}, & \text{otherwise} \\ 0, & \text{and } a_1 \geq m_2 \end{cases} \tag{3.1}$$

3.3.2 Fuzzy E-AHP

Saaty is the inventor of the analytical hierarchy process decision-making process [192] in 1990. According to Ayag [193], The analytical hierarchy process technique is the most often used approach for calculating the weights of criteria. In the study, the Fuzzy Extended-Analytical Hierarchy Process is used to analyze the relative importance of the sub-criteria for economic, environmental, and social considerations. The Extended Fuzzy AHP making decisions method is built on Saaty's [192] analytical hierarchy process technique combined with fuzzy set theory [194]. A membership-based feature, which is a real number between 0 and 1, is used to portray fuzzy numbers in this manner. The linguistic factors used for weighting the criterion are shown in Table 3.2. Each decision-maker must assign weights used in various groups of economic, environmental, and social factors. Wang et al.'s technique was applied in this investigation [195]. The fuzzy E-AHP flow chart is shown in Figure 3.4. The following are the implementation steps:

Step 1: The combined fuzzified pairwise comparison matrix is obtained by using the input of all decision-makers.

Step 2: The fuzzy pairwise comparison matrix was transformed into a crisp matrix using the Geo Metric mean method.

$$\tilde{G} = \left(\prod_{i=1}^{K} \tilde{a}_{ijk} \right)^{\frac{1}{K}} = \begin{bmatrix} \tilde{g}_{11} & \tilde{g}_{12} & \cdots & \tilde{g}_{1n} \\ \tilde{g}_{21} & \tilde{g}_{22} & \cdots & \tilde{g}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{g}_{n1} & \tilde{g}_{n2} & \cdots & \tilde{g}_{nn} \end{bmatrix} \tag{3.2}$$

Step 3: Normalizing the fuzzified combined pairwise comparison matrix using below equation.

$$\bar{C}_{ij} = \left(\frac{\sum_{i=1}^{I} a_{ij}}{\sum_{t=1}^{I} a_{ij} + \sum_{t=1}^{I} \sum_{j=1}^{J} m_{ij}}, \frac{\sum_{i=1}^{I} n_{ij}}{\sum_{t=1}^{I} \sum_{j=1}^{J} n_{ij}}, \frac{\sum_{t=1}^{I} m_{ij}}{\sum_{i=1}^{I} m_{ij} + \sum_{i=1}^{I} \sum_{j=1}^{J} a_{ij}} \right) \tag{3.3}$$

Step 4: The crisp Analytical Hierarchy Process (AHP) method was employed to calculate the Consistency Index (CI).

Step 5: Using the membership function shown in Eq. (3.1), to compute the degree of possibility.

Step 6: Using the fuzzy comparison matrix, to compute the precedence vector or values $W = (w_1, w_2, \ldots, w_I)^T$

$$w_i = \frac{\min V(M_i \geq M_k)}{\sum_{i=1}^{J} \min V(M_i \geq M_k)} \tag{3.4}$$

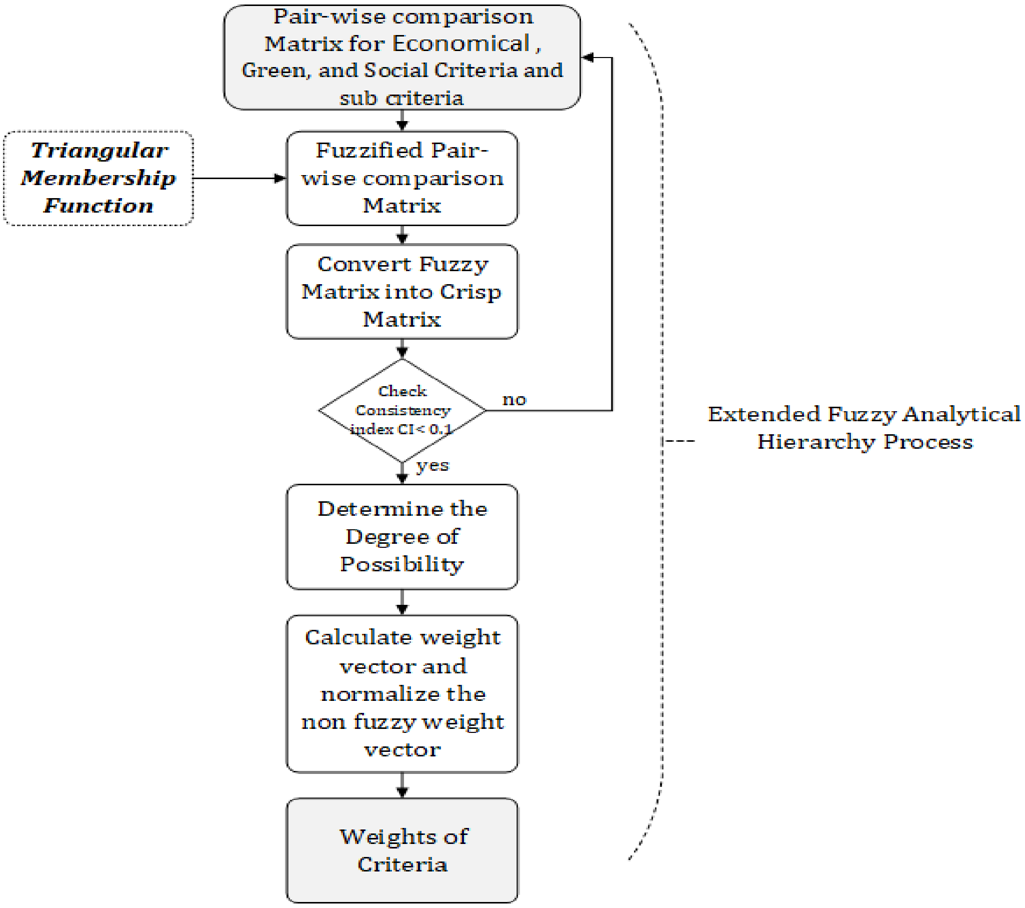

FIGURE 3.4: Fuzzy E-AHP Flow Chart

3.3.3 Fuzzy TOPSIS

Fuzzy TOPSIS was employed in this research to rate candidate locations based on three long-term criteria: economic, environmental, and social. For the sake of simplicity, triangular fuzzy numbers were used in this investigation instead of triangular ones. Table 3.2 lists the linguistic traits that were taken into consideration while ranking the possible choices based on three criteria. As illustrated in Figure 3.5, Each of these sets of fuzzy words has three language rating factors: low, medium, and high. Fuzzy numbers were converted to crisp numbers using Chen's study [196]. For example, the language phrase low "L" can be represented by the numbers (1, 3, and 5). To use fuzzy TOPSIS, decision-makers must give weights to each alternative for the aforementioned criteria. Figure 3.6 depicts the flow chart for implementing fuzzy TOPSIS [197]. The following are the implementation steps:

Table 3.2: Linguistic Variables and Fuzzy Numbers

Linguistic Variable	**Crisp Number**	**Fuzzy TOPSIS Numbers**	**Fuzzy E-AHP Number**
Very low (VL)	1	$(0, 1, 3)$	$(0, 0.1, 0.3)$
Low (L)	3	$(1, 3, 5)$	$(0.1, 0.3, 0.5)$
Medium (M)	5	$(3, 5, 7)$	$(0.3, 0.5, 0.7)$
High (H)	7	$(5, 7, 9)$	$(0.5, 0.7, 0.9)$
Very high (VH)	9	$(7, 9, 10)$	$(0.7, 0.9, 1.0)$
Intermediate Values	$2, 4, 6, 8$		

Step 1: The opinions of each decision maker are combined to create a single decision matrix.

$$a_{ij} = \min\left[a_{ij}^{k}\right], \quad n_{ij} = \frac{1}{K}\sum_{k=1}^{K} n_{ij}^{k}, \quad m_{ij} = \max\left[m_{ij}^{k}\right] \tag{3.5}$$

Where i indicates the providers and j is the criterion. The fuzzy numbers a, n, and m are emphasized in Table 3.2.

Step 2: After normalizing the fuzzy decision matrix, a normalized decision matrix has been generated using the equation shown below.

$$\bar{e}_{ij} = \left(\frac{a_{ij}}{\sqrt{\sum_i m_{ij}^2}}, \frac{n_{ij}}{\sqrt{\sum_i m_{ij}^2}}, \frac{m_{ij}}{\sqrt{\sum_i m_{ij}^2}} \right) \tag{3.6}$$

Step 3: By scaling the resultant matrix by the weight for every criterion, the weighted normalized decision matrix was constructed.

$$\tilde{v}_{ij} = [\tilde{c}_{ij} \cdot w_j] \tag{3.7}$$

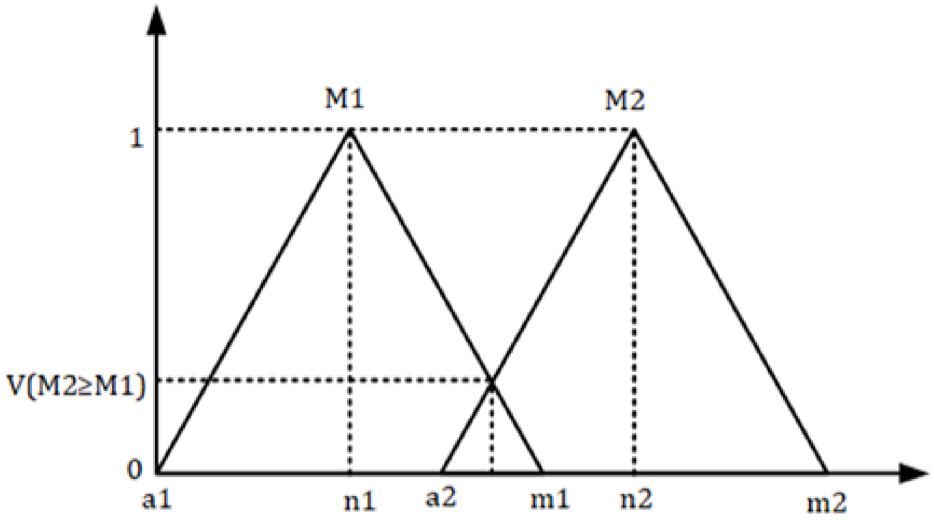

Figure 3.5: Membership function for Criteria

Step 4: The equations described below give a positive perfect (best) and an unfavorable ideal (worst) solution.

