DEVELOPMENT OF MULTI-CRITERIA DECISION-MAKING FRAMEWORK FOR SELECTING A SUITABLE TECHNIQUE FOR SUSTAINABLE PAVEMENT

By

AL-HUMAIRI SARMAD FARAJ ISMAEL

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Doctor of Philosophy

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DEDICATION

I dedicate my research to

my supervisor Dr. Aidi Hizami Bin Ales@ Alias for his support and Motivation throughout my research without his help this research wouldn't be easy for me. Also, I would like to dedicate my hard work to my family, my wife, and my beloved daughter who has been there for me since day one. Last but not least I am honored to dedicate this research to W. T. Byler Inc., Co. as a way of expressing my gratitude for your unwavering support throughout the research process. None of this would have happened without their support. Finishing my studies without their unwavering support over the past few years would have been impossible.

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September 2023

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Pavement techniques are essential for achieving environmental, economic, and social sustainability. Numerous challenges have emerged associated with pavement techniques, such as evaluation criteria, criteria trade-offs, criteria conflict, and criteria importance classified to the evaluation and selection of pavement techniques under complex multi-criteria decision-making (MCDM) approach. Accompanying the development of pavement technique builds a motivation to achieve the goal of less heating release. No study to date has developed an evaluation framework for selecting the most appropriate pavement technique to be used to achieve environmental, economic, and social sustainability considering a multi-criteria evaluation of pavement techniques and sustainable solutions. In this study, a pavement selection strategy based on a new extension of fuzzy MCDM methods is presented. Two phases are used to develop the methodology. Firstly, the ‘multi evaluation criteria’ and ‘pavement techniques’ are intersected to formulate the evaluation decision matrix. Secondly, the proposed MCDM methods are developed: multi-layer dual hesitant fuzzy weighted zero inconsistency (DH-FWZIC) to assign weights to the pavement’s evaluation criteria followed by dual hesitant fuzzy decision by opinion score method (DH-FDOSM) for selecting the best pavement technique. Based on 30 criteria, four alternatives namely flexible/asphalt, rigid/concrete, reflective, and evaporative alternatives pavement techniques are evaluated. The findings are as follows: (i) The evaluation criteria for pavement techniques have been consistently weighted using the multi-layer DH-FWZIC method at three layers, and the results show that a region's environment criterion has the highest final weight (0.1215) and the lowest importance value (0.0089) assigned to its wind criterion. (ii) The flexible/asphalt pavement is ranked first among the four pavement techniques with both dual hesitant fuzzy weighted averaging (DHFWA) and dual hesitant fuzzy weighted geometric (DHFWG) operators, according to DH-FDOSM. Meanwhile, the reflective pavement set at the end of the list is ranked fourth as obtained by the DHFWA operator. This escalated to the third rank and moved permeable pavement to the fourth rank as obtained by the DHFWG operator. Furthermore, the

sensitivity analysis was used to investigate the robustness of the developed framework by examining the impact of the most important criterion on the ranking results. A comparison study was conducted to compare the weighting and ranking methods with other MCDM approaches. Finally, the outcomes of this study can assist project managers in selecting the most optimal pavement technique. Future researchers can use this study's results as a reference for deep investigation of pavement types under different conditions.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

PEMBANGUNAN RANGKA KERJA KEPUTUSAN PELBAGAI KRITERIA UNTUK PEMILIHAN TEKNIK TURAPAN YANG MAMPAN

Oleh

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Teknik turapan adalah penting untuk mencapai kelestarian alam sekitar, ekonomi dan sosial. Terdapat pelbagai cabaran yang dihadapi berkait denganteknik turapan; iaitu melalui kaedah kriteria-pelbagai dalam membuat keputusan kompleks (MDCM) seperti kriteria penilaian, kriteria penggantian, kriteria konflik, dan kriteria kepentingan klasifikasi penilaian dan pemilihan teknik turapan. Pembangunan teknik turapan adalah seiring dengan matlamat untuk mencapai pengurangan pelepasan pemanasan. Namun, sehingga kini masih tiada kajian yang membangunkan kerangka penilaian bagi pemilihan teknik turapan yang paling sesuai digunakan untuk mencapai kelestarian alam sekitar, ekonomi dan sosial dengan mengambil kira penilaian kriteria-pelbagai strategi teknik dan penyelesaian mampan. Kajian ini menggunakan teknik turapan berdasarkan kepada kaedah lanjutan MCDM kabur. Terdapat dua tahap dalam membangunkan metodologi kajian. Pertama, persilangan ‘kriteria penilaian’ dan ‘senarai teknik turapan’ menghasilkan matriks penilaian keputusan. Kedua, cadangan kaedah MCDM dibangunkan: kekaburan dwi ragu pelbagai-lapisan pemberat ketaktekalan sifar (DH-FWZIC) digunankan untuk menentukan pemberat kepada kriteria penilaian turapan diikuti oleh keputusan kekaburan dwi ragu menggunakan kaedah skor anggapan (DH-FDOSM) dalam memilih teknik turapan terbaik. Penilaian dilaksana berdasarkan kepada 30 kriteria Empat alternatif iaitu fleksibel/asfalt, tegar/konkrit, reflektif dan teknik turapan alternatif telap. Dapatan kajian adalah seperti berikut. (i). kriteria penilaian bagi teknik turapan telah ditimbang secara konsisten menggunakan kaedah DH-FWZIC pelbagai-lapisan pada tiga lapisan. Dapatan menunjukkan kriteria persekitaran di rantau tersebut adalah paling berat (0.1215) dan nilai kepentingan terendah (0.0089) bagi kriteria angin. (ii). Turapan fleksibel/asfalt adalah di kedudukan tertinggi di antara Empat v turapan dengan kedua-dua pengendali DHFWA dan DHFWG, berdasarkan kepada FDOSM. Manakala, turapan reflektif adalah yang terendah diantara empat teknik tersebut melalui pengendali DHFWA. Ia turut meningkat ke kedudukan ketiga dan turapan telap di kedudukan terakhir melalui pengendali DHFWG. Selain itu, analisis kepekaan digunakan untuk mengkaji keteguhan kerangka yang dibangunkan dengan mengkaji kesan kriteria terpenting terhadap dapatan pemeringkatan. Analisis bandingan

telah dilaksanakan unutk membandingkan kaedah pemberat dan kaedah pemeringkatan dengan kaedah-kaedah MCDM yang lain. Akhir sekali, dapatan kajian ini akan membantu pengurus projek dalam pemilihan teknik turapan optimal dan akan membantu penyelidik menggunakan dapatan kajian sebagai rujukan untuk mengkaji dengan lebih mendalam mengenai keseluruhan jenis turapan di dalam pelbagai keadaan.

