INTEGRATED MODELLING TOOL OF GEOSPATIAL CRITERIA FOR ECO-INDUSTRIAL PARK SITE SELECTION

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DEDICATION

This thesis is dedicated to my mother (Nah Uhoman Nuhu) of blessed memory, who taught me that even the largest task can be accomplished if it is done one step at a time. It is also dedicated to my father, who taught me that the best kind of knowledge to have is that which is learned for its own sake. And to my wife, children and siblings who stood beside me in prayers, with courage, understanding and love.

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ABSTRACT

Single multi-criteria decision-making (SMCDM) approaches are limited by inconsistencies in the evaluation of criteria weights, making it unreliable for industrial park (IP) site selection. This led to wrong industrial site choice, difficulty to attract industry symbiosis clusters and often resulted in brownfield industrial parks (BFIP) with excessive greenhouse gas emissions. Many BFIPs are being phased out in favour of eco-industrial parks (EIP) with favourable locations for industrial clusters to synergise and manage materials efficiently. Industrial site selection heavily depends on criteria weighting and ranking. This study aimed to develop an integrated multi-criteria decision-making (IMCDM) tool and MCDM-GIS model that would enable researchers to consolidate the advantages and eliminate the weaknesses of SMCDM. To address the mentioned limitations, the analytic hierarchy process (AHP), analytic network process (ANP), and fuzzy-analytic hierarchy process (F-AHP) tools were constructed using the eigenvalue, limit supermatrix and triangular fuzzy numbers. The spatial criteria weights and ranking of water bodies, roads, residential areas, existing industries, land surface temperature and slope were evaluated. The SMCDM priority vectors were alternately integrated to produce the IMCDM methods which were also used in assessing the criteria weights. All criteria weights were subjected to sensitivity analyses and standard deviation. To test the weighting consistency of the SMCDM, IMCDM and the model efficiency, the spatial criteria data of 2009 and 2019 of Tanjung Langsat Industrial Area (TLIA) were collected using the geographic information system (GIS) and screened by the Boolean logic. The Landsat-7 enhanced thematic mapper and the kompsat-3 imager obtained the land use land cover data through PLANMalaysia. The GIS prepared the Euclidean distance and reclassified raster layers. The single and integrated weights percent were separately overlaid in the MCDM-GIS model with the 2009 criteria dataset. The SMCDM and IMCDM approach identified the water bodies as suitable brownfield eco-industrial park (BF-EIP) sites. This shows tool inconsistency using sparse criteria because industries cannot be built inside water bodies. Using the 2019 data, the AHP, ANP and F-AHP identified 5%, 2% and 3% as very-highly-suitable sites all in the northern part of the TLIA. The small spots were found away from the existing industries' location when superimposed with the criteria layers. The integrated hierarchy network-fuzzy analytic process and hierarchy network analytic process methods identified vast sites of different suitability but included 12% part of the water bodies as low-suitable, hence considered as inconsistent. The hierarchy fuzzy-analytic process (H-FAP) and network fuzzy hierarchy-analytic process (NFh-AP) measured large different suitable sites with explicit identification not including water bodies, hence consistent and reliable tools. When overlaid with the criteria layer, the very-highly-suitable site was identified in the centre of the TLIA, falling in place with the existing industries. The integrated H-FAP and NFh-AP algorithms become consistent and the best because of the interplay of hierarchical, geometric ratio and networking tools coming from different groupings of paired comparison and uncertainty, as well as their weights being close to the averages of the criteria set as evaluated by the standard deviation. The IMCDM tools are consistent only with concentrated criteria. However, the SMCDM tools are weak with both the sparse and concentrated criteria. This can lead to the wrong choice of an industrial site. Both SMCDM and IMCDM measured the economic, environmental, and social attributes as the most important in supporting the criteria to achieve the BF-EIP site selection. The MCDM-GIS model is efficient as the outputs of suitable EIP site layers under different criteria weights and distinguished spatial data. The H-FAP, NFh-AP have been proven to be the consistent criteria weight assessment algorithms and a flexible MCDM–GIS is hereby presented to support the government, EIP investors/developers, and researchers. This is to achieve an easy 4IR-driven modelling process to select brownfields for EIPs.