$$\bar{Z}_j^+ = \max_{i=1}^{n}\{\bar{Z}_i'\}, \bar{Z}^+ \quad = \{\bar{Z}_1^+, \bar{Z}_2^+, \bar{Z}_3^+, \ldots, \bar{Z}_m^+\}. \tag{3.8}$$

$$\bar{Z}_{j'-} = \min_{i=1}^{n}\{Z_{1y^r}\}, \bar{Z}^- \quad = \{\bar{Z}_1^-, \bar{Z}_2^-, \bar{Z}_3^-, \ldots, \bar{Z}_m^-\}. \tag{3.9}$$

Step 5: Use the equation below to calculate the Euclidean distance between the fuzzy positive ideal result and the fuzzy negative ideal solution.

$$\mathrm{Sep}^{+} = \sum_{j=1}^{n} d(\bar{v}_{ij}, \bar{v}_j^{+}), \quad \mathrm{Sep}^{-} = \sum_{j=1}^{n} d(\bar{v}_{ij}, \bar{v}_j^{-}). \tag{3.10}$$

Step 6: Finally, the RC_i of the option to the optimal answer was estimated and graded on a scale of 0 to 1. The option with the closest value to one was chosen as the best.

$$RC_i = \frac{Sep_i^{-}}{Sep_i^{-} + Sep_i^{+}} \tag{3.11}$$

3.4 Development of Mathematical Model for Infectious Waste Disposal Site (Phase 2)

This section explains how to obtain a multi-objective optimization model of a multi-echelon hospitals infectious waste network. In 1909, Alfred Weber introduced the concept of the warehouse placement problem to minimize the overall distance between a warehouse and a set of clients. This marked the inception of the first systematic exploration of facility location problems in theoretical research. Daskin [24] categorized discrete facility location problems into three main types: covering-based problems, median-based problems, and miscellaneous challenges. Covering-based problems are further categorized into three distinct types: set covering problems, maximum covering problems, and p-center problems. Similar to set coverage issues, the goal of this study is to attain the lowest overall cost. Consequently, a site selection mathematical model was devised using the framework of set coverage problems to address this situation. This model helps determine the sites for hazardous waste disposal. The MSLP model (Multi-Size Location Problem) aims to tackle the optimization problem associated with selecting appropriate incinerator sizes for site selection. The Model includes minimization of Total Cost (TC), Total Travel Time (TTT), Environmental Impact (EI), and maximization of the Total Sustainability Value of the Selected Site (TSVSS).

3.4.1 Sets

i = 1,2,3,. . . ,m Set of Municipality locations

j = 1,2,3,. . . ,j Set of Hospitals (n = 40)

k = 1,2,. . . ,k Set of incinerator

3.4.2 Parameters

f_k = Facility cost (\$/day).

O_k = Operating cost (\$/day).

dt_{ij} = Distance between municipality i and hospital j (km).

UTC = Unit Ash transportation cost (\$/km).

Q_j = Quantity of Waste generated from Hospital j (kg/day).

$CO2_{ij}$ = CO_2 gram per km emission while traveling from municipality “i” to hospital “j” (g/km).

DOX = Dioxin (highly toxic compound) emission in grams while burring the quantity of waste through the incinerator.

s_k = Size of each incinerator i (kg).

V_t = Velocity of vehicle “t” (km/s).

$W_i^{Economic}$ = Fuzzy TOPSIS Weight of Economic criteria for candidate site ”i”.

$W_i^{Enviormental}$ = Fuzzy TOPSIS Weight of Environment criteria for candidate site ”i”.

W_i^{Social} = Fuzzy TOPSIS Weight of Social criteria for candidate site ”i”.

w_i^{eco} = Extended Fuzzy AHP weight of economic criteria.

w_i^{env} = Extended Fuzzy AHP weight of economic criteria

w_i^{sc} = Extended Fuzzy AHP weight of social criteria.

3.4.3 Decision variables

X_{ij} is a binary decision variable; $X_{ij} = 1$ if the hospital j is served by municipality i : $X_{ij} = 0$ otherwise.

Y_i is a binary decision variable; $Y_i = 1$ if Municipality is open else 0.

Z_{ik} is a binary decision variable;$Z_{ik} = 1$ if the municipality i is opened by selecting incinerator k : $Z_{ik} = 0$ otherwise.

3.4.4 Objective Function 1: Total Cost (TC)

This function's purpose is to reduce Total Cost, which includes Facility Location Cost for the municipality, Operation cost to run the municipality and incinerator, and unit transportation cost for an actual distance between municipality "*i*" and hospital "*j*".

$$\text{Min TC} = \sum_{i=1}^{m}\sum_{k=1}^{K} f_k \cdot Z_{i,k} + \sum_{i=1}^{m}\sum_{k=1}^{K} o_k \cdot Z_{i,k} + \sum_{i=1}^{m}\sum_{j=1}^{n} UTC \cdot dt_{ij} \cdot X_{i,j} \tag{3.12}$$

3.4.5 Objective Function 2: Total Time Travel (TTT)

This function's purpose is to shorten the overall trip time from Hospital "*j* to Municipality "*i*". It includes ash-transportation time. The minimization of total travel time is expressed as follows.

$$\text{Min TTT} = \sum_{i=1}^{m}\sum_{j=1}^{n} \frac{\mathrm{dt}_{ij}}{V} \cdot X_{i,j} \tag{3.13}$$

3.4.6 Objective Function 3: Environmental Impact (EI)

This function's purpose is to reduce overall atmospheric carbon dioxide (CO2) release during transportation and incineration, as well as dioxin emissions during incineration. The following equation shows how to reduce carbon dioxide and dioxin emissions.

$$\text{Min EI} = \sum_{i=1}^{m}\sum_{j=1}^{n} \text{CO2} \cdot dt_{ij} \cdot X_{i,j} + \sum_{i=1}^{m}\sum_{j=1}^{n}\sum_{k=1}^{K} \text{DOX} \cdot Q_j/s_k \cdot Z_{i,k} \tag{3.14}$$

3.4.7 Objective Function 4: Total Sustainability Value of Selected Site (TSVSS)

The goal of this function is to maximize the total value of the chosen site/location by balancing the weights of economic, social, and environmental considerations. The fuzzy E-AHP criteria weights are multiplied by the fuzzy TOPSIS supplier weights. The equation below explains how to maximize the overall value of the sustainable selected site.

$$\begin{aligned}\text{Max TSVSS} = &\sum_{i=1}^{m}\sum_{j=1}^{n} W_i^{\text{Economic}} \cdot w_i^{\text{eco}} \cdot X_{i,j} + \sum_{i=1}^{m}\sum_{j=1}^{n} W_i^{\text{Environmental}} \cdot w_i^{\text{env}} \cdot X_{i,j}\\ &+ \sum_{i=1}^{m}\sum_{j=1}^{n} W_i^{\text{Social}} \cdot w_i^{\text{sc}} \cdot X_{i,j}\end{aligned} \tag{3.15}$$

3.4.8 Constraints

Demand Constraint:

This constraint ensures that the demand of each hospital j is fulfilled by any of the municipality i.

$$\sum_{i=1}^{m} X_{ij} = 1 \quad \text{for all } j \quad (j = 1, 2, \ldots, n) \tag{3.16}$$

Capacity Constraint:

These constraints ensure that the service offered by a location cannot go beyond its capacity, and they also ensure that the selected towns must utilize only k-size incinerators.

$$\sum_{j=1}^{n} Q_j \cdot X_{ij} \leq \sum_{k=1}^{K} s_k \cdot Z_{ik} \quad \text{for all } i \quad (i = 1, \ldots, m) \tag{3.17}$$

$$\sum_{i=1}^{m} \sum_{k=1}^{K} s_k \cdot Z_{ik} \geq \sum_{j=1}^{n} Q_j \quad \text{for all } i \quad (i = 1, \ldots, m) \tag{3.18}$$

$$\sum_{k=1}^{K} Z_{ik} = Y_i \tag{3.19}$$

Non-Negativity and Binary Constraint:

The Decision Factors X_{ij}, Z_{ik}, and Y_i are Binary and are shown below.

$$\begin{aligned} X_{ij} &\in \{0, 1\}, \\ Y_i &\in \{0, 1\}, \\ Z_{ik} &\in \{0, 1\}. \end{aligned} \tag{3.20}$$

3.5 Solution Methods (Phase 3)

3.5.1 Augmented Epsilon Constraint 2

The AUGMECON2 method was utilized to solve the suggested MINLP model. Mavrotas and Florios created AUGMECON2 [198], which is an upgraded version of the AUGMECON technique. It incorporates the slack variable at each iteration to accommodate for the difficulties of discrete variables and non-convex situations. This approach converts a multi-objective optimization issue into a mono-objective problem by treating one of the objectives as the main objective function and treating the other objectives as constraints subject to certain values. The following is the generic model:

$$\max\left(f_1(x)+\varepsilon\left(\frac{S_2}{r_2}+\left((10-1)\frac{S_3}{r_3}+\ldots+(10-(n-2))\frac{S_n}{r_n}\right)\right)\right) \tag{3.21}$$

Subject to

$$f_2(x)-S_2=\varepsilon_2$$
$$f_3(x)-S_3=\varepsilon_3$$
$$\ldots$$
$$f_n(x)-S_n=\varepsilon_n$$

where, ϵ_2, ϵ_3,. . . , ϵ_n are each objective function's RHS values, S_2, S_3,. . . , S_n are the variables with slack, r_2, r_3,. . . , r_n are the objective function ranges and $\varepsilon \in [10^{-6}, 10^{-3}]$ The model modification aids in the lexicographic optimization process (i.e. sequentially optimizing f_2 f_3 . . .,f_n) to produce the exact Pareto sets. The flowchart of the AUGMECON2 technique is shown in Figure 3.8. The following are the implementation steps:

Step 1: Converting a multi-objective optimization issue to a single-objective optimization problem.