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LIST OF ABBREVIATIONS

UHI	Urban Heat Island
MCDM	Multi Criteria Decision Making
DH-FWZIC	Dual Hesitant Fuzzy Weight Zero Inconsistency
DH-FDOSM	Dual Hesitant Fuzzy Decision by Opinion Score Method
DHFWA	Dual Hesitant Fuzzy Weight Average
DHFWG	Dual Hesitant Fuzzy Weight Geometric
PCM	Phase Change Material
GHG	Greenhouse Gas
LCCA	Analysis of Life Cycle Cost
LCA	Life Cycle Assessment
FHWA	Federal Highway Administration
SLR	Systematic Literature Review
GDM	Group Decision Making
EDM	Expert Decision matrix
SDG	Sustainable Development Goals

CHAPTER 1

INTRODUCTION

1.1 Introduction

Pavement techniques are a broad and complex concept, and one of the most significant issues in the construction industry. This concept is new prototype in the building and construction industries for achieving the sustainable development goal. Many studies are taking into consideration to develop pavement techniques but there is still a significant lack of integrated paving issues with the surrounding area (Elizondo-Martínez et al., 2020; C. Wang et al., 2021a). Therefore, this research attempts to address this gap.

This chapter aims to show the research direction. It starts with a brief background of the study area, to approach a problem statement. This is followed by the outlines of the research objectives, and the research significance. Next is the scope and limitations of the study. And finally, the outline and organization of the dissertation.

1.2 Background of the Study

In recent years, the topics of global warming, earth overheating, and local climate change have been gaining extensive research attention. Rapid urbanization (development of cities) and urban expansion have caused people to migrate from rural area to the cities, causing unregulated growth of cities. It is expected that 66% of the world's population will be concentrated in cities by 2050, and developed countries will hit 82% (Pan et al., 2022b). Weaknesses in urban design planning, replacement of green surfaces and natural terrain with industrialized materials, the release of heat and increased heat stored by urban structures, lack of water bodies, built environment, and human activity contribute to a higher urban temperature leading to environmental hazard called the Urban Heat Island (UHI) effect. UHI occurs when there is higher air temperature in densely populated urban areas compared to the suburban and rural environments. This phenomenon has become a global issue facing the 21st century (Md Tukiran et al., 2015; Liu et al., 2018). Researchers projected increased temperature levels in the Los Angeles region of up to 2.5 ℃ by 2050 (Gilbert et al., 2016).

UHI has significant impact on human health in addition to causing deterioration in the comfort levels of pedestrians in cities, increased energy consumption of cooling during summer, reduced air quality leading to increased concentration of harmful pollutants, and higher mortality rates due to intense heat and heat waves that cause thermal stress (Buchin et al., 2016). It also has a significant effect on the urban economy (Pasetto et al., 2019).

Engineered pavements with 30% to 45% coverings (Pan et al., 2022b) are considered one of the main causes contributing to the urban heat island effect (J. Yang et al., 2016).

Large thermal inertia and the darker color surface of conventional impervious pavements tend to absorb solar heating, store solar irradiation, and negate evaporation cooling. At night, absorbed solar is released into the urban air thus contributing to the UHI phenomenon.

Recently, several studies have been conducted with the aim of combatting the UHI effect. Some of the pavement techniques have been applied in the field and some others require further investigation (Li, He, et al., 2016). Cool pavement is a valuable technology applied on the ground level to mitigate urban warming. Cool pavement technologies fall into many categories depending on the design, material, mechanical system, and technique. Reflective pavements, evaporation pavements, heat-harvesting pavements, and phase change material are among the main strategies for the cool pavement system (Qi et al., 2019).

Conventional impervious pavements have low initial cost and short project length, but have big thermal inertia whilst the dark color surface of the materials tend to absorb solar heating and store solar radiation, which contributes to the development of urban heat island (UHI) (Qi et al., 2019).

Cool pavements can reduce the UHI effect (Rossi et al., 2018). Reflective pavement has significant advantages, i.e., it is low initial cost compared with other cool pavement techniques and can be easily applied in addition to the existing conventional pavement (Akbari et al., 2016). It can maintain low surface temperature, increase the durability of the construction thus resulting in lower maintenance works, and saves money. High reflectance causes glare and aesthetic problems (Xie et al., 2019). Evaporation pavement keeps the air surface cooler by holding water at the pavement layers to evaporate with high temperatures (Hendel et al., 2016). This kind of pavement will be hot as conventional pavements if there is no water (Yong Liu et al., 2018). It is currently used for walkways, parking lots, and roads with low loads. Continual maintenance is needed to remove the clogging dirt so as to open the porous surface pavement which also means additional cost (Qin, 2015). Other techniques such as phase change material and heat harvesting pavements are under research; since there is no real data provided, further examination in the field is needed (Nwakaire et al., 2020a).

During the construction project, a construction project that balances the environment, economy, and social performance will require the selection of suitable paving techniques to achieve sustainable transportation.

Criteria such as the cost, material, climate of regions, and purpose of use all that are making differentiate the pavement alternatives; for these reasons, this research collects readily available data from previous studies. Furthermore, expert opinion and residents have a direct influence on pavement selection and are used to fill out missing data. Various pavement technical information are integrated to choose the best alternative among the many conflicting criteria by using a multi-criteria decision-making (MCDM) method, taking into consideration the pros and cons of the base criteria for evaluating the alternatives. The variety of structural elements and a great number of factors influence the choice of an appropriate solution which makes decision-making more difficult.

1.3 Problem Statement

First of all, performance of a pavement changes during the day, time, location, and seasons. The UHI phenomenon can happen over the year. It is stronger during the night with regions covered by conventional pavement (asphalt, and concrete) causing high heat capacity (Nwakaire et al., 2020a). Meanwhile heat harvesting pavement and phase change material pavement reduce UHI intensity during the daytime (Qi et al., 2019). Phase change material (PCM) absorbs part of the heat during a hot summer day and releases again to the ambient when the environment temperature drops at night time; the latent heat released does not significantly affect the surface temperature (Tsoka et al., 2018). On summer days conventional pavements tend to absorb and store solar radiation more than on winter days thus making UHI more intensive (Wu et al., 2017).

Secondly, there are several factors have impact on pavement performance such as the wind, shading, and water. Some types of pavements such as permeable pavement use water to cool the surface via evaporation whereby water is withheld in the pores (Qin, 2015; Cortes et al., 2016; Cortes et al., 2016; Anupam et al., 2021). When the pavement layers lose the water, it will result in a hot surface which is even hotter than impermeable pavement (Junsong Wang et al., 2018). During windy days, open permeable pavement cools down again (Wu et al., 2017). Integrating shading with most of the pavement helps to reduce air surface temperature, thus providing thermal comfort (Battisti et al., 2018; Zhao & Fong, 2017).