ABSTRAK

Pendekatan membuat keputusan pelbagai kriteria tunggal (SMCDM) adalah terhad oleh penilaian pemberat kriteria yang tidak konsisten, menjadikannya kurang berkesan untuk pemilihan tapak taman industri (IP). Ini membawa kepada pilihan tapak perindustrian yang kurang sesuai, sekaligus menjadikan kelompo simbiosis industri kurang menarik dan mengakibatkan pelepasan gas rumah hijau yang berlebihan dalam taman perindustrian brownfield (BFIP). Banyak BFIP sedang dilupuskan secara berperingkat dan digantikan dengan taman eko-industri (EIP) pada lokasi yang sesuai bagi membolehkan kelompok industri bersinergi dan mengurus bahan dengan cekap. Pemilihan tapak industri sangat bergantung pada pemberat dan kriteria kedudukan. Matlamat kajian adalah untuk membangunkan kaedah membuat keputusan berbilang kriteria bersepadu (IMCDM) dan model MCDM-GIS yang membolehkan penyelidik menggabungkan kelebihan dan menghapuskan kelemahan SMCDM. Untuk menangani kelemahan yang dinyatakan, proses hierarki analitik (AHP), proses rangkaian analitik (ANP) dan proses hierarki analitik-kabur (F-AHP) telah dibina menggunakan nilai eigen, had supermatriks dan nombor kabur segi tiga. Berat kriteria spatial dan kedudukan sumber air, jalan raya, kawasan perumahan, industri sedia ada, suhu permukaan tanah, dan cerun telah dinilai. Vektor keutamaan SMCDM disepadukan secara bergilir-gilir dan menghasilkan kaedah IMCDM yang juga digunakan dalam menilai wajaran kriteria. Semua berat kriteria tertakluk kepada analisis sensitiviti dan sisihan piawai. Untuk menguji keseragaman pemberat SMCDM, IMCDM dan kecekapan model, data kriteria spatial 2009 dan 2019 kawasan perindustrian Tanjung Langsat (TLIA) telah dikumpulkan menggunakan sistem maklumat geografi (GIS) dan disaring oleh logik Boolean. Landsat-7 pemeta tematik dipertingkatkan dan pengimej kompsat-3 dan kompsat-3 imager memperoleh data tutupan tanah dan guna tanah melalui PLANMalaysia. GIS menyediakan jarak Euclidean dan mengklasifikasikan semula lapisan raster. Peratus pemberat tunggal dan bersepadu telah ditindih secara berasingan dalam model MCDM-GIS dengan set data kriteria 2009. Pendekatan SMCDM dan IMCDM telah dikenal pasti termasuk sumber air sebagai tapak taman eko-industri brownfield (BF-EIP) yang sesuai. Ini menunjukkan tidak konsisten nya kaedah menggunakan kriteria jarang oleh kerana industri tidak boleh dibina di dalam air. Menggunakan data 2019, AHP, ANP dan F-AHP mengenal pasti 5%, 2% dan 3% sebagai tapak yang sangat sesuai semuanya di bahagian utara TLIA. Bintik-bintik kecil ditemui jauh dari lokasi industri sedia ada apabila ditindih dengan lapisan kriteria. Kaedah rangkaian hierarki proses analitik kabur dan proses analitik rangkaian hierarki bersepadu mengenal pasti tapak yang luas dengan kesesuaian yang berbeza tetapi termasuk 12% bahagian sumber air sebagai kurang sesuai, oleh itu dianggap tidak konsisten. Proses analitik kabur hierarki (H-FAP) dan proses hierarki-analitik rangkaian kabur (NFh-AP) mengukur tapak besar berbeza yang sesuai dengan pengenalan yang jelas tanpa memasukkan sumber air, justeru mendapati alat yang konsisten dan boleh dipercayai. Apabila ditindih dengan lapisan kriteria, ianya adalah tapak yang sangat sesuai yang dikenal pasti di tengah-tengah TLIA, sesuai dengan industri sedia ada algoritma H-FAP dan NFh-AP bersepadu menjadi konsisten dan terbaik kerana interaksi hierarki, nisbah geometri dan alatan rangkaian yang datang daripada kumpulan berbeza perbandingan berpasangan dan ketidakpastian, serta beratnya hampir dengan purata kriteria yang ditetapkan seperti yang dinilai oleh sisihan piawai. Alat IMCDM hanya konsisten dengan kriteria tertumpu. Walau bagaimanapun, alatan SMCDM adalah lemah dengan kedua-dua kriteria yang jarang dan tertumpu. Ini boleh menyebabkan pilihan tapak perindustrian yang salah. Kedua-dua SMCDM dan IMCDM mengukur sifat ekonomi, alam sekitar dan sosial sebagai yang paling penting untuk menyokong kriteria untuk mencapai pemilihan tapak BF-EIP. Model MCDM-GIS adalah cekap kerana keluara lapisan tapak EIP yang sesuai di bawah berat kriteria yang berbeza dan data spatial dibezakan. H-FAP, NFh-AP telah dibuktikan sebagai algoritma penilaian berat kriteria yang konsisten dan MCDM–GIS yang fleksibel telah dihasilkan bagi membantu pihak kerajaan, pelabur/pemaju EIP serta penyelidik, sekaligus menghasilkan proses pemodelan dipacu 4IR yang mudah untuk memilih medan brownfileds untuk EIP.