Step 2: Create a payout table using the techniques shown below:

1. build p_t as payoff table 2D array;
2. Set counter i with value 1 (i is the row of the reward table);
3. $f(i)$ optimization challenge to solve (minimize for i_3);
4. 4. Save the following result to the payout table: p_t(i, j) = $f(j)$ where j =1,..,4
5. add i to 1;
6. if $i \leq 4$ true, proceed to step 3; otherwise, proceed to step 7;
7. The End.

Step 3: Using the processes indicated below, compute the ranges of objective functions:

1. Make a r array (which stores the ranges of the OFs) and f_lb array (which contains the lower bounds of the OFs);
2. initialize counter i with value 2 (i is OF number);
3. Calculate min and max values for OF_i using payoff table ($\min_i = \min(p_t(i,j)), \max_i = \max(p_t(j,i))$) where $j = 1, \ldots, 4$.
4. Save the minimum value to the f_lb array (f_lb (i) $= min_i$), and the difference to the r array array ($r(i) = max_i$ - min_i);
5. raise i to 1;
6. if $i \leq 4$ is true, proceed to step 10; otherwise, proceed to step 14;
7. The End.

Step 4: Obtain ϵ-values values for each goal function using the techniques outlined below:

1. Initialize the grid intervals and the solutions array;
2. Set the value of counter i_4 to 0;
3. calculate ϵ for OF 4: $\epsilon(4) = f_lb$ (4) + i_4 *(1/n)*r (4);
4. Set the value of counter i_3 to 0;
5. calculate ϵ for OF 3: $\epsilon(3) = f_lb$ (3) + i_3*(1/n) *r (3);
6. Set the value of counter i_2 to 0;
7. calculate ϵ for OF 2: $\epsilon(2) = f_lb$ (2) + i_2*(1/n) *r (2);

Step 5: Solve the issue for the current ϵ values of each goal function, and if the solution is possible, add it to the solutions array

Step 6: If the outcome is feasible, use the following processes to iterate to find a workable solution:

1. if result is in feasible then increase i_2 to n + 1 and go to step 29;
2. Bypass coefficient: b = integer part of $n * s(2)/r(2)$, if b = 0 then b = 1;
3. raise i_2 to b;
4. if $i_2 \leq n$ then go to step 25;
5. raise $i_3$to 1;
6. if $i_3 \leq n$ then go to step 23;
7. raise i_4 to 1;
8. if $i_4 \leq n$ then go to step 21;
9. output solutions array;

The mathematical model is converted for Pareto solutions as shown in Equations (3.21)-(3.25). The major objective function in this work is total cost reduction, with other goal functions considered restrictions.

$$\text{Minimize } Z = \text{Minimize Total Cost (TC)} \tag{3.22}$$

$$\begin{gathered}\text{Minimize } TTT \leq \varepsilon_1 \\ [\text{Min } TTT^{\text{min}} \leq \varepsilon_1 \leq \text{Min } TTT^{\text{max}}]\end{gathered} \tag{3.23}$$

$$\begin{gathered}\text{Min } EI \leq \varepsilon_2 \\ [\text{Min } EI^{\text{min}} \leq \varepsilon_2 \leq \text{Min } EI^{\text{max}}]\end{gathered} \tag{3.24}$$

$$\begin{gathered}\text{Max } TSVSS \leq \varepsilon_3 \\ [\text{Max } TSVSS^{\text{min}} \leq \varepsilon_3 \leq \text{Max } TSVSS^{\text{max}}]\end{gathered} \tag{3.25}$$

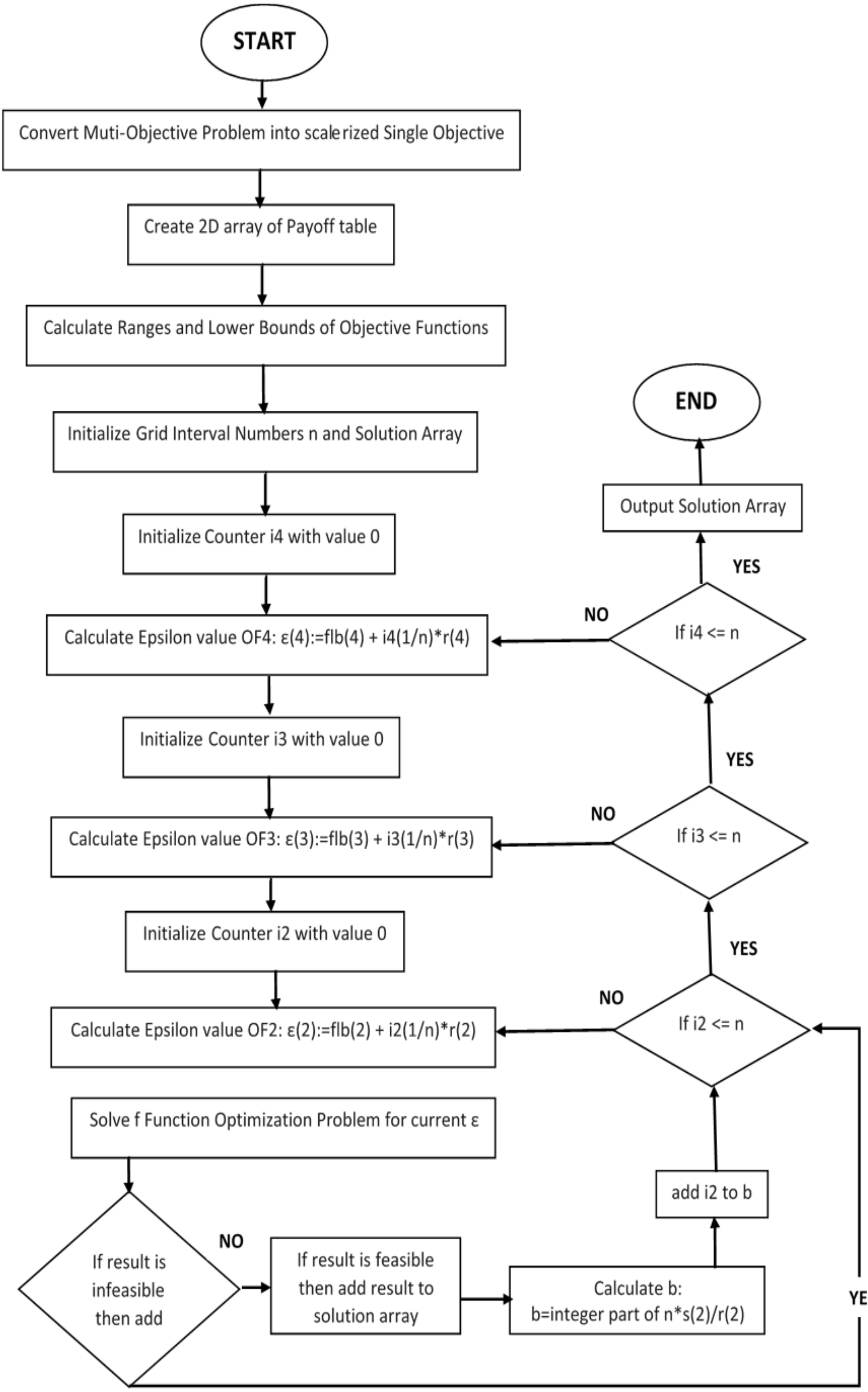

Figure 3.6: Flow Chart of AUGMECON-2

3.6 Best Pareto Solution Selection (Phase 4)

The methods for choosing the best Pareto solutions are described in this section generated by the solving algorithms mentioned in the previous section. The Pareto solutions are analyzed using MCDM methods. The goal of applying these strategies is to help decision-makers use an analytical approach rather than intuition when selecting the optimal answer.

3.6.1 CRITIC Weight Method

The CRITIC Method is employed to provide weight so that every goal function's best answer is obtained. This approach incorporates the difference in strength and disagreement over features that happened within the context of the process of decision-making [199]. In this work, the CRITIC weight technique was used to calculate the relative importance of the parameters (i.e. Objective Functions) necessary to appraise the final Pareto solution. It is worth noting that this solution does not rely on attributes. dependence and may transform qualitative characteristics into quantitative attributes [200]. The features examined the objective functions used in the present investigation, which applies the CRITIC technique, are those for which adopting multi-objective optimization algorithms results in the Pareto optimal solutions. This strategy is put into action as follows:

Step 1: The decision matrix was built using the Pareto optimum findings obtained by optimizing the multi-objective model.

Step 2: To convert dimensional attributes into non-dimensional qualities, a normalized decision matrix was developed.

$$X_{\perp_{ij}} = \frac{X_{ij} - X_j^{\text{"worst"}}}{X_j^{\text{"best"}} - X_j^{\text{"worst"}}} \tag{3.26}$$

Step 3: Using a normalized decision matrix, the standard deviation of each criterion is then computed.

$$\sigma_j = \sqrt{\frac{\sum_{i=1}^{N}(X_i - \mu)^2}{N}} \tag{3.27}$$

Step 4: The linear relationship factor between characteristics was determined using Whang and Zhang's equation [194].

$$\operatorname{corr}(X_{ij}) = \frac{n(\sum X_{ij}) - (\sum X_i)(\sum X_j)}{\sqrt{[n\sum(X_i)^2 - (\sum X_i)^2][n\sum(X_j)^2 - (\sum X_j)^2]}} \tag{3.28}$$

Step 5: The provided equation computes a relative index C for each attribute.

$$C_j = \sigma_j \sum_{k=1}^{m}(1 - r_{jk}) \tag{3.29}$$

Where, r_{jk} yielded in Step 4 association matrix.

Step 6: The characteristic weights were finally calculated in the following way:

$$w_j = \frac{C_j}{\sum_{j=1}^{n} C_j} \tag{3.30}$$

3.6.2 TOPSIS

Several ways have been developed to analyze Multi-Criteria Decision Making challenges using complex algorithms and hypotheses. In this work, we employed the TOPSIS a model that was constructed by Hwang and Yoon [201]. The fundamental idea of TOPSIS states that the preferred choice must be not only the closest to the helpful perfect solution but also the farthest away from the opposing ideal solution [202]. The term "positive optimal answer" means the most cost-efficient or most effective choice available. In contrast, an unfavorable perfect solution was the less productive and most expensive alternative among multiple feasible options [203]. TOPSIS was utilized in this work to find the best solution from a set of Pareto optimum solutions generated by optimizing the multi-objective model. The process diagram of the TOPSIS improved with the CRITIC weight technique used to construct the Final Pareto solution is shown in Figure 3.10. [204].