Next, a trade-off happens as a result of the assessment criteria's opposing associations. Conventional pavements (Concrete pavement, Asphalt pavement) are commonly used in different regions. Flexible pavement (Asphalt pavement) is more common because of its short construction length and lower initial cost than rigid pavement (Concrete pavement); however, rigid pavement is more long-term, and more initial cost compared with flexible pavement and thus required less maintenance (Ibrahim et al., 2018). Although, the maintenance cost of flexible pavement is inexpensive, it requires a higher frequency of maintenance (Ibrahim et al., 2018). Another economic benefit of rigid pavement is vehicle fuel saving on the rigid pavement; it has been reported that truck fuel savings can come up to 15% (Ibrahim et al., 2018). The lower usage of fuel results in lower associated emissions, thus resulting in lower environmental impacts. In short, rigid pavements are more environmentally friendly. Additional rigid pavement outperforms safety terms (Yong Liu et al., 2018). Then the new rigid pavement has more reflectance than flexible pavement causing the dark color; reflectance with aged concrete pavement decreases because of dirt, and increases with asphalt pavement because the aggregates become exposed (Mohajerani et al., 2017). Both of them are considered the biggest contributor to the UHI effect (Kolokotsa et al., 2018).

On the other hand, researchers found that cool pavement techniques contribute to the decrease in heat emissions to the environment; some of these strategies were applied on the ground and others only have lab results (Plati, 2019). Generally, contractors are worried about working on cool pavements due to the extra cost and performance risk (Qin, 2015). Reflective pavement can simply be applied on new or existing pavements, with no limit to special climate regions, low initial and maintenance costs and convenient construction, safe driving, and energy-saving for roads at night (Yong Liu et al., 2018). However, it causes glare problems in the daytime because of reflective visual light (Xie et al., 2019). A surface with high albedo reflects solar radiation and keeps the surface cooler than conventional pavement, and has the capability to reduce heat release thus lowering impact on the environment; at the same time, the re-radiation of solar radiation cause discomfort for pedestrians (Taleghani & Berardi, 2018; Taleghani, 2017). Albedo efficiency reduces with the time consequence of weathering and aging, but the surface remains cooler than conventional pavement. Secondly, permeable pavement is considered an effective solution for thermal discomfort and glare faced with reflective pavement but has a negative impact when there is water loss (C. Wang et al., 2021b). It also helps reduce traffic noise and the risk of hydroplaning (Nwakaire et al., 2020a). It saves energy for cooling usage, but incurs extra cost for yearly implementation and maintenance, in addition to a complex implementation (Qin, 2015). It can only be used with low traffic loads. Harvesting and phase change materials (PCM) cools the pavement during the daytime. Due to its high cost and risk implementation, it cannot be used on high volume roads. All these factors make them difficult to market.

Every single one of these techniques has advantages and disadvantages related to the climate, ability to provide the material, purpose of the used area, complexity in applying, and the age of the structure. There is also the need to examine their impact on the people, the environment, and social system of cities (Akbari et al., 2016). Therefore, the selection process is rather complicated.

Additionally, there is no standardization for cool pavements (Xu, Wang, Xiao, Ei-badawy, et al., 2021). There is a lack of information regarding the UHI effect in many cities, and inadequate comprehension regarding some types of cool pavement (Ibrahim et al., 2018; Anupam et al., 2021; Wang et al., 2021; Wardeh et al., 2022). This indicates that as each form of pavement is considered to be unique. To date, no study has presented an evaluation framwork for selecting the most optimal pavement technique to be utilized as a way to achieve sustainable cities and communities transformation as a part of sustainable development goals, considering multicriteria evaluation of pavement techniques and sustainable solutions. No valid attempt has been made to consider all evaluation and selection issues. Thus, the evaluation and selection of pavement type technique is a complex multi criteria decision making (MCDM) issue because every pavement type is treated as different from the other. MCDM approach must be used to evaluate and choose the best paving technique.

1.4 Research Questions

The determination of the type of pavement is an important part of managing the transportation infrastructure since it has a direct impact on the environmental, social, economic, and efficiency of roads. The best pavement technique must be chosen in order for pavements to function well and endure as long as feasible. The three key questions listed below can assist to choose the appropriate alternative among numerous parameters by guiding the decision-makers.

- What are the key parameters that affect the selection of pavement technique types? And how can expert opinions be used to identify the most effective criteria for evaluating pavement performance?
- How to weigh pavement evaluation criteria? And how can be ranking pavement techniques?
- How does changing the weights of criteria affect the results of the proposed MCDM model, and how can the efficiency of the approach be validated through sensitivity analysis?

1.5 Thesis Objectives

This research aims to develop new multi-criteria decision-making framework for pavement technique selection based on two new developed formulation (DH-FWZIC and DH-FDOSM). It can be applied to projects building roads and highways. The objectives are as follows: -

- To identify and prioritize the key parameters influencing pavement technique selection using a comprehensive literature review, expert opinions, and data analysis.

  A systematic literature review is conducted to collect all articles related to the research scope and to identify the various pavement types as well as the criteria related to the alternatives. Filtration extracted criteria through expert opinion are derived to identify the most effective criteria for on pavement performance.

- To develop an innovative and comprehensive MCDM framework for pavement technique selection considering multiple criteria and stakeholder perspectives.

  A new formulation of multi-layer dual hesitant fuzzy weighted zero-inconsistency (DH-FWZIC) is developed which can be used for weighting the pavement evaluation criteria.

  A new formulation of a dual hesitant fuzzy decision by opinion score method (DH-FDOSM) is developed which can be used for ranking the pavement techniques.

  A novel pavement technique selection based on a formulated decision matrix using DH-FWZIC and DH-FDOSM is developed.

- To evaluate and validate the developed MCDM framework through sensitivity analysis, comparison with previous studies, and focus group discussions.

    A sensitivity analysis- is used to validate the MCDM framework based on changing weights of criteria to examine the different results and prove the efficiency of the proposed approach.

    A comparison study- to compare the used methods in this study with other well-know DH-based MCDM approaches to demonstrate the stability and superiority of the DH-FWZIC and DH-FDOSM methods over other MCDM approaches.

Focus group discussion- A group of construction professionals with in-depth knowledge and expertise in the area of the study were given the produced framework; their responses and feedback were gathered and taken into consideration to strengthen the study's model.