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LIST OF ABBREVIATIONS

AHP	-	Analytic Hierarchy Process
AI	-	Artificial Intelligence
ANN	-	Artificial Neural Network
ANP	-	Analytical Network Process
ArcGIS	-	Aeronautical Reconnaissance Coverage Geographic Information System
ArcMap	-	Aeronautical Reconnaissance Coverage Map
BF-EIP	-	Brownfield Eco-Industrial Park
BFIP	-	Brownfield Industrial Park
BIP	-	Brownfield Industrial Park
BOCR	-	Benefits, Opportunities, Costs, And Risks
CI	-	Consistency Index
CR	-	Consistency Ratio
DEFRA	-	Department for Environment, Food and Rural Affairs
DELPHI	-	Documentation and Exchange of Lively and Pure Homeopathic Information
DEMATEL	-	Decision Making Trial and Evaluation Laboratory
DSS	-	Decision Support System
EIA	-	Environmental Impact Assessment
ELECTRE	-	Elimination of Choice Translating Reality
ETM	-	Enhanced Thematic Mapper
EVec	-	Eigenvector
EZ	-	Economic Zone
F-AHP	-	Fuzzy Analytic Hierarchy Process
FDI	-	Foreign Direct Investment
FTN	-	Fuzzy Trapezium Numbers
GA	-	Genetic Algorithm
GF-EIP	-	Greenfield Eco-Industrial Park
GFIP	-	Greenfield Industrial Park
GIS	-	Geographic Information System
GIZ	-	German Development Cooperation

GNU - GNU’s Not Unix
GPS - Global Positioning System
GRA - Grey Relational Analysis
GT - Geospatial Technology
GTP - Green Technology Park
H-FAP - Hierarchy-Fuzzy Analytic Process
HMCDM - Hybrid Multi-Criteria Decision-Making
HNAP Hierarchy Network Analytic Process
HN-FAP - Hierarchy Network-Fuzzy Analytic Process
IC - Industrial Corridor
IP - Industrial Park
IZ - Industrial Zones
KIS - Kalundborg Industrial Symbiosis
LULC - Land Use Land Cover
MADM - Multi-Attribute Decision Making
MAUT - Multi-Attribute Utility Theory
MCDA - Multi-criteria Decision Attribute
MCDM - Multi-criteria Decision-making
MODM - Multi-objective Decision making
MOO - Multi-objective Optimisation
MOORA - Multi-objective Optimization Ratio Analysis
NFh-AP - Network Fuzzy hierarchy Analytic Process
NISP - British National Industrial Symbiosis Program
NVec - New Vector
OLI - Operational Land Imager
OPVec - Overall Priority Vector
PROMETHEE - Preference Ranking Organization Method for Enrichment Evaluations
PVec - Priority Vector
R & D - Research and Development
RE - Renewable Energy
RI - Random Index
SA - Sensitivity Analysis
SAW - Simple Additive Weighting