Step 1: Based on the Pareto optimal results, a decision matrix was developed by optimizing a multi-objective model.

Step 2: To convert dimensional attributes into non-dimensional qualities, a normalized decision matrix was developed.

$$w_j = \frac{C_j}{\sum_{j=1}^{n} C_j} \tag{3.31}$$

Step 3: Normalized weighted decision matrix was developed.

$$WNDM = W_j \cdot NDM_{ij} \tag{3.32}$$

Step 4: The last stage consisted of comparing the favorable ideal (best) and unfavorable ideal (lowest) alternatives.

$$Z_j^{+} = \text{best}(Z_{ij})_{i=1}^{n}, Z^{+} \quad = \{Z_1^{+}, Z_2^{+}, Z_3^{+}, \ldots, Z_m^{+}\} \tag{3.33}$$

$$Z_{(j')}^{-} = \text{worst}(Z_{(ij')})_{i=1}^{n}, Z^{-} \quad = \{Z_1^{-}, Z_2^{-}, Z_3^{-}, \ldots, Z_m^{-}\} \tag{3.34}$$

Where j=1, 2...... m are helpful traits and j'=1, 2...... m' are not advantageous characteristics. It is the highest or lowest possible value for a certain characteristic out of all possible values for that characteristic.

Step 5: Euclidean distances were used to determine the separation measure between options.(i.e. SEP_i^{+} and, SEP_i^{-})

$$\sqrt{\sum_{j=1}^{m} (Z_{ij} - Z_j^{+})^2} \tag{3.35}$$

$$\sqrt{\sum_{j=1}^{m} (Z_{ij} - Z_j^{-})^2} \tag{3.36}$$

Step 6: Finally, the location' position on the ideal solution was evaluated, and the candidate's location was ranked appropriately.

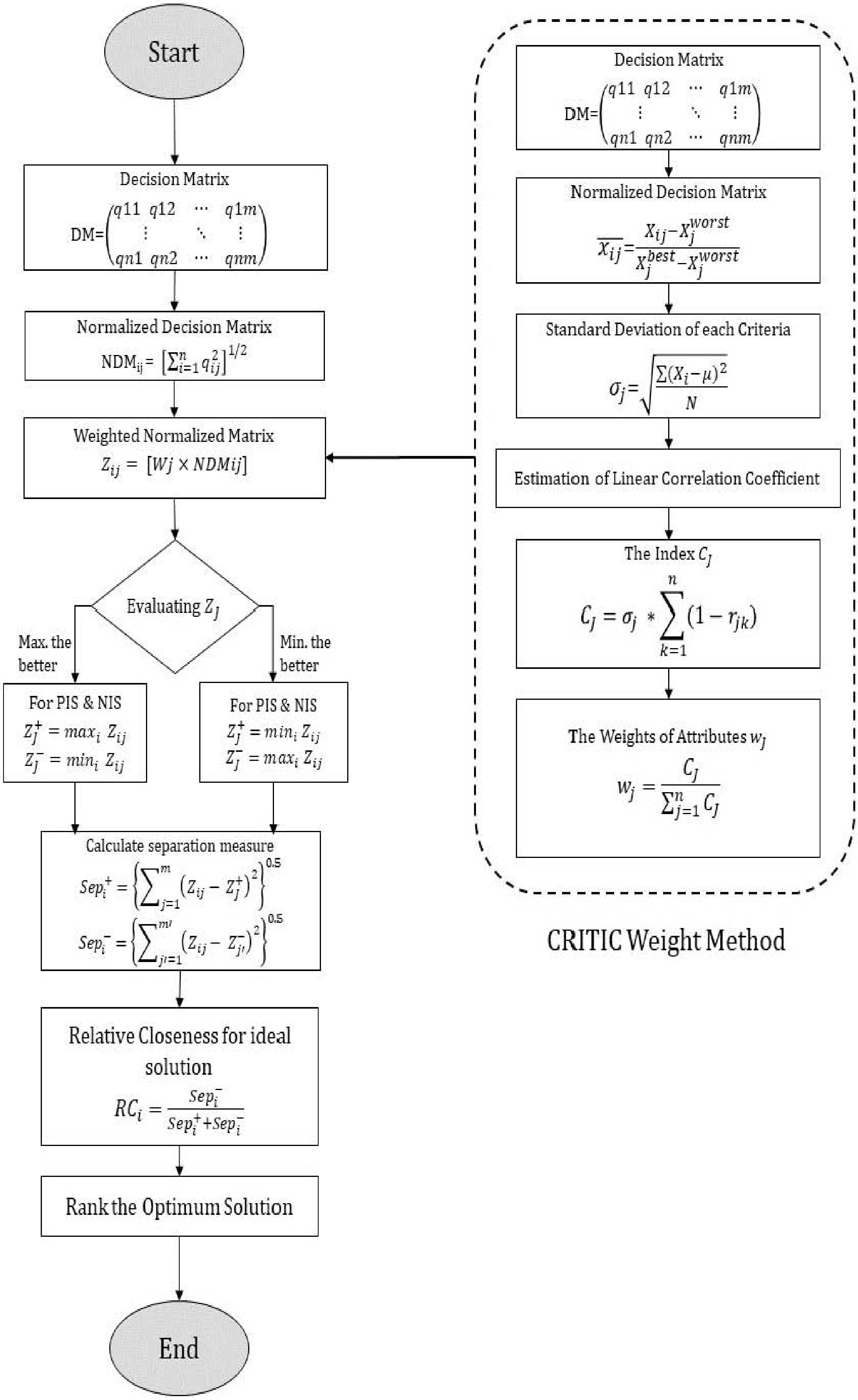

FIGURE 3.7: CRITIC Weight Method Flow Chart

$$\mathrm{RC}_i = \frac{\mathrm{Sep}_i^-}{\mathrm{Sep}_i^- + \mathrm{Sep}_i^+} \tag{3.37}$$

3.7 System Requirements

The following software is used to implement the different strategies mentioned above.

1. The following software is used to implement the different strategies mentioned above.
2. 2. Python 3.7 (Jupiter Notebook) software and the GEKKO library are used on a personal computer with a Core i5 3.2 GHz CPU and 16 GB of RAM to solve the MINLP model.

Chapter 4

Results and Analysis

The proposed methodology was adopted and analyzed in this chapter utilizing a real-time hospitals infectious waste network. The factors considered for infectious waste disposal site selection are per day waste generation of the hospital, distance of each hospital from the candidate location, operating cost to operate the incinerator of different capacities, facility establishing cost, and per unit ash transportation cost. The input data for this case study is included in Appendix C.1. The network of the Hospital waste comprises thirty-eight Hospitals, and three candidate sites for the incineration of hospital waste named as "Municipality", and have two different capacities of incinerators at each candidate site shown in Figure 4.1. Hospital j supplies the waste Qj generated per day to any suitable candidate site i. Moreover, each candidate site can incinerate the waste by using any of its two incinerators based on the amount of waste received at the candidate site.

4.1 Facility Location Selection

4.1.1 Weighting of Sustainable Criteria

The relative importance of every sustainable criterion was determined in the initial step (economic, environmental, and social) and was analyzed using Fuzzy E-AHP based on decision-makers preferences. Following that, the weights of each sub-criterion were also calculated. The final weights of each criterion are shown in Table 4.1.

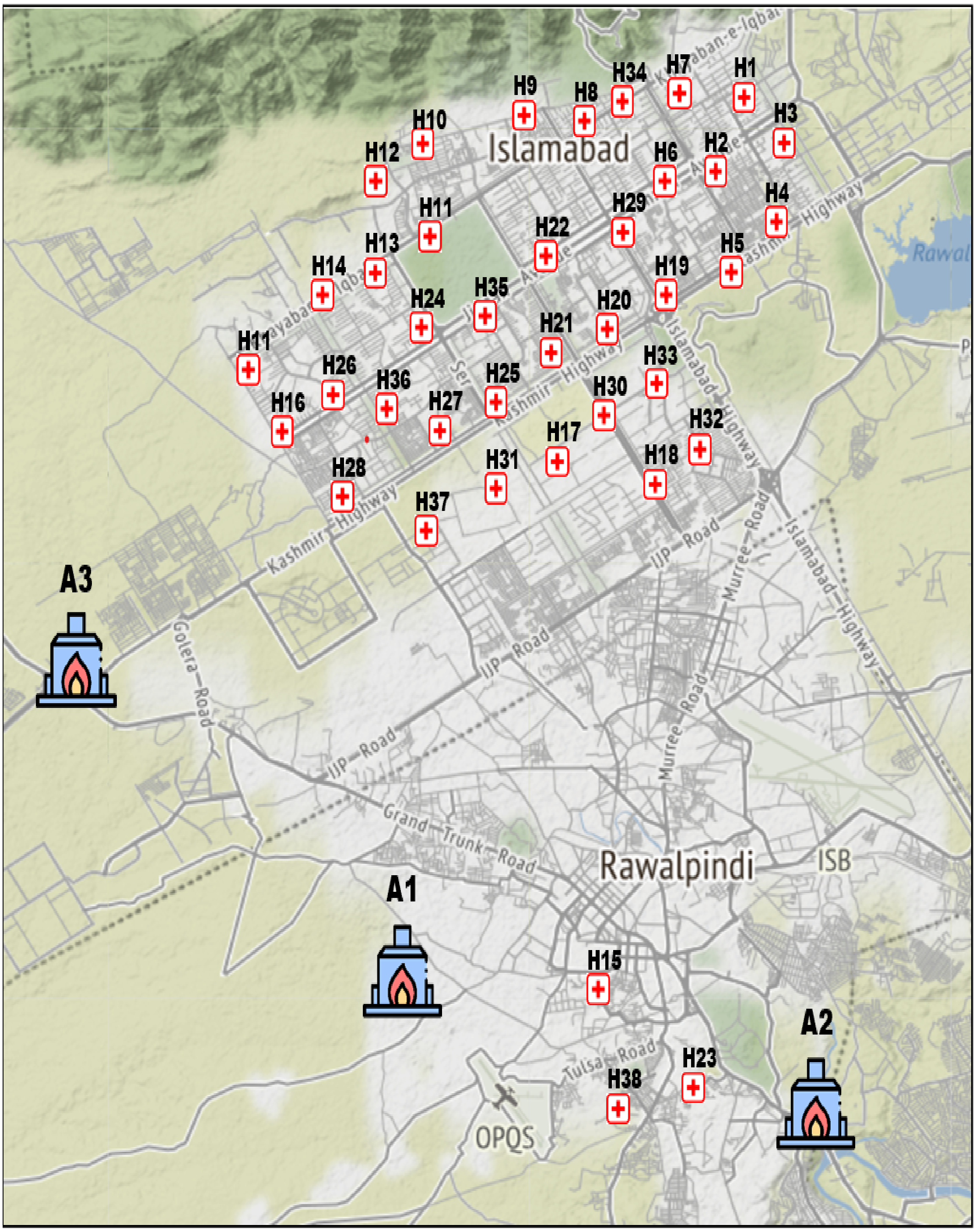

FIGURE 4.1: Case Study Multi-Echelon Operation Management Network

For decision-makers accessing candidate sites, the results/ranking for the sustainable standards were given as economic > environmental > social. The initial phase involves calculating the Consistency Ratio (CR) for the decision-making process. This is done by using the given formula and considering the weights assigned to each sustainability criterion through fuzzy E-AHP.