1.6 Significance and Contribution

The current literature shows the different types of pavements with various criteria which control pavement performance, including the impact on UHI. However, to date, most of the pavement designs and selections have neglected the effect of the pavement on UHI. Furthermore, the current literature on this new alternative pavement research and UHI is segregated, where most of the research tends to study an individual type of alternative pavement. It is the firm basis of this research that these criteria of pavement need to be integrated into a single model, comprising UHI, urban surface, air temperature, canyon, age, physical properties, environment, day and night ratios, season, human comfort, strength, driving safety, economic and energy usage, initial cost, maintenance, implementation, shading, and pavement limitation. The novelty of this study is:

1- Integration of sustainability parameters of pavement techniques in a new development of formulation of the decision matrix (Ismael et al., 2023). The paper (Farhadi et al., 2019) studied mitigating UHI to reduce average air temperature. The paper by (He et al., 2021) studied UHI adverse impacts on human thermal comfort. And the paper by (Xu, Wang, Xiao, EI-Badawy, et al., 2021) studied UHI significant impact on energy consumption, and. All three elements environmental, social, and economic have been combined in a new development of formulation for pavement selection.

2- The new developing formulation of a multilayer dual hesitant FWZIC (DH-FWZIC) for weighting the pavement techniques, and a dual hesitant FDOSM (DH-FDOSM) for ranking the pavement techniques (Ismael et al., 2023). Variable factors such as changes in the place, climate conditions, purpose of use, economic factors, impact on the human and thermal environment, and a variety of factors influence pavement performance. Subjective evaluation is the best option for evaluating the selected criteria depending on human opinion. As a result, the selection policy in this study evolved into an extensible model that offers a structured quantitative methodology for huge, complex projects outside the bounds of the narrow scope.

3- Developing a novel pavement technique selection based on a formulated decision matrix (novel 1) using the two developing formulations DH-FWZIC and DH-FDOSM (novel 2) (Ismael et al., 2023). To date there is no integrated framework of the effect of pavement on UHI. This study uses MCDM framework to integrate the factors affecting UHI from pavement into one single model which can be used for decision making purposes. This can provide decision-makers insight when assessing new pavement technologies and their effect on UHI during the design stage.

1.7 Research Scope and Limitations

The research study involves sequential steps to support and make the right decision related to suitable selection of pavement techniques as part of sustainable development goals (SDG) to achieve sustainable cities and communities transformation. Cities are particularly vulnerable to climate change, but most cities are far from meeting the triple objective of being economically productive, socially inclusive and environmentally sustainable. Sustainable and efficient mobility is a second priority in sustainable cities and communities transformation after water matter. This includes infrastructure for roads, railways and ports, as well as public transport systems and ride-sharing. Therefore, cities need to enhance resilience against climate change and extreme weather events. By suitable pavement selection is a critical aspect of transportation infrastructure planning and requires a comprehensive evaluation of sustainability performance parameters beyond just design and loading considerations. Regardless, the current lack of comprehensive evaluation of environmental, social, and economic factors of pavement types still presents a significant knowledge gap. In addition, the opposite association among measures produces a tradeoff among the evaluation criteria of pavement performance evaluation that will impact directly pavement performance changes with time and place differences.

However, the scope of the study is limited to select conventional pavements flexible/asphalt, rigid/concrete, or modified pavement reflective, and evaporative, i.e., pavement techniques which includes cooling pavements. Other cooling techniques such as reflective roof coating, green area, and blue area are not taken into consideration.

This study focuses on assessing the sustainability performance parameters of different pavement types, including environmental impact, social considerations, and cost factors, to aid in decision-making for selecting the best pavement type for a specific area. The integration of these parameters provides a valuable insight into sustainable pavement selection, but it is important to note that further research is necessary to combine this sustainability framework with design parameters to fully identify the most suitable pavement type for a given area.

This study limitation is on the impact of the variable criteria on the environmental, social, economic, and efficiency of roads. Some of the cooling pavements such as heat storage modified pavements that have recharged underground water, and energy generated are beyond the scope of this study because there is missing information and no actual data.

An appropriate alternative is selected by developing an MCDM framework. Since we are working with a human perspective, we have to start with one of the techniques to measure subjective opinion. In this study, a fuzzy weighted zero-inconsistency (FWZIC) is used because it has zero inconsistency problem. Concerning ranking alternatives, a fuzzy decision-by-opinion score method (FDSOM) is used to provide logical decisions based on the expert opinion. Additionally, it can deal with inconsistent behaviour for the human approach, and cuts down on the time needed to perform comparisons. Moreover, it decreases the number of the mathematical equations. Furthermore, by using fuzzy numbers, the vagueness of the data can be overcome.

The case study or data collection is conducted in the United States. More mature pavement technologies can be found in Phoenix, Arizona (J. Yang et al., 2016), the Los Angeles county, El Monte in California (Taleghani et al., 2016), and Sacramento, Los Angeles in California (Li, He, et al., 2016).

1.8 Thesis Organizational

Chapter 1 of this thesis begins with the background of the research problem, which establishes a problem statement for the scope of our study. The course of this study is drawn by three objectives. The novelty is shown in a brief paragraph describing the importance and contribution. Followed by the scope and limitations of the research. The essential topics are covered in chapter 2, which is important for comprehending the problem statement. A systematic literature review (SLR) was performed to gather previous studies from multi-sources. The current approaches to pavement technique selection were further explored by analysis challenges, motivations, and stockholder's issues. Furthermore, multi-criteria decision-making methods in pavement technique scope are reviewed. Chapter 3 the main topic is the strategies used to achieve each objective. The process of data collecting is explained, and a flowchart of the research methodology is displayed to show the procedures that were done during the research. Chapter 4 discusses the analysis of the acquired data, identification of the criteria, and sub-criteria affecting pavement performance. Sensitivity analysis and comparison analysis study applied to evaluate developed framework. Chapter 5 concludes with a summary of all the findings on the planned knowledge activity, contribution to the body of knowledge, limitation, and future recommendations.

1.9 Summary of Chapter

This chapter clarified the introduction for the topic of the study followed by a brief background of the study area started with the main topic of global warming, factors help to develop the UHI issue, caused on human health, environment, economy, and the strategies to reduce that effect as well the methodology used in that purpose. The problem statement section explains in detail the previous studies problems divided into four sections. first performance of a pavement change with the day, time, location, and seasons. Secondly, there are several factors that affect pavement performance such as the wind, shading, and water. Third, a trade-off occurs due to opposite association among the evaluation criteria. Fourth, there is no standardization for cool pavements and a lack of information regarding the UHI effect in many cities. Next section proposed three research questions followed by three objectives. Followed by three contributions novelty, Integration of sustainability parameters of pavement techniques in a new development of formulation of the decision matrix, new developing formulation of a multilayer dual hesitant, and developing a novel pavement technique selection based on novel 1 and novel 2. have been explained in significance and contribution section. This study was limited to select conventional pavements flexible/asphalt, rigid/concrete, or modified pavement reflective, and evaporative. As well as study the impact of the variable criteria on the environmental, social, economic, and efficiency of roads. Last section in this chapter is thesis organizational to give a general idea about the content of each chapter in this thesis.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

The purpose of this chapter is to review the background for our research scope by studying previous works and discussing them to inform the literature part in this research. A systematic review is employed to obtain all articles and efforts that have been done related to pavement technology types associated with urban heat islands (UHI). Moreover, focus will be on studies that had used the MCDM approach in the construction sector. All these articles are combined in this study. As such, we cover all pavement studies for both research and theoretical sides.