SDGs - Sustainable Development Goals

SEPA - State Environmental Protection Agency

SMCDM - Single Multi-Criteria Decision-Making

SRTM - Shuttle Radar Terrain Mission

TFN - Triangular Fuzzy Number

TI - Traditional Industry

TLBIA - Tanjung Langsat Brownfield Industrial Area

TLIA - Tanjung Langsat Industrial Area

TOPSIS - Technique for Order Preference by Similarity to the Ideal Solution

UNIDO - United Nations Industrial Development Organisation

USGS - United States Geological Survey

VIKOR - Viekriterijumsko Kompromisno Rangiranje

WBG - World Bank Group

WLC - Weighted Linear Combination

WOA - Weighted Overlay Analysis

WSM - Weighted Sum Model

LIST OF SYMBOLS

$\tilde{r}_1$ - Geometric Mean

$\widetilde{w}_1$ - Fuzzy Weight

M_i - Crisp Value

$\tilde{\alpha}_{in}$ - Fuzzy Dimension Number

.shp - Shapefile

.tif - Image files

dpi - Dots Per Inch

k - Number of successive powers a weighted supermatrix is raised

$k \rightarrow \infty$ - Number of Successive Powers to Infinity

km - Kilometre

kth - Steady State Raised to a Power

l - Lower Value

m - Medium value

u - Upper Value

N_i - Normalised Weight

λ_{max} - Maximum Eigenvalue

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Background

A Traditional Industry (TI) is a production method of the pre-industrial period which was carried out on a small scale within a family in a small workshop or space and located in cities, characterised by spillages, wastes and noise pollution (Moreau *et al*., 2017). Due to these problems, the need for TIs to be placed in one area out of the city was planned and referred to as Industrial Park (IP) where all factories were moved. As a result of the lack of suitable locations, pollution management from isolated traditional industries, regulatory challenges arise, and industrial parks are eventually abandoned (Neves et al., 2020). IP started in Trafford, Manchester, England in mid-1896 (Beers et al., 2019). IP is described as an area of land out of a city partitioned and formed into plots with or without constructed factories and basic amenities by a team of captains of industry (UNIDO, 2016). Based on product demand and economic expansion, IP gradually spread to Naples, Italy, in 1904, Clearing Industrial District near Chicago, the United States of America in 1907, Singapore in 1951, Germany, the Netherlands, Austria, and cities in the Nordic countries of Sweden, Denmark and Norway, and to other parts of the world (Beers et al., 2019). The Environmental Impact Assessment (EIA) is the common practice of assessing areas for industrial development (Sarmiento & Vargas-Berrones, 2018). EIA is used for the identification and evaluation of the potential effects and consequences of proposed projects, programs or policy actions relative to the physical, cultural and economic components of the total environment (Loomis & Dziedzic, 2018). The EIA process is time-consuming and produces inaccurate results because of the number of dependents, independents, manual, and incomplete acquisition of variables associated with industrial locations (Loomis & Dziedzic, 2018). As a result, most IPs were sited in unsuitable locations due to a lack of scientific, geospatial, or multi-criteria decision-making criteria weight assessment methods for conducive industrial sites, resulting in brownfield industrial park (BFIP) (Kolhoff et al., 2018). A BFIP is "an abandoned or underutilised existing industrial site where industries, resources and services are disconnected and therefore lacks industrial resource exchange" (Klusacek *et al*., 2018); (Giamalaki & Tsoutsos, 2019)**;** (Massard et al., 2018) and (UNIDO, 2021).

Most IPs lacked suitable locations for groups of industry synergy, water and wastewater treatment methods, waste and pollution control systems, process automation, energy and material efficiency, and infrastructure, therefore, they emit carbon. To drive industrial dynamics, IPs did not attract Foreign Direct Investment (FDI) due to the absence of these elements (Torabi-Kaveh et al., 2016). IP brought about negative environmental and social impacts including greenhouse gas (GHG) emissions, related public interference, and high operating costs (Doorga *et al*., 2019). At that stage, since the traditional industries cannot manage the industrial and environmental guidelines geared towards abating greenhouse gas (GHG), the search for Economic Zones (EZ) or Industrial Corridors (IC) began. An EZ is designed to be a top-down and carefully selected industrial district, which can provide economic and regulatory advantages to companies located in its site, protect the environment and the social wellbeing (Stucki et al., 2019). The EZ is divided into several types one of which is the Eco-Industrial Park (EIP). An EIP is a new type of industrial organisation based on the circular economy for optimisation and sustainable development in which by-products and waste are recycled as raw materials to another company in the park and optimised for sustainable development. UNIDO, (2016) defined an EIP as "a concentration of clusters or interconnected manufacturing, engineering, and mutual service companies or industries located in a favourable site and linked by sharing products, by-products and a common management in the pursuit for green, profitable and social activity through a partnership in handling environmental and resource issues". EIPs must meet some environmental, social, economic, and technical conditions.