$$CI = \frac{\lambda_{\max} - n}{n - 1} \tag{4.1}$$

$$CR = \frac{CI}{RI} \tag{4.2}$$

Where $\lambda_{\max}$ is the highest Eigen-value, n is matrix dimension, RI stands for random consistency index, while CI is for closeness index, which is used to calculate CR. The CR level has been set at 10%. Appendix A.1 contains the steps for calculating CR. After the decision matrices had been validated, extended fuzzy AHP was used to assess the significance of sustainability criteria using the approaches described in Appendix A.2. Economic criteria were considered first by decision-makers, followed by environmental and social concerns. The most important sub-criteria among the nine economic sub-criteria is facility location cost. Similarly, in terms of environmental and social factors, decision makers regarded Green House Gas Emissions and Employee Health and Safety as important sub-criterion for selecting a sustainable Infectious Waste Disposal Site. These results give information for decision makers to take essential activities to obtain the lowest facility site cost and also minimizing Greenhouse gas emissions while keeping employee health safety in mind. Appendices A.2.1 show the step-by-step computations.

Table 4.1: Weights for Fuzzy Extended-AHP Criteria and Sub Criteria

Criteria	**Global Weights**	**Sub-Criteria**	**Local Weights**	**Ranking**
Economic	0.58	Facility Location Cost	**0.33**	1
		Operating Cost	0.24	2
		Transportation Cost	0.02	3

Environmental	0.30	Green House Gas - Emission	**0.13**	1
		Distance from Waters	0.10	2
		Distance from Society	0.065	3
		Resource Consumption	0.004	4
Social	0.12	Employee Health & Safety	**0.06**	1
		Staff Personal and Technical Development	0.05	2
		Impact on Society	0.003	3

4.1.2 Sustainable Candidate Site (Facility) Ranking

Following the evaluation of the weights for sustainable parameters, the prospective site is rated based on economic, environmental, and social factors. The relative weights of each potential site were determined using Fuzzy TOPSIS about sustainable criterion while grading the candidate site. Four decision-makers were involved in this procedure to appraise the possible candidate location based on predetermined criteria. To begin, fuzzy TOPSIS was used to analyze the relative closeness matrix for each prospective site in terms of sustainable criteria. Following that, TOPSIS was used to derive site location rankings, which is shown in Table 4.2. Appendix B.1 has the step-by-step computations.

Table 4.2: TOPSIS CC for Sustainable Location Selection

Candidate Sites	**Economic Criteria**	**Environmental Criteria**	**Social Criteria**	**Overall Closeness Coefficient**	**Rank**
Morgah(A1)	0.51	0.19	0.40	0.37	2
Rawat(A2)	0.23	0.57	0.64	0.24	3
Tarnol(A3)	0.85	0.81	0.62	0.99	**1**

Table 4.2 highlights that the top two potential sites, determined by evaluating their sustainable performance using Candidate Site ratings, are Tarnol A3 and Morgah A1. This ranking is based on the Overall Closeness Coefficient.

4.2 Operations Management of Infectious Waste Site

Initially, the mathematical model was solved by analyzing each objective function independently. The goal was to find the best outcomes for the two most favorable candidate sites, evaluated through Candidate Site ratings considering long-term performance criteria. Table 4.3 illustrates the precise solutions derived from the MINLP solver for each objective function. Following that, all objectives were then solved simultaneously using AUGMECON2 algorithms. To achieve the final Pareto answer, the Pareto solution generated from this methodology is further analyzed using TOPSIS enhanced with the CRITIC weight method. The proximity coefficient matrix of this approach is compared to obtain ultimate outcome based on greater values of the proximity coefficient.

Table 4.3: Non-linear Optimization of Each Objective Function.

Objective Function	**Total Value**	**Ideal Solution Breakdown**
Total Cost	\$7532.30	Facility Location Cost = \$3826.6
		Operating Cost = \$633.14
		Transportation Cost = \$3072.56
Total Time Travel	7.69 hrs.	N/A
Environmental Impact	34635 grams	CO2 Emission = 34635 grams
		Dioxin Emission = 2.359e-8 grams
Total Sustainable value for Selected Site	29.693	N/A

The candidate sites selected by compiling the total cost objective using a non-linear mixed integer solver (MINLP) were highlighted in Table 4.4 which also complements the results obtained from Fuzzy E-AHP and Fuzzy TOPSIS as the candidate sites selected from these techniques are the same as of MINLP solver.

Table 4.4: Optimal Solution from MINLP Solver.

Candidate Site	**Incinerator Size (kg/day)**	**Hospitals**
Morgah (A1)	1200	H4, H9, H10, H15, H20, H22, H24, H31, H32, H33, H36
Tranol (A3)	1200	H1, H2, H3, H5, H6, H7, H8, H11, H12, H13, H14, H16, H17, H18, H19, H21, H23, H25, H26, H27, H28, H29, H30, H34, H35, H37, H38

4.2.1 Evaluation of Optimal Solution Using AUGMECON2

The four objective functions are solved using AUGMECON2 algorithm. In the first step minimum and maximum value of each objective function were derived from equations (3.21)-(3.25). Table 4.5 shows the highest and minimum values.

Table 4.5: Payoff Table for Objective Functions with Minimal and Highest Values.

Objective Function	**TC**	**TTT**	**EI**	**TSVSS**
TC	7447.3076	7.6354	34359.2452	25.6956
TTT	8983.9396	7.6354	34359.249058	25.6956
EI	8935.0489	7.6354	34359.2451	25.6956
TSVSS	9750.3914	9.5348	42906.8171	29.9667

Each objective function solution values are:

Table 4.6: Objective Function Values

Objective Function	**Max**	**Min**
TC	9750.391	7447.307
TTT	9.5348	7.6354
EI	42906.81	34359.24
TSVSS	29.966	25.6956

The Ideal Solutions are TC= \$7447.308, TTT = 7.6354 hrs., EI= 34359.24, TSVSS = 30.0418, after determining the lowest and maximum values, epsilon values are assigned (ϵ_2, ϵ_3,ϵ_4) Table 4.7 shows the possibilities of ϵ-values with a step interval of 2 using equation (3.21)-(3.25).

Table 4.7: ϵ-values

ϵ_2	ϵ_3	ϵ_4
7.6354	34359.2451	25.8309
8.5851	34359.2451	25.8309
9.5348	34359.2451	25.8309
7.6354	38633.0311	25.8309
8.5851	38633.0311	25.8309
9.5348	38633.0311	25.8309
7.6354	42906.8170	25.8309
8.5851	42906.8170	25.8309
9.5348	42906.8170	25.8309
7.6354	34359.2451	27.9364
8.5851	34359.2451	27.9364
9.5348	34359.2451	27.9364
7.6354	38633.0311	27.9364
8.5851	38633.0311	27.9364
9.5348	38633.0311	27.9364
7.6354	42906.8170	27.9364
8.5851	42906.8170	27.9364
9.5348	42906.8170	27.9364
7.6354	34359.2451	30.0418
8.5851	34359.2451	30.0418

To obtain the Pareto optimal solution, the iteration procedure is repeated for each combination of values. The maximum number of iterations has been set to 50,000. Table 4.8 shows the Pareto solutions derived using these ϵ-values.

Table 4.8: Pareto Solutions of Four Objective Functions using AUGMCON2

Sr. No.	**TC**	**TTT**	**EI**	**TSVSS**
1	7447.00	7.6354	34359.2456	25.8315
2	7823.00	8.5851	38633.031	25.8659
3	8198.00	9.5348	42906.8169	25.8858
4	7823.00	8.5851	38633.0311	25.8563
5	7823.00	8.5851	38633.0311	25.8660
6	8198.00	9.5348	42906.8169	25.8804
7	8198.00	9.5348	42906.817	25.8809
8	8198.00	9.5348	42906.817	25.8806
9	8198.00	9.5348	42906.817	25.8798
10	7600.00	8.0217	36097.6212	27.9364
11	7823.00	8.5851	38633.031	27.9445
12	8198.00	9.5348	42906.8169	27.9622
13	7823.00	8.5851	38633.0311	27.9445
14	7823.00	8.5851	38633.0311	27.9438
15	8198.00	9.5348	42906.8169	27.9553
16	8198.00	9.5348	42906.817	27.9512
17	8198.00	9.5348	42906.817	27.9552
18	8198.00	9.5348	42906.817	27.9590
19	8198.00	9.5348	42906.8149	30.0418
20	8198.00	9.5348	42906.8149	30.0418

4.2.2 Selection of Best Solution using TOPSIS and CRITIC weight

TOPSIS enhanced with CRITIC weight approach is utilized to produce the best result from the aforementioned AUGMECON2 Pareto solutions, as stated in Section 3.6. Appendix D.1 has the criterion weight computations. The function weights are determined using Equation (3.35) and are shown in Table 4.9.