2.2 Overview Background of Roads

Daily traveling and transportation-related activities rely heavily on the pavement as a type of shared public transit infrastructure. Conventional pavements, also known as impermeable pavement, make up a sizable portion of cities including highways, parking lots, and driveways, all of which have increased dramatically as a result of global urbanization and industrialization. The percentage of people in the globe who live in cities has risen above 50% today. By 2050, this percentage is anticipated to reach two-thirds (De Pascale et al., 2023). Cities that are more densely inhabited create additional highways, structures, and infrastructures that supplant greenery and urban green spaces. Critical components of the transportation infrastructure are pavements. Highway spending in the United States in 2017 totalled US$181 billion, making it the highest infrastructure expenditure (Salehi et al., 2021).

Conventional or impermeable pavement has a surface that is dark in color and has high thermal inertia, which results in reduced infiltration, drainage, and heat dissipation, leading to continuous solar thermal radiation absorption and a rapid rise in surface temperature (Guan et al., 2021). This is likely to worsen the urban heat island (UHI) effect and cause the pavement to permanently distort.

2.3 Urban Heat Island (UHI) Phenomenon

The urban heat island (UHI), a phenomenon where the urban temperature is much greater than that of the surrounding suburban area, is a well-known urban climate disaster (Shimazaki et al., 2021). UHI is widely acknowledged to be a result of both climate change and urbanization. Researchers have progressively been to paying attention to the UHI problem as it has grown more problematic since the 1980s (He et al., 2021; Qin et al., 2022). As a result of changing land use patterns, accelerating urbanization, and dwindling plant and water supplies, UHI has dramatically grown over the past ten years (Battista et al., 2023). Changes in urban undersurface features, urban air pollution, irrational urban design, and artificial urban heat sources are the biggest factors of UHI (He et al., 2021). One of the most significant of them is the alteration of urban subsurface characteristics (Tan et al., 2021; Qin et al., 2022). For the scientific planning of urban buildings, an accurate assessment of the UHI effect is necessary. Millions of people around the world are currently being impacted by the UHI phenomenon. In comparison to the nearby countryside, temperatures are higher in urban areas. The UHI impact has posed a serious hazard to human living. Numerous research that looked at how UHI affected locals showed that it worsened thermal comfort, raised pollution levels, and put human health at risk. In addition, it was discovered that UHI would increase energy demand on days with high temperatures, with an increase in power consumption of 0.45% - 4.6% for every degree of outdoor thermal air.

Figure 2.1 shows the annual worldwide temperatures from 1880 to 2022 compared to the average in the 20th century. Since 1880, the average surface temperature has increased by 0.14 degrees Fahrenheit per ten years. Since 1981, the rate of warming has more than doubled according to the data reported by the National Centers for Environmental Information, National Oceanic and Atmospheric Administration.

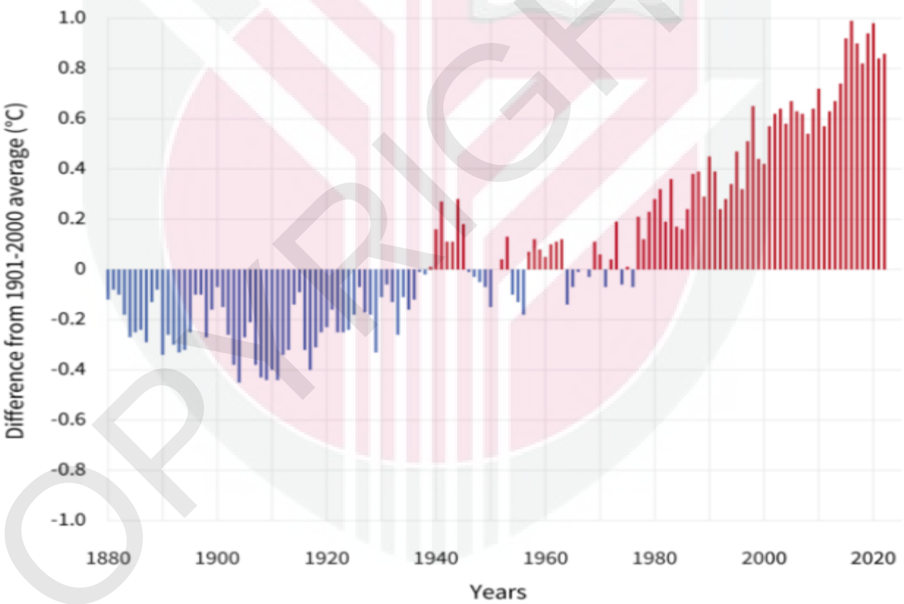


Figure 2.1 : Global Average Surface Temperature (Climate.gov, 2022)

Figure 2.2 shows the temperature changes on the surface between 1993 and 2022. Oceans warmed more slowly than land regions overall. The portions in dark red are the northern high latitudes whilst the portions of Eurasia and the Middle East are subjected to the greatest warming, based on the data reported by the National Centers for Environmental Information, National Oceanic and Atmospheric Administration.

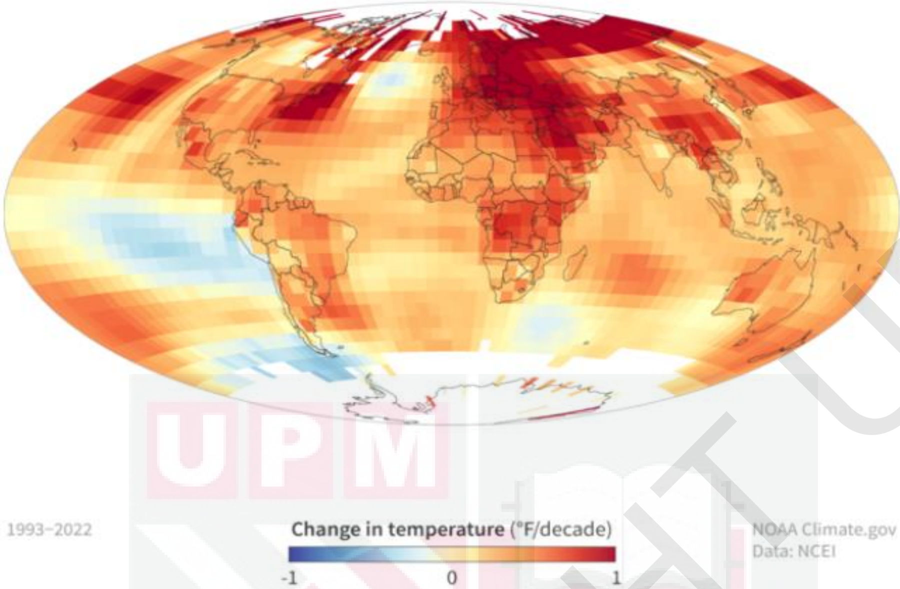


Figure 2.2 : Recent Temperature Trends (1993-2022) (Climate.gov, 2022)