The EIP location is heavily influenced by spatial criteria, which necessitate strong decision-making criteria weight assessments and ranking (Giamalaki & Tsoutsos, 2019). As a result, the challenges of socio-economic, technical, and environmental issues caused by segregated factories in an IP or brownfield can be addressed through a carefully selected area that carries the features for EIP development (Maiolo & Pantusa, 2018). The industrial clusters constraint inspires GHG and the resultant global warming (Sarmiento & Vargas-Berrones, 2018). The key EIP site feature is a suitable location for industry cluster synergy and symbiosis for cleaner production which the IP lacked and failed (Asadabadi et al., 2019). EIP site selection is most effective when many criteria are used to investigate a wide variety of information about the area (Piengang *et al*., 2019). The suitable location reflects on water bodies, scalable available land, proven infrastructural development (for example, roads, railways, airports, electric grid, and seaports), utilities/amenities (such as electricity, portable water and telecommunication facilities), and existing industries for training (Belaud et al., 2019). Other features include proximity to raw materials, restricted areas (such as mining camps, agricultural farms, wetlands, slopes and mountains), institutions such as religious, health, financial, and academic for research and development (R&D) (Chumaidiyah et al., 2020). Amongst others are the proximity to urban settlement for the search of skilled and unskilled labour, closeness to the market for raw materials, by-products, and finished products supplies (Ajibade et al., 2019). Other crucial factors are the presence and proximity to coastal areas, favourable climatic conditions which can supply sufficient annual rainfall, wind and solar radiation to supplement the generation of clean energy (Geng et al., 2016). The EIP site selection and design are a strategic economic growth problem-solving and the initial process to an industrial carbon emission control and reduction from brownfields. The systematic site selection connects the bridge between favourable locations and several separate industry clusters to synergise and resolve resource management and pollution problems and produce solutions to abate carbon emissions. It links location, innovation, technology, and research to provide competitive advantage across environmental, economic, social and technical aspects through cleaner production and services (Neves et al., 2020). Therefore, the EIP site selection procedure becomes an intricate multi-criteria study.

It is estimated that around 80% of the data used for EIP site selection decision-making is spatial and the rest is 20% non-spatial (Das & Gupta, 2021). This was not taken into account when industrial parks were selected (Donni et al., 2017). This meant that there was limited research available on suitable industrial sites, resulting in poor site selection and the emergence of brownfields. The high percentage of spatial criteria required for suitable EIP site selection makes it a complex multi-criteria study that demands the use of geospatial and strong multi-criteria decision-making (MCDM) technologies for criteria assessment and suitability selection (Bansal *et al.*, 2017). Geospatial technology is “the range of modern machinery that is used to obtain, stock, and operate geographic data that is positioned to the earth. The data is used to analyse, model, simulate and imagine the location data for human, environment and the earth” (Avtar *et al.*, 2019). The technology gives well-informed choices based on the status and precedence of sites (Yatim, Ngan, & Lam, 2017). Geospatial technology takes forms such as the Geographic Information System (GIS), which gives a completely different way in which maps are formed to manage our societies and industry’s suitability locations (Loomis & Dziedzic, 2018).

The MCDM approach employs decision support systems (DSS) tools that quantitatively analyse, weighs and ranks the importance of a criterion for a specific project site selection (Rahmat et al., 2017). MCDM applies to different procedures that aid decision-makers to discover improved answers, where the purpose is to use the value-oriented method and generate the decision choices of criteria and/or attributes as the essential component in the industrial site selection decision study. MCDM estimates normalised data which achieves evaluations in suitability sites including industrial park location issues where it is crucial to correlate a few qualitative and quantitative measures in an extremely unspecified and unclear location (Zarin et al., 2021a).

MCDM tools are numerous which include the Analytical Hierarchy Process (AHP) (Wind & Saaty, 1980), Fuzzy Analytic Hierarchy Process (F-AHP) (Ohnishi *et al.*, 2017), Analytical Network Process (ANP) (Gnanasekaran & Venkatachalam, 2019), Weighted Linear Combination (WLC), Technique for Order Preference by Similarity to the Ideal Solution (TOPSIS) (Feyzi *et al.*, 2019), and Elimination of Choice Translating Reality (ELECTRE) (Ohnishi *et al.*, 2017) as few examples. MCDM tools have been widely employed to explore site selection results and to establish the ideal choice of project locations. However, previous studies have established that traditional single multi-criteria decision-making (SMCDM) methods have limitations (Donni et al., 2017; Qin et al., 2020) that often give inconsistent criteria weight and ranking for site suitability selection. Most MCDM tools struggle in the assessment of criteria that are near in weight, or dependent (Liu & Ma, 2021), for example, TOPSIS and F-AHP do not link criteria, while AHP and ANP do not resolve the uncertainty among criteria (Tavana et al., 2017).