TABLE 4.9: Objective Functions and CRITIC Weights

Objective Functions	**CRITIC Weights**
TC	0.16
TTT	0.16
EI	0.16
TSASS	0.51

After determining the weights of the criterion, TOPSIS is used to compute the closeness coefficient (CC) matrix. Appendix D.2 has the TOPSIS computations enhanced with CRITIC weights. Table 4.10 displays the findings of the CC matrix.

TABLE 4.10: CC Values

Sr.No.	**CC**
1	**1.000**
2	0.768
3	0.611
4	0.768
5	0.768
6	0.611
7	0.611

8	0.611
9	0.611
10	0.578
11	0.499
12	0.380
13	0.499
14	0.499
15	0.381
16	0.381
17	0.381
18	0.380
19	0.000
20	0.000

Out of the 20 solutions, the closest proximity coefficient values is highest for the solution at position one. As a consequence, AUGMECON2 will be recognized as the best ideal option.

TABLE 4.11: Objective Function AUG-2 Solution Values

Objective Functions	**Values**
TC	\$7447
TTT	7.64 hrs.
EI	34359 grams
TSVSS	25.83

The Table 4.11 shows an optimized value as compared to the MINLP solver. It can be seen that the TC value changes from TC = \$7532 to TC = \$7447 and TTT value changes from TTT = 7.69 hrs to TTT = 7.64 hrs and EI values change from

EI = 34635 grams to EI = 34359 grams and value of TSVSS changes from TVSSS = 14.175 to TSVSS = 25.83. A comparison of MINLP-Solver and Augmecon-2 objective function values is shown in Figure 4.2.

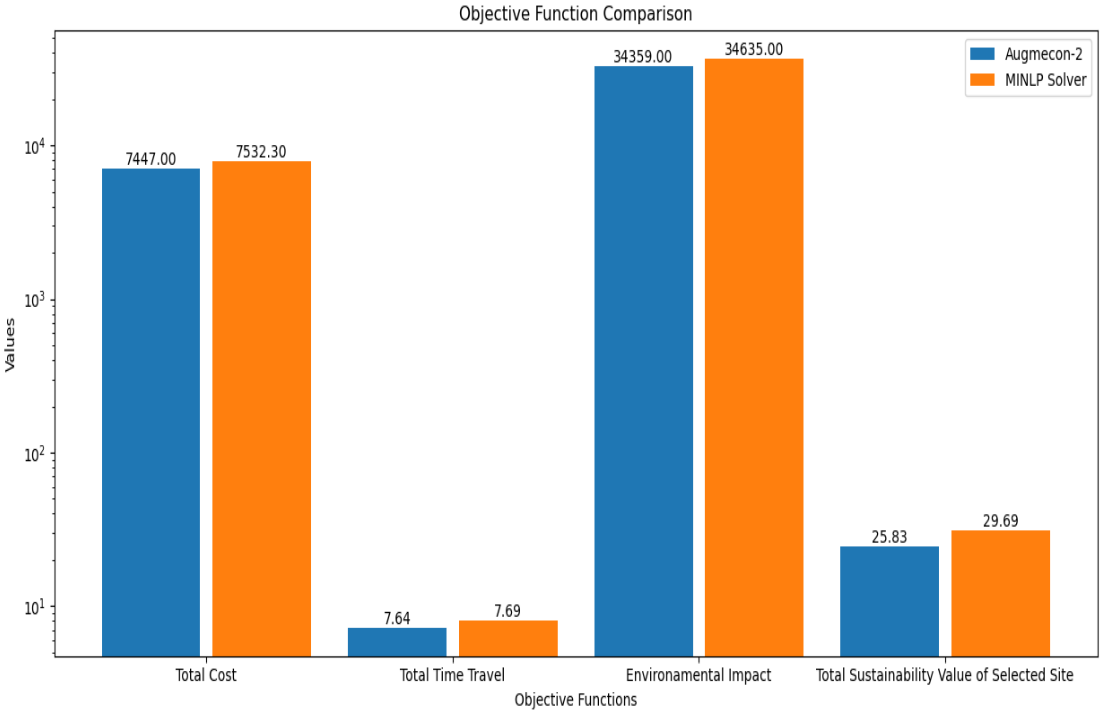

FIGURE 4.2: Comparison of Objective Function Values.

4.3 Final Solution Selection

Due to the small differences in the values of the four objective functions, decision-makers have a difficult challenge in selecting a final answer from the methodologies utilized in the research. According to F-AHP and Fuzzy TOPSIS, the two best sites were selected, the calculation is based on the survey in which four experts give weights to each criterion and the candidate locations. The solution obtained by solving the mathematical model designed for the operations management of the infectious waste using a Nonlinear programming solver also compliments the solution obtained from Fuzzy TOPSIS and Fuzzy E-AHP by selecting the same candidate site. Therefore, the problem is further solved using the AUGMECON2 algorithm which gives almost twenty results from different comparisons of all four objective functions with each other, to obtain the best solution from the AUGMECON2 results, the CRITIC Weight Method along with TOPSIS is used. The CC matrix obtained by applying TOPSIS is used to select the best AUGMECON2 result. Table 4.12 presents the comparison results of all techniques results.

TABLE 4.12: Site Selection Status of Different Solvers

Candidate Site	**Fuzzy TOPSIS**	**MINLP Solver**	**AUGMECON-2**
Morgah (A1)	**Selected**	**Selected**	**Selected**
Rawat (A2)	Not Selected	Not Selected	Not Selected
Tranol (A3)	**Selected**	**Selected**	**Selected**

The Table 4.13 Shows the result of two different techniques in comparison with the allocation of hospitals to the selected sites. MINLP Solver gives the below result by only using the one objective function of minimizing Total Cost, however, AUGMECON-2 gives the result by making a trade-off between all four objective functions to give the best possible solution. The results in Table 4.13 and Figure 4.3 clearly show that the **Candidate Site A3** is the best site.

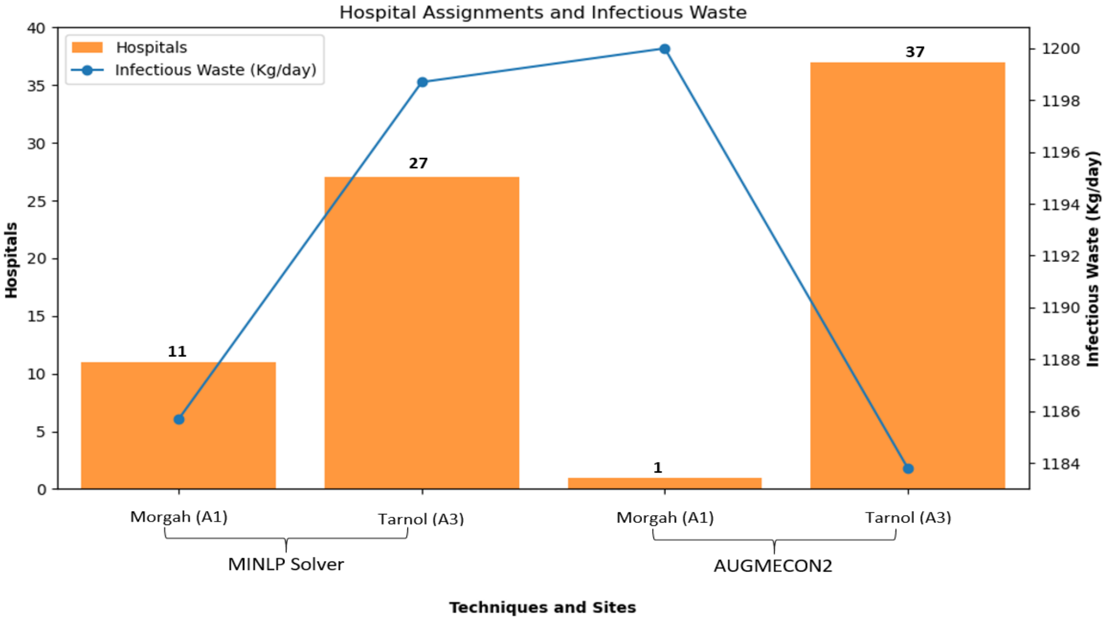

FIGURE 4.3: Comparison of Sites Selected using MINLP-Solver and AUG-2.

Table 4.13: Allocation of Hospital to Selected Site

Technique	**Candidate Site**	**Incinerator Size (kg/day)**	**Hospitals**	**Waste (Kg/day)**
MINLP Solver	Morgah (A1)	1200	H4, H9, H10, H15, H20, H22, H24, H31, H32, H33, H36	1185.7
	Tranol (A3)	1200	H1, H2, H3, H5, H6, H7, H8, H11, H12, H13, H14, H16, H17, H18, H19, H21, H23, H25, H26, H27, H28, H29, H30, H34, H35, H37, H38	1198.7
AUGMECON-2	Morgah (A1)	1200	H4	1200
	Tranol (A3)	1200	H1, H2, H3, H5, H6, H7, H8, H9, H10, H11, H12, H13, H14, H15, H16, H17, H18, H19, H20, H21, H22, H23, H24,H25, H26, H27, H28, H29, H30, H31, H32, H33, H34, H35, H36, H37, H38	1183.8

4.4 Managerial Implications

The following are the management implications of the above-described outcomes:

1. A thorough sustainability-based analysis was conducted to solve the IWDS location and management problem by utilizing the developed integrated framework.
2. The suggested decision-making system may be utilized to pick a candidate site for infectious waste disposal based on economic, environmental, and social sustainability factors.
3. Carbon and dioxin emissions have been incorporated into the mathematical model to offer a more comprehensive picture of the environmental effect of hospital and incineration networks.
4. The Total Sustainability Value of Selected site provides and overall metrics in the proposed framework provides decision-makers flexibility.

4.5 Theoretical Contribution

The theoretical contributions of this research can be summarized as follows:

1. An integrated framework was developed for comprehensive sustainability analysis in the selection and management of Infectious Waste Disposal Sites.
2. The framework supports decision-makers in selecting IWDS based on economic, environmental, and social sustainability factors.
3. Incorporation of carbon and dioxin emissions into the model enhances environmental assessment.
4. Introduction of the Total Sustainability Value simplifies evaluation by providing a single, flexible metric encapsulating economic, environmental, and social aspects.