2.4 Overall Climate-Changing Weather Factors

There is evidence that the climate is changing from earlier investigations. For instance, between 1880 and 2012, the average global surface temperature increased by 0.85 °C, and in more recent decades, the rate of change has accelerated. Globally, the sea level has been increasing, and many areas have seen an increase in the frequency of extreme weather events including floods, hurricanes, and heat waves. Climate change will likely to continue in the future (Qiao et al., 2020). Pavements are climate-sensitive infrastructure, and climate can affect their rate of deterioration, subsequent maintenance, and life-cycle costs. Weather temperature directly affects the temperature of the pavement and depends on energy balance, particularly on the pavement surface. A pavement surface's reflection coefficient (albedo) is essential to determine how much solar energy is absorbed. This may be a significant factor in determining the maximum pavement temperature. The amount of heat that is lost through convection and radiation from the pavement depends on the air's temperature and the wind's velocity. Most people agree that increased wind speed is good for pavements since it can lower the temperature of the pavement surface. When the ambient air temperature is higher, such as during the daytime or on a sunny day, the variance is greater. One of the most crucial elements influencing the design and performance of rigid and flexible pavements is pavement temperature (Qin et al., 2022). Engineers working on urban planning and design can benefit from accurate pavement surface temperature predictions based on variables like air temperature. The most frequent climate stressors, according to the literature temperature and moisture are often the factors that affect pavement performance the most, and the long-term effects of climatic stresses can be significant.

2.5 Greenhouse Gas (GHG) Emissions

In addition to being impacted by climate change, pavements can also cause it. At various stages of a pavement's life cycle, a significant amount of greenhouse gases (GHG) are released. Asphalt pavement is the most common type of surface structural layer in modern road structure designs and is extensively used in the expressway and urban road networks. In 2019, 420 million tons of asphalt mixture were manufactured in the United States and utilized on 80% of airport runways and 94% of public highways. According to data from 2020 compared to 1990, the US transportation sector significantly increases GHG emissions by 49% (Climate.gov, 2022) as shown in Figure 2.3.

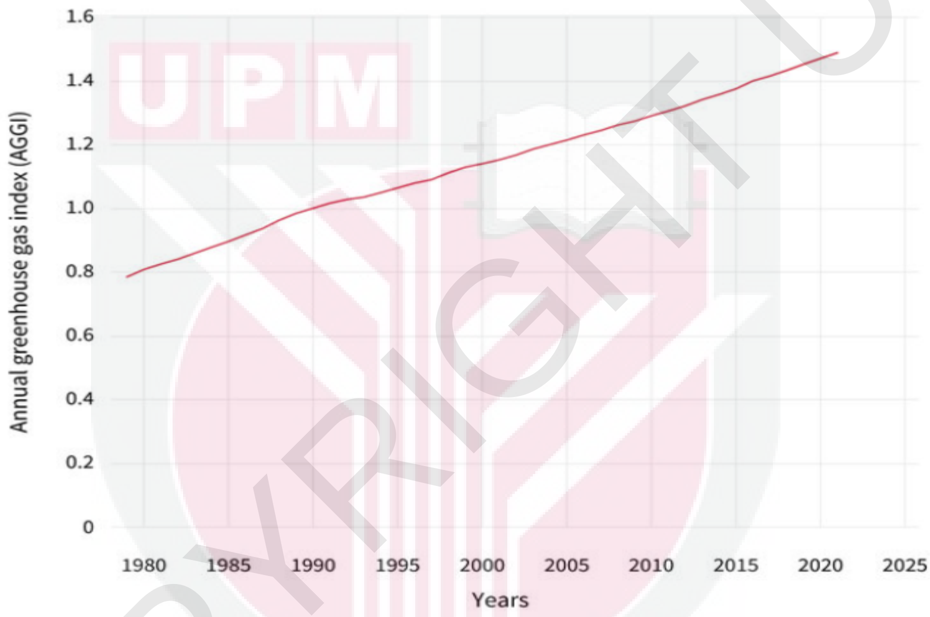


Figure 2.3 : Annual Greenhouse Gas Index (Climate.gov, 2022)

The graph's colorful shapes in Figure. 2.4 depict the relative contributions of several greenhouse gases to the overall energy imbalance in the Earth's atmosphere. When compared to 1750, these gases together contained roughly 3.2 Watts of heat energy per square meter in 2021.

Therefore, any modifications to the pavement that can lower these emissions will probably significantly reduce GHG warming on heavily traveled highways. To slow down the process of climate change and urban warming, mitigation involves actions to reduce highway GHG emissions throughout their lifetimes as well as the heat storage capacity of pavements. The purchase of raw materials, production, transportation, operation, maintenance, and end-of-life recycling are only a few of the phases of a pavement life cycle where GHG emissions may occur.

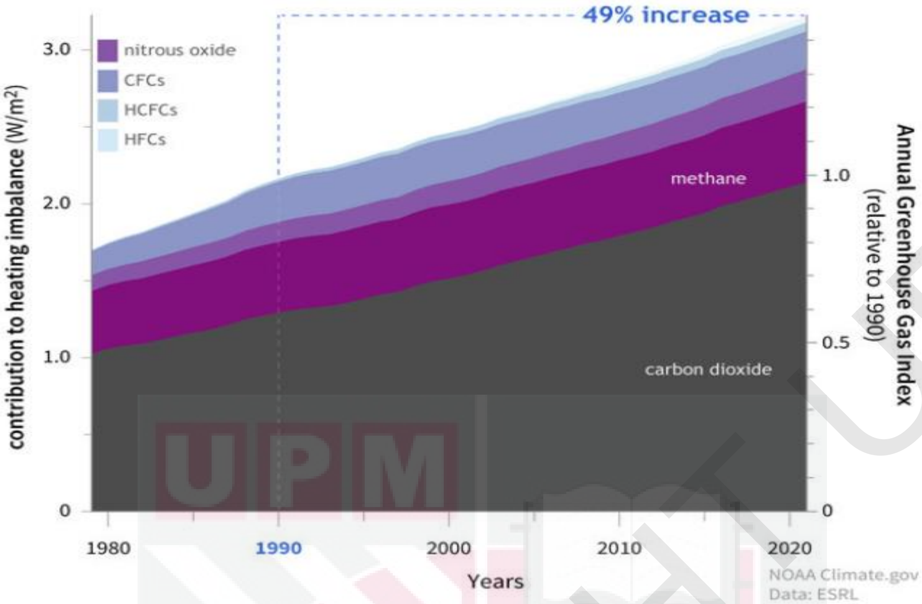


Figure 2.4 : Combined Heating Influence (Climate.gov, 2022)