When the number of criteria exceeds three, the consistency ratio frequently goes beyond the threshold of 0.1 (Paul, 2015), making its reliability uncertain and reasonable ranking difficult (Rahmat et al., 2017). These have shown that SMCDM techniques in the criteria weight assessment for EIP site suitability selection each have their capabilities and weaknesses. To overcome these, therefore, integrating the SMCDM approaches (Ahmed et al., 2020) can work out the limitations to eliminate the weaknesses and consolidate their strengths (Qin et al., 2020). When an SMCDM technique is combined with two or more methods, integrated multi-criteria decision-making (IMCDM) method is created (Walls & Paquin, 2015; Chumaidiyah et al., 2020;). The integration utilises the strength of SMCDM from different groupings to effectively and objectively evaluate consistent criteria and attribute eigenvectors for EIP site suitability selection. Osra & Kajjumba, (2019); Chumaidiyah et al., (2020) reiterated that the academic study of EIP site suitability selection using a robust approach for consistent criteria weight assessment should commence preventing any EIP site from being a brownfield.

1.2 Problem Statement

Brownfield industrial parks (BFIP) as manufacturing parks that are partially inhabited, underutilised, or derelict, are found all over the world which emit carbon to the environment. BFIPs suffer a variety of issues, such as unsuitable location, insufficient expansion area, shortage of existing industries, isolation, waste and wastewater management challenges, material and energy inefficiencies, and a lack of information (Qin et al., 2020). BFIPs generate GHG that pollute the environment, risk human health, destroy flora and fauna, and climate change and contribute to global warming. Unsuitable locations (Luthra et al., 2020) are the leading causes of BFIP, which emerge mostly as a result of insufficient or absent site criteria evaluation or the use of single traditional assessment procedures that struggle with spatial and consistent decision-making abilities. Many researchers have reported that single techniques have site criteria weights assessment consistency problems, which can result in wrong industrial sites suitability choices (Paul, 2015); (Rahmat et al., 2017); (Ahmed et al., 2020). It is a fact that the application of MCDM in the site criteria weighting and ranking has a significant impact on the selection of suitable industrial locations (Asadabadi et al., 2019).

The 2015 Paris Agreement committed governments to keep global temperature below 1.5°C by embarking on green manufacturing techniques to reduce GHG emissions and reduce global warming. Since BFIP emit carbon dioxide, methane, and nitrous oxides, which contribute to 28% of global GHG emissions (IPCC, 2019), it was recommended that they be transformed into eco-industrial parks (EIP). The mission of the EIP is to bring together industries in a strategic location for a circular economy, which is a new model that strives to systematically emulate natural symbiotic concepts of reducing, reusing, and recycling resources for cleaner manufacturing. Symbiosis minimises raw material consumption in EIPs by encouraging energy and waste reuse while also improving material efficiency and industry competitiveness among clusters. Synergy in EIPs promotes the sites' economic, environmental, social, and technological advantages, all of which contribute to minimizing the overall carbon footprint from industrial activities.

As BFIPs are being mapped to be converted to EIPs for industrial symbiosis, a detailed investigation of the spatial brownfield sites criteria using GIS and integrated MCDM methods, which are currently lacking, is required to determine the suitability of the location. Criteria such as favourable geographic proximity to urban/residential and industrial locations, a suitable climate for renewable energy resources, and accessible transportation and utility infrastructure are necessary. Other factors include the availability of water bodies, labour and markets, stable political areas, and available land for industry and development.

Since each SMCDM tool has a specific goal, it may not be suitable to be used to evaluate goals that they are not designed for. These make SMCDM tools constrained in assessing spatial variables that are nearly identical in rank and/or connected, and inconsistency threshold index when several criteria are employed. In this study, three MCDM procedures (AHP, ANP, and F-AHP) are to be assessed and integrated to build a consistent multi-criteria decision-making tool that can produce dependable criteria weights for selecting BFIP to a suitable EIP site. The integrated multi-criteria decision-making (IMCDM) algorithm would overcome the shortcomings of each SMCDM tool and improve its strengths to accurately assess brownfield spatial criteria weight for EIP site selection. The GIS with its power of collecting, evaluating, producing, and storing spatial criteria will be used to capture the spatial criteria of a selected brownfield. An MCDM-GIS model will be developed to run the results of the SMCDM and IMCDM methods to compare the criteria weight consistencies by the suitability layers of the BFIP for decision-making to EIP site conversion.