Chapter 5

Conclusion and Future Work

The selection of a sustainable candidate site and operations management of infectious waste disposal, assists hospitals in moving towards Sustainable Development Goals (SDGs). This thesis proposes a comprehensive decision support system for selection and operations management of IWDS. The suggested approach is evaluated using a real-time case study. The following are the primary conclusions:

1. The results from Fuzzy E-AHP clearly show that among the global criteria (Economic, environmental, and Social) the Economic Criteria have the highest weightage.
2. The result from fuzzy TOPSIS showed that among the sustainable sub–criteria Facility location cost, Greenhouse gas emission, and Employee health and safety ranked highest.
3. The facility location cost, transportation cost, and operating cost contribute 50.8%, 40.8%, and 8.4% to the Total Cost.
4. Comparing CO2 and Dioxin emision, the CO2 emission contributes 99.9% to the entire environmental impact of IWDS.
5. The sites that are selected by implementing the proposed integrated framework for IWDS are Morgah (A1) and Tarnol (A3).

6. The total amount of waste for all hospitals is 2384.4kg/day which lead to opening of 1200kg/day capacity incinerator at each selected candidate site.
7. The allocation of hospitals to each selected sites are as follow: one hospital assigned to Morgah (A1) and thirty seven hospitals assigned to Tarnol (A3).

5.1 Future Recommendations

This thesis contributes valuable insights into the realm of Sustainable Site Selection and Operations Management in context of IWDS, several avenues for future research and improvement can be explored. The following recommendations highlight potential directions that can enhance and expand upon the findings of this study:

1. For a large-scale case study, the suggested technique may be enhanced by combining multi-product and multi-period scenarios.
2. More advanced algorithms (such as AUGMECON-R, AUGMECON-Py) to solve multi-objective problems to find more effective solutions.
3. The resilience criterion can be incorporated into the proposed integrated.
4. Future studies might consider combining new technologies such as ML (Machine Learning) and AI (Artificial Intelligence) to improve site selection and operations management.

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Appendix

A.1 Fuzzy AHP Calculation of Global Criteria

Combined Decision Matrix

Sustainable Criteria	Economical	Environmental	Social
Economical	1.00	3.84	3.84
Environmental	0.35	1.00	4.97
Social	0.35	0.24	1.00

Normalized Weight Matrix

For normalized decision matrix

$$\text{NDM} = \frac{\sum_{j=1}^{n} x_{ij}}{n}$$

where i is row and j is column of matrix.

Sustainable Criteria	Economical	Environmental	Social
Economical	0.59	0.76	0.39
Environmental	0.20	0.20	0.51
Social	0.20	0.05	0.10

Weight Calculations

$$\text{Weight} = \frac{\sum_{i=1}^{n} x_{ij}}{n}$$

where i is row and j is column of matrix.

Sustainable Criteria	**Weight**
Economical	0.58
Environmental	0.30
Social	0.12

Eigen Value and Consistency Ratio

$\lambda_{\mathbf{max}} = 3.02$

CI $= 0.01$

CR $= 0.02$

A.2 Fuzzy E-AHP Calculation

A.2.1 Sustainable Sub-Criteria Weights Calculation

A.2.1.1 Economical Sub-Criteria

Combined Decision Matrix

Sustainable Criteria	FLC	OC	TRC
FLC	4.96	9.60	13.51
OC	3.28	5.68	7.85
TC	1.34	1.52	2.23

Fuzzy E-AHP Normalized Decision Matrix

SubCriteria	a	n	m
Facility Location Cost	0.21	0.57	1.41
Operating Cost	0.14	0.34	0.82
Transportation Cost	0.06	0.09	0.23

Degree of Possibility

$S1 > S2$	1.00
$S1 > S3$	1.00
$S2 > S1$	0.72
$S2 > S3$	1.00
$S3 > S1$	0.04
$S3 > S2$	0.27

Weight Vector

Facility Location Cost	1.000
Operating Cost	0.722
Transportation Cost	0.044

Normalized Weight Vector

Facility Location Cost	0.57
Operating Cost	0.41
Transportation Cost	0.02

A.2.1.2 Environmental Sub-Criteria

Combined Decision Matrix

Sustainable Criteria	**GHGE**	**DFW**	**DFS**	**RC**
GHGE	1	4.98	5.41	3.00
DFW	0.23	1.00	3.66	3.84
DFS	0.21	0.37	1.00	3.84
RC	0.51	0.35	0.35	1.00

Fuzzy E-AHP Normalized Decision Matrix

SubCriteria	**a**	**n**	**m**
Green House Gas Emission	0.18	0.48	1.23
Distance from Water	0.10	0.29	0.78
Distance from Society	0.07	0.18	0.47
Resource Consumption	0.03	0.06	0.19

Degree of Possibility

$S1 > S2$	1.00
$S1 > S3$	1.00
$S1 > S4$	1.00
$S2 > S1$	0.76
$S2 > S3$	1.00
$S2 > S4$	1.00
$S3 > S1$	0.49
$S3 > S2$	0.77
$S3 > S4$	1.36
$S4 > S1$	0.03
$S4 > S2$	0.30
$S4 > S3$	0.52

Weight Vector

Green House Gas Emission	1.00
Distance from Water	0.76
Distance from Society	0.49
Resource Consumption	0.03

Normalized Weight Vector

Green House Gas Emission	0.44
Distance from Water	0.33
Distance from Society	0.22
Resource Consumption	0.01

A.2.1.3 Social Sub-Criteria

Combined Decision Matrix

Sustainable Criteria	EHS	SPTD	IS
EHS	4.55	8.99	13.15
SPTD	4.09	6.43	8.74
IS	1.32	1.49	2.10

Fuzzy E-AHP Normalized Decision Matrix

SubCriteria	a	n	m
Employee Health & Safety	0.19	0.53	1.32
Staff Personal & Technical Development	0.17	0.38	0.88
Impact on Society	0.06	0.09	0.21

Degree of Possibility

$S1 > S2$	1.00
$S1 > S3$	1.00
$S2 > S1$	0.82
$S2 > S3$	1.00
$S3 > S1$	0.05
$S3 > S2$	0.12

Weight Vector

Employee Health & Safety	1.000
Staff Personal & Technical Development	0.819
Impact on Society	0.045

Normalized Weight Vector

Employee Health & Safety	0.54
Staff Personal & Technical Development	0.44
Impact on Society	0.02

B.1 Fuzzy TOPSIS Calculations

B.1.1 Closeness Matrix Calculation for Economic Criteria

Decision Makers Response Gathering

Decission Maker 1

	Facility Location Cost			**Operating Cost**			**Transportation Cost**		
CL1	5	7	9	3	5	7	7	9	10
CL2	5	7	9	3	5	7	7	9	10
CL3	5	7	9	3	5	7	7	9	10

Decission Maker 2

	Facility Location Cost			**Operating Cost**			**Transportation Cost**		
CL1	5	7	9	7	9	10	5	7	9
CL2	7	9	10	5	7	9	3	5	7
CL3	5	7	9	3	5	7	1	3	5

Decission Maker 3

	Facility Location Cost			**Operating Cost**			**Transportation Cost**		
CL1	1	3	5	5	7	9	5	7	9
CL2	5	7	9	5	7	9	7	9	10
CL3	3	5	7	5	7	9	3	5	7

Decission Maker 4

	Facility Location Cost			**Operating Cost**			**Transportation Cost**		
CL1	7	9	10	5	7	9	5	7	9
CL2	7	9	10	5	7	9	5	7	9
CL3	7	9	10	5	7	9	5	7	9

Combined Decision Matrix

	Facility Location Cost			**Operating Cost**			**Transportation Cost**		
CL1	7	9	10	5	7	10	5	7.5	10
CL2	5	8	10	3	6.5	9	3	7.5	10
CL3	3	7	10	3	6	9	1	6	10

Normalized Decision Matrix

	FLC			**OC**			**TRC**		
CL1	0.082	0.535	0.823	0.247	0.576	0.823	0.412	0.618	0.823
CL2	0.392	0.628	0.784	0.235	0.510	0.706	0.235	0.588	0.784
CL3	0.273	0.636	0.909	0.273	0.545	0.818	0.091	0.545	0.909

Weighted Normalized Decision Matrix

	FLC			**OC**			**TRC**		
CL1	0.017	0.305	1.161	0.035	0.196	0.675	0.025	0.056	0.189
CL2	0.082	0.358	1.106	0.033	0.173	0.579	0.014	0.053	0.180
CL3	0.057	0.363	1.282	0.038	0.185	0.671	0.005	0.049	0.209

Best and Worst Solution

	FLC			**OC**			**TRC**		
Z+	0.082	0.363	1.282	0.038	0.196	0.675	0.025	0.056	0.209
Z-	0.017	0.305	1.106	0.033	0.173	0.579	0.005	0.049	0.180

Euclidean Distances

	FLC	**OC**	**TRC**	**Sep-**
CL1	0.086	0.002	0.011	0.099
CL2	0.101	0.057	0.018	0.176
CL3	0.014	0.007	0.012	0.033

	FLC	**OC**	**TRC**	**Sep-**
CL1	0.032	0.057	0.013	0.102
CL2	0.048	0.000	0.005	0.054
CL3	0.109	0.054	0.017	0.179

B.1.2 Closeness Matrix Calculation for Environmental Criteria

Normalized Decision Matrix

	GHGE			**DFW**			**DFS**			**RC**		
CL1	0.327	0.523	0.653	0.065	0.457	0.653	0.327	0.555	0.653	0.196	0.457	0.653
CL2	0.210	0.525	0.701	0.210	0.490	0.701	0.350	0.525	0.701	0.070	0.455	0.701
CL3	0.368	0.588	0.735	0.074	0.515	0.735	0.074	0.441	0.735	0.074	0.441	0.662

Weighted Normalized Decision Matrix

	GHGE			**DFW**			**DFS**			**RC**		
CL1	0.059	0.251	0.804	0.007	0.133	0.510	0.023	0.100	0.307	0.006	0.027	0.124
CL2	0.038	0.252	0.862	0.021	0.142	0.546	0.025	0.095	0.329	0.002	0.027	0.133
CL3	0.066	0.282	0.904	0.007	0.149	0.573	0.005	0.079	0.346	0.002	0.026	0.126