2.6 Conventional Pavement

Urban pavements mostly use asphalt concrete with poor albedo. The radiant heat that the pavement surface absorbs throughout the day will be disseminated at night throughout the entire city as longwave radiation. Impervious pavements also prevent water from moving freely around the city, which lowers the heat of vaporization and exacerbates the UHI impact (Qin et al., 2022). The pavement's layers convey heat to those beneath them. The temperature profile of the pavement is mostly determined by the heat capacity and thermal conductivity of the paving materials. The urban heat island effect is significantly influenced by the paved surfaces' ability to radiate or convect previously absorbed heat, hence albedo and the thermal properties of the pavement materials are also indirect local warming factors.

2.7 UHI and Climate Impacts on Pavement Performance

As challenges, the assumption of historical local climatic conditions has virtually always been used in the design and upkeep of these pavements. The need to adapt pavement infrastructure to the changes brought on by climate change cannot be overstated. Environmentally sensitive infrastructure includes flexible pavements. Inversely, pavement deterioration can happen more quickly when environmental circumstances alter negatively. The expense of resolving this may be increased for road authorities in areas where the detrimental modifications would take place. Without maintenance, users will be responsible for paying the price in terms of losses like increased fuel usage, safety risks, and lost time. This implies that extra funds will be required in the future for climate adaptation and mitigation on a national scale as the total expenditures associated with climate change could rise significantly (Qiao et al., 2020).

In general, environmental conditions can be directly impacted by climate change, which can impact pavement performance. Climate stresses can disrupt a pavement's energy and moisture balance, which in turn can modify the pavement's long-term performance (i.e., the direct impact). The modulus of an asphalt mixture varies with temperature as is usual for materials that are temperature sensitive. As a result, the temperature has a big impact on the load-carrying capacities and pavement performances of asphalt pavements. The temperature distribution within the pavement is also directly or indirectly related to several typical types of damage to asphalt pavements, including low-temperature cracking, high-temperature rutting, and fatigue damage.

Flexible pavements may experience indirect effects of climate change. Indirect effects include variations in vegetation shade because of growth disparities brought on by climate change, following population changes brought on by migrations connected to the environment. Migration brought on by climate change is thought to have an impact on the population of particular regions and the evolution of local transportation demand. Pavement damage is primarily caused by traffic, particularly heavy-load vehicles. As a result, there may be a big indirect effect of climate change on the functionality of flexible pavements.

In the area of pavement studies, it is well-acknowledged that the pavement layers are mostly affected by temperature. For example, rising temperatures may cause asphalt materials to become less stiff, which may limit the pavement's capacity to respond to stress and strain and lessen the ability of a pavement structure to distribute loads (American Association of State Highway and Transportation Officials, 2015) (Gong et al., 2023a). In extreme circumstances, where the temperature experiences considerable daily/hourly rises, it is possible to anticipate a rapid onset of permanent deformation. As a result of rising temperatures brought on by climate change, asphalt layers may be subjected to greater thermal stresses, increasing the risk of thermal cracking. Additionally, hotter temperatures can expedite the aging of asphalt mixtures and make pavements more brittled, increasing their susceptibility to cracking (Abouelsaad & White, 2022).

2.8 Internal and External Factors Impacts on Pavement Performance

Outlining the factors that impact pavement temperature is necessary for urban design that reduces UHI. Micro-meteorological factors such as air temperature, solar radiation, relative humidity, and wind speed are influenced by urban morphology and its features when it comes to evaluating thermal comfort (Huang et al., 2023). To increase outdoor thermal comfort and inhabitants' quality of life, UHI mitigation techniques must be incorporated into urban planning. Urban planners have put out many measures to reduce UHI in the last few decades, such as raising the amount of green shade on the pavement and adopting high-albedo pavements to lessen heat storage (Shao & Kim, 2022). Additionally, by properly planning metropolitan areas, the surface temperature can be lowered. By aligning the design of the building with the wind conditions, the wind speeds surrounding the buildings can be raised. Future urban planning must place a high priority on the choice of pavement materials because they are important in urban settings (Ghenai et al., 2023). The outcome of the thermal material parameter analysis is that material selection and sensible structure combinations can actively manage pavement temperature, hence lowering UHI. Increasing albedo percentage can help to reduce pavement surface temperatures. Albedo has the largest impact on the temperature field of the whole pavement structure (Mohammad et al., 2021).

2.9 Pavement Sustainability

Pavement sustainability is inevitably one of the highest-level issues for a transportation infrastructure system and not just an added feature because sustainability is a system characteristic that alludes to the triptych, often known as the "triple-bottom line," which consists of economic, environmental, and social dimensions. Sustainable refers to the effects on the environment, economics, and society at all stages, including material selection, design, construction, as well as preservation measures, in the transportation sector as a structural infrastructure, more specifically on pavements. The sustainability triple bottom line is depicted in Figure 2.5 below.

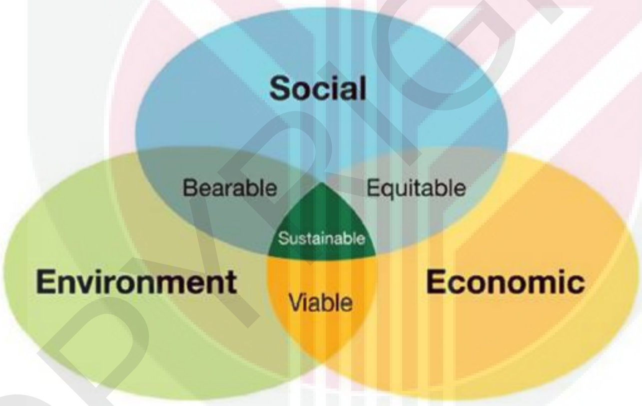


Figure 2.5 : Sustainability Triple-Bottom Line (Plati, 2019)

Because these three fundamental factors are difficult to measure, it is more challenging to achieve sustainability targets for pavements. For instance, it is challenging to evaluate social and environmental implications properly, and it is still not viable to optimize these areas. There are many trade-offs to be thought about as a result. To help advance sustainability generally, businesses, organizations, agencies, and worldwide political policies must cope with these trade-offs. Although there are no clear guidelines or criteria to precisely define sustainability, it is a good idea to keep in mind that none of these factors should be ignored. In the absence of these, the intended outcomes would not be achieved, and a durable solution might not be found (Qin et al., 2022).