1.3 Research Goal

The study aims to develop an IMCDM algorithm and an MCDM-GIS model that can assess consistent criteria weights and accurately select brownfields for suitable and sustainable EIP sites.

The objectives of the research are:

(a) To establish the weightage for ranking for the selection of BF-EIP site using the SMCDM (AHP, ANP and F-AHP). To subsequently integrate the SMCDM methods to create an IMCDM algorithm weighting process for the assessment of a consistent criteria weight for the selection of a BF-EIP site.

(b) To design an MCDM-GIS model for the weighted overlay analysis of the SMCMD and IMCDM weights and spatial criteria.

(c) To use GIS to collect and prepare the spatial criteria to test the SMCDM and IMCDM methods weight assessment consistencies and ranking, and the resilience of the model in the selection of brownfield for conversion to an EIP site.

1.4 Scope of Work

To achieve the specific objectives of the research, the scope of the work is as follows:

(a) Review and identify the brownfield industrial area spatial criteria.

(b) Use the AHP, ANP, and F-AHP SMCDM to evaluate the weight percent of each criterion.

(c) Integrate the SMCDM methods to create an IMCDM algorithm and use them to assess the criteria/alternative weights of importance.

(d) Evaluate the sensitivity analyses and standard deviations of both the SMCDM and IMCDM weights.

(e) Design an MCDM-GIS model for the overlay of the spatial criteria and criteria weights assessed by the SMCDM and IMCDM methods to simplify and accurately select brownfield sites for EIP.

(f) Use the GIS to obtain 2009 and 2019 (a ten-year interval) spatial criteria data of Tanjung Langsat Brownfield Industrial Area (TLBIA), analyse, classify, and store them. Obtain the land use land cover (LULC) data of the TLBIA from PLANMalaysia.

(g) Prepare the Euclidean distance by assigning the desired distances (km), and non-distance criteria in percent (%) and degree Celsius (°C). Reclassified the Euclidean distance raster layers by considering a scale of 1 to 5 (5 being the preferred whether near or far, and 1 unpreferred whether close or farther).

(h) Perform weighted overlay analysis (WOA) of the SMCDM and IMCDM separately with the 2009 spatial criteria data and LULC in the MCDM-GIS model. Examine the consistencies of the SMCDM and IMCDM techniques and the performance of the model in each case.

(i) Further, perform WOA using the SMCDM and IMCDM algorithm weights with the 2019 spatial data. Compare the weight assessment consistencies and the resilience of the model in all cases for the conversion of a brownfield site to EIP.

1.5 Significance of the Study

The importance of this study is

(a) Since SMCDM methods have limitations in the assessment of consistent criteria weights for industrial site selection, as reported by many studies which have brought about the emergence of abandoned and/or underutilised industrial parks, integrated MCDM algorithms are required to provide assessments of consistent criteria weights upon which the EIP site selection depends.

(b) The IMCDM algorithm will provide reliable weights and the MCDM GIS-based model will make the EIP site selection easy to stimulate the redevelopment of brownfield to EIP. This will promote EIP development to mitigate industrial emissions for the global reduction of GHG to 1.5^{o}C or less by 2030 as mandated by the 2015 Paris Agreement.

(c) The design of the integrated algorithm and the model will help spur governments, brownfield-EIP developers, and research students in brownfield EIP site selection activities to attract investors in brownfield-EIP development.

1.6 Thesis Outline

This thesis comprises five chapters as follows:

Chapter 1 begins with an overview of the study, which is the background to study, problem statement, research objectives, the scope of work, and significance of the study.

Chapter 2 presents the critical review of the previous literature on geographic information system and multi-criteria decision-making technologies used in the selection of industrial sites. This chapter also highlights the problems of SMCMD tools in criteria weight assessment, the challenges of the GIS application for EIP site selection, the application of MCDM issues on EIP site selection, the impact of GIS on land use and EIPs. The chapter also discusses the AHP, ANP, and F-AHP weighting tools. The EIP concept, objectives, planning, development, challenges, the categories, and types of EIPs, EIP development projects in Kalundborg, the United Kingdom and around the world are also discussed. The chapter finally addressed the research gap based on the literature review.