Best and Worst Solution

	GHGE			DFW			DFS			RC		
Z+	0.066	0.282	0.904	0.021	0.149	0.573	0.025	0.100	0.346	0.006	0.027	0.133
Z-	0.038	0.251	0.804	0.007	0.133	0.510	0.005	0.079	0.307	0.002	0.026	0.124

Euclidean Distances

	Sep+	Sep-
CL1	0.030	0.127
CL2	0.081	0.062
CL3	0.124	0.029

B.1.3 Closeness Matrix Calculation for Social Criteria

Normalized Decision Matrix

	EHS			SPTD			IOS		
CL1	0.077	0.538	0.769	0.384	0.576	0.769	0.384	0.615	0.769
CL2	0.393	0.629	0.786	0.236	0.550	0.786	0.079	0.550	0.786
CL3	0.400	0.600	0.800	0.080	0.480	0.800	0.400	0.640	0.800

Weighted Normalized Decision Matrix

	EHS			SPTD			IOS		
CL1	0.015	0.285	1.015	0.065	0.219	0.676	0.023	0.055	0.161
CL2	0.075	0.333	1.037	0.040	0.209	0.691	0.005	0.049	0.165
CL3	0.076	0.318	1.056	0.014	0.182	0.704	0.024	0.058	0.168

Best and Worst Solution

	EHS			**SPTD**			**IOS**		
Z+	0.076	0.333	1.056	0.065	0.219	0.704	0.024	0.058	0.168
Z-	0.015	0.285	1.015	0.014	0.182	0.676	0.005	0.049	0.161

Euclidean Distances

	Sep+	**Sep-**
CL1	0.071	0.048
CL2	0.040	0.072
CL3	0.045	0.075

C.1 Input Data

Set of Candidate Location/Municipalities = 3

Set of Incinerator = 2

Set of Hospitals = 38

Set of Transportation Mode = 1 (Road)

Transportation Cost ($/km)

Unit Transportation Cost of Ash (UTC) = 4.39

Velocity of Mode [205]

Mode	Velocity (km/hr)
Sea	35
Rail	60
Road	90

Information Related to Gas Emission [206], [207]

CO_2 Emission for Road **(grams/km)** = 50

Dioxin Emission is in nano gram so it is 5 ng/m3 to convert it into ng/kg we will multiply it with 0.95m3/kg (v of gas emitted in m3) to get 4.75ng/kg then we divide it with 10-9 to get in grams

Dioxin Emission **(nano grams)**= 4.75e-9

Resource Data

Hospitals	Morgah Dist.(km)	Rawat Dist.(km)	Tarnol Dist.(km)	Infectious Waste (kg/day)
H1	22.5	32.2	20.8	139.4
H2	22.6	34.1	23.1	211.1
H3	21.9	31.6	20.1	33.4

H4	20.0	28.2	19.5	1115.2
H5	25.6	35.0	22.2	38.3
H6	23.7	33.1	21.0	33.8
H7	21.6	21.2	19.8	16.4
H8	26.2	37.0	13.8	91.1
H9	15.3	28.3	20.2	2.6
H10	13.2	33.3	12.7	7.2
H11	23.5	34.9	21.0	3.7
H12	22.7	32.1	20.7	2.9
H13	22.5	31.9	20.5	37.2
H14	25.3	36.2	23.1	159.2
H15	17.3	27.3	20.9	0.3
H16	22.7	32.2	20.9	0.6
H17	29.8	39.9	19.7	0.3
H18	25.7	35.2	16.8	0.5
H19	26.7	37.5	14.3	0.3
H20	11.0	8.6	35.4	0.5
H21	22.9	31.7	28.3	51.3
H22	11.8	15.2	36.8	0.4
H23	23.0	32.3	21.5	75.8
H24	8.1	13.0	32.4	32.0
H25	23.0	32.0	21.3	27.6
H26	17.1	35.2	9.5	151.8
H27	22.6	31.3	20.6	2.7
H28	21.5	31.2	19.2	25.8
H29	22.4	31.2	20.4	0.9
H30	21.5	31.0	19.4	0.2
H31	23.1	19.3	28.4	3.9
H32	11.4	15.8	37.0	6.3
H33	14.5	14.6	36.4	0.3
H34	25.5	34.7	24.0	3.2
H35	23.8	32.6	21.1	85.4
H36	11.3	15.4	35.2	17.1
H37	21.8	31.3	19.5	1.8
H38	22.3	31.0	20.3	3.8
Total	**787.4**	**1108.6**	**857.8**	**2384.4**

Incinerator Information

Incinerator Capacity **(kg/day)** = 800, 1200

Total Number of Worker = 3

Average Salary **($/day** = 4.62

Ash transfer Cost **($/kg)** = 0.10

Ash Production is 20% of Total Waste.

Cleaning System Cost is 40% of Incinerator Cost.

Maintenance Cost is 25% of Incinerator Cost.

Incinerator Daily Facility Location Cost ($/kg)

Facility Cost	**Incinerator 800(Kg/day)**	**Incinerator 1200 (Kg/day)**
Incinerator Cost	831.87	1247.81
Landfill Cost	83.19	124.78
Storage Cost	27.73	41.59
Cleaning System Cost	332.75	499.12
Total	**1275.54**	**1913.3**

Incinerator Daily Operating Cost ($/kg)

Operating Cost Category	**Incinerator 800(Kg/day)**	**Incinerator 1200(Kg/day)**
Labor Cost	4.62	4.62
Maintenance Cost	207.97	311.95
Total	**212.59**	**316.57**

D.1 CRITIC Weight Calculations for AUGMECON2

Normalized Decision Matrix

$f1$	$f2$	$f3$	$f4$
1.00	1.00	1.00	1.00
0.50	0.50	0.50	0.99
0.00	0.00	0.00	0.99
0.50	0.50	0.50	0.99
0.50	0.50	0.50	0.99
0.00	0.00	0.00	0.99
0.00	0.00	0.00	0.99
0.00	0.00	0.00	0.99
0.00	0.00	0.00	0.99
0.80	0.80	0.80	0.49
0.50	0.50	0.50	0.49
0.00	0.00	0.00	0.48
0.50	0.50	0.50	0.49
0.50	0.50	0.50	0.49
0.00	0.00	0.00	0.49
0.00	0.00	0.00	0.49
0.00	0.00	0.00	0.49
0.00	0.00	0.00	0.49
0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00

Standard Deviation

	$f1$	$f2$	$f3$	$f4$
Std. Deviation	0.32	0.32	0.32	0.33

Symmetric Matrix

	$f1$	$f2$	$f3$	$f4$
$f1$	1.00	1.00	1.00	0.21
$f2$	1.00	1.00	1.00	0.21
$f3$	1.00	1.00	1.00	0.21
$f4$	0.21	0.21	0.21	1.00

Conflict Measurement

	$f1$	$f2$	$f3$	$f4$
$f1$	0.00	0.00	0.00	0.79
$f2$	0.00	0.00	0.00	0.79
$f3$	0.00	0.00	0.00	0.79
$f4$	0.79	0.79	0.79	2.38

Quality of Information

	Average
$f1$	0.26
$f2$	0.26
$f3$	0.26
$f4$	0.80

D.2 TOPSIS using CRITIC Weight for AUGMECON2

Normalized Decision Matrix

$f1$	$f2$	$f3$	$f4$
0.207591	0.187640	0.187639	0.211911
0.218072	0.210979	0.210978	0.212193
0.228526	0.234318	0.234318	0.212356
0.218072	0.210979	0.210978	0.212114
0.218072	0.210979	0.210978	0.212194
0.228526	0.234318	0.234318	0.212312
0.228526	0.234318	0.234318	0.212316
0.228526	0.234318	0.234318	0.212314
0.228526	0.234318	0.234318	0.212307
0.211856	0.197133	0.197132	0.229178
0.218072	0.210979	0.210978	0.229245
0.228526	0.234318	0.234318	0.229390
0.218072	0.210979	0.210978	0.229245
0.218072	0.210979	0.210978	0.229239
0.228526	0.234318	0.234318	0.229333
0.228526	0.234318	0.234318	0.229300
0.228526	0.234318	0.234318	0.229333
0.228526	0.234318	0.234318	0.229364
0.228526	0.234318	0.234318	0.246450
0.228526	0.234318	0.234318	0.246450

Weighted Normalized Decision Matrix

$f1$	$f2$	$f3$	$f4$
0.033215	0.030022	0.030022	0.108074
0.034892	0.033757	0.033757	0.108218
0.036564	0.037491	0.037491	0.108302
0.034892	0.033757	0.033757	0.108178
0.034892	0.033757	0.033757	0.108219
0.036564	0.037491	0.037491	0.108279
0.036564	0.037491	0.037491	0.108281
0.036564	0.037491	0.037491	0.108280
0.036564	0.037491	0.037491	0.108277
0.033897	0.031541	0.031541	0.116881
0.034892	0.033757	0.033757	0.116915
0.036564	0.037491	0.037491	0.116989
0.034892	0.033757	0.033757	0.116915
0.034892	0.033757	0.033757	0.116912
0.036564	0.037491	0.037491	0.116960
0.036564	0.037491	0.037491	0.116943
0.036564	0.037491	0.037491	0.116960
0.036564	0.037491	0.037491	0.116976
0.036564	0.037491	0.037491	0.125690
0.036564	0.037491	0.037491	0.125690

Positive Ideal (best) and Negative Ideal (worst) Solution

	$f1$	$f2$	$f3$	$f4$
$Z+$	0.033215	0.030022	0.030022	0.108074
$Z-$	0.036564	0.037491	0.037491	0.125690

Euclidean Distances

	Sep+	*Sep−*
1	0.000000	0.020810
2	0.005543	0.018328
3	0.011083	0.017388
4	0.005542	0.018367
5	0.005543	0.018328
6	0.011082	0.017411
7	0.011082	0.017408
8	0.011082	0.017410
9	0.011082	0.017413
10	0.009090	0.012470
11	0.010433	0.010377
12	0.014221	0.008701
13	0.010433	0.010377
14	0.010431	0.010380
15	0.014203	0.008730
16	0.014193	0.008747
17	0.014203	0.008730
18	0.014213	0.008714
19	0.020810	0.000000
20	0.020810	0.000000

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