The Brundtland Commission Report (Chatterjee, 2011), which is frequently used as the starting point for definitions of sustainability, was published by the World Commission on Environment and Development (WCED) and may be found here:

"Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs."

This definition focuses on the idea of "needs" and the constraints placed on the environment's capacity to supply present and future needs by the state of technology and social structure. For a long time, the economic component dominated the decision-making process, but in more recent years, the environmental and social components have begun to gain ground (even though there are some current limitations associated with their measurement and assessment). Consequently, a focus on sustainability can be interpreted to mean that all elements of the triple-bottom line are important. However, the relative importance of these factors (and how each is considered) depends heavily on the objectives, requirements, characteristics, and constraints of a particular project.

According to (Acai et al., 2019), "sustainability" in the context of pavements refers to system qualities that include a pavement's capacity to:

- Meet the engineering objectives for which it was built.
- Maintain and, preferably, restore the environmental in the area.
- Make prudent use of the environmental, human, and financial resources.
- Provide for fundamental human needs including enjoyment, comfort, and work, as well as for equity, safety, and health.

2.9.1 Pavement Live Cycle

For benchmarks to be set and progress to be evaluated, sustainability must first be "measured"(Heidari et al., 2020a). The assessment and definition of pavement sustainability can be done using a variety of measurement methods and techniques, each of which has advantages and disadvantages and can be used alone or in combination. The following is a description of the most useful measures or techniques for quantifying sustainability-related factors:

Performance Assessment: the evaluation of pavement performance in terms of intended use is known as performance assessment. The way that performance is evaluated is most frequently in comparison to the industry norm. For instance, if the current standard asphalt pavement surfacing is predicted to last 15 years, the value of an alternative surfacing (such as an open-graded friction course, stone matrix asphalt, or rubberized asphalt concrete) is based on the projected service life of the considered alternative relative to the 15-year service life of the standard surface. The most prevalent belief is that alternatives must perform equally with or better than the presently accepted approach Performance may also be discussed in terms of particular physical characteristics (such as the structural capability of pavement, material characteristics, and condition or distress measures), as well as the behavioural mechanisms connecting these characteristics to anticipated performance.

Analysis of Life Cycle Costs (LCCA): Economic analysis is used in the LCCA analysis technique to determine the overall cost of an investment choice in constant dollars during the analysis. As a result, it primarily addresses the economic aspect of sustainability. The advantages of the options under consideration are assumed to be equal by the LCCA; therefore only costs (or differential costs) need to be taken into account. Clean air and water, habitat impacts and the creation of liveable community circumstances are several examples of societal or environmental issues that LCCA does not directly address unless they can be valued and addressed as expenses. When monetizing environmental issues, care should be taken to avoid duplicate counting, which is sometimes prohibited due to (a) problems in establishing a monetary value and (b) the possibility of double counting when both life-cycle assessment (LCA) and LCCA are carried out. According to their 1981 Pavement Type Selection Policy Statement (Federal Register 1981), the Federal Highway Administration (FHWA) recommends the use of LCCA as a decision-support tool and has supplied instructions in an Interim Technical Bulletin (Walls & Smith, 1998). The FHWA's Real Cost program is the most widely used pavement LCCA software tool (FHWA 2011; Salehi et al., 2021).

Life-Cycle Assessment (LCA). LCA is a method for assessing and quantifying the environmental effects of a system, process, or product. By looking at all of the inputs and outputs throughout the life cycle, from the manufacture of raw materials through end-of-life, LCA offers a thorough method for evaluating the overall environmental impact of a product or process. This methodical methodology locates the most important impacts and areas for change while highlighting potential trade-offs. Although LCA is a field of science that is still developing, it has shown practical value over the past 20 years by assisting businesses, governments, and other organizations in determining what environmental issues are important to them and then outlining the necessary steps to reduce those impacts (Heidari et al., 2020a).

Figure 2.6 describes and outlines the overall pavement LCA technique. The pavement life cycle has been mentioned as a helpful way to explain the steps that a pavement goes through from the beginning of its design creation to the end of its useful life. An LCA examines the environmental effects during the whole life cycle of the pavement.

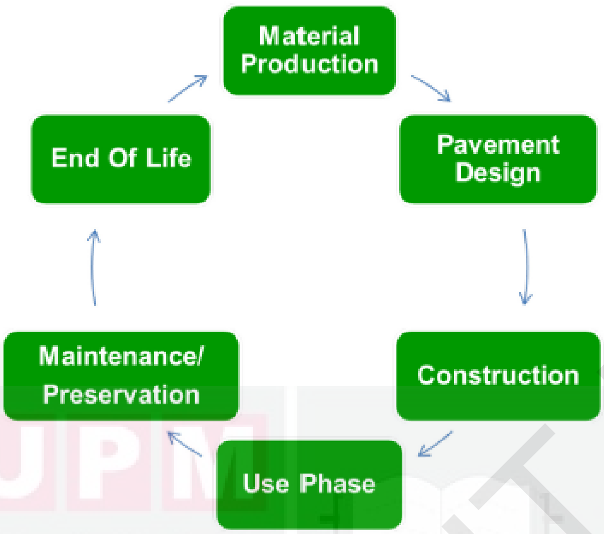


Figure 2.6 : Pavement Life Cycle

- Material Production. The processes involved in acquiring and processing raw materials, such as mining and crude oil extraction, are together referred to as material production.
- Design. The process of determining the structural needs of a pavement for specific site characteristics, such as the subgrade, climate, traffic, existing pavement structure, as well as the selection of the pavement's supporting elements, is referred to as the design stage.
- Construction. All procedures and tools necessary to build the initial pavement are part of the building stage.
- Use Phase. The time when the pavement is being used and interacting with traffic and the surrounding area is referred to as the use phase.
- Maintenance/Preservation. These procedures are used periodically during the pavement's life to preserve its general serviceability.
- End of Life. When a pavement reaches the end of its useful life, it is disposed of in its final location before being reused, processed, or recycled.

The activities of design, building, maintenance, operation, and disposal of the pavement system are interdependent. These other phases as well as pavement deterioration will be impacted by climate change. Hence, in order to create environmentally beneficial and economically viable adaptation and mitigation strategies