Chapter 3 explains the research method for the EIP site selection. This consists of outlining the software and tools used and data collection. There is the criteria construction of the structures, formation of the pairwise comparison matrices, supermatrix, triangular fuzzy numbers and criteria/attribute weight assessments of the single/traditional AHP, ANP, and F-AHP tools. The chapter also performs normalisation, consistency confirmation evaluation, the overall priority ranking and sensitivity analysis of the weight outcomes. This chapter also deals with the integration of the AHP, ANP, and F-AHP, and evaluates the standard deviation of the criteria weight outcomes. The processing of the criteria spatial data by GIS, which includes Boolean logic criteria screening and classification, conversion and preparation of Euclidean distance raster layers, reclassification of the raster layers, and land use land cover layers acquisition. Finally, the chapter explains the development of the MCDM GIS-based algorithm model, testing the model, generating, and selecting the suitable EIP site.

Chapter 4 presents and discusses all the outcomes from the application of the methods described in chapter 3 and provides the best-integrated algorithms for the evaluation of the consistent criteria weight of importance for use and a guide to a suitable BF-EIP site selection.

Chapter 5 summarises the research findings, enumerates the contributions to knowledge and recommendations for future works.

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LIST OF PUBLICATIONS

Journal with Impact Factor

1) **Nuhu, S. K**., Manan, Z. A., Wan Alwi, S. R., & Md Reba, M. N. (2021). Roles of geospatial technology in eco-industrial park site selection: State-of-the-art review. *Journal of Cleaner Production*, 309, 127361. https://doi.org/10.1016/j.jclepro.2021.127361 **(Q1, IF: 9.297).**

2) **Nuhu, S. K**., Manan, Z. A., Wan Alwi, S., Reba, N. M. (2021). A New Hybrid Modelling Approach for an Eco-Industrial Park Site Selection. *Chemical Engineering Transactions.* 89, 343-348 DOI:10.3303/CET2189058 (**Q3, IF: 0.683**).

3) **Nuhu, S. K**., Manan, Z. A., Wan Alwi, S. R., & Md Reba, M. N. (2021). Integration of the Modelling Tools Used for Site Selection of an Eco-Industrial Park. *Journal of Cleaner Production* (**IF 9.297: Q1**), (Under review).

Non-Indexed Conference Proceedings

1) **Nuhu, S. K**., Manan, Z. A., Wan Alwi, S. R., & Md Reba, M. N. (2020). Improvement of the Site Selection Guide for Brownfield Eco-Industrial Park: The Fuzzy Analytic Hierarchy Process. 3rd *Scientia Academia International Conference (SAICon-2020),* Scientia Academia Malaysia, 26 – 27 December 2020.

2) **Nuhu, S. K**., Reba, N. M., Manan, Z. A., Wan Alwi, S. (2021). Assessing the Criteria of Eco-Industrial Park Site Selection for the SDG Initiatives. *Regional Conference in Civil Engineering and Sustainable development Goals in Higher Education Institutions 2020,* Universiti Teknologi Malaysia, 23 – 24 January 2021.

3) **Nuhu, S. K**., Manan, Z. A., Wan Alwi, S., Reba, N. M. (2021). A New Hybrid Modelling Approach for an Eco-Industrial Park Site Selection. *7th International Conference on Low Carbon on Asia & Beyond.* “Circular Economy Towards Sustainable Development” 18th & 19th October 2021, Johor Bahru, Malaysia.

Book Chapter (Indexed)

1) **Nuhu, S. K**., Manan, Z. A., Wan Alwi, S., Reba, N. M. (2021). Development and Design of Eco-Industrial Park Toward Circular Economy; (Chapter 11) in the book Process Design and Optimisation for Circular Economy. First Edition 2021, Edited by Azizul Azri Mustaffa & Peng Yen Liew. Published by Penerbit UTM, Malaysia. *ISBN 978-983-52-1790-6.*

2) **Nuhu, S. K**., Reba, N. M., Manan, Z. A., Wan Alwi, S. (2021). Assessing the Criteria of Eco-Industrial Park Site Selection for the SDG Initiatives; (Book

Chapter) in a Book “Sustainability Management Strategies and Impact in Developing Countries. By *Community, Environment and Disaster Risk Management* (CEDRM) Book Series Volume. Emerald Publisher **(indexed by MDPI)** (accepted, in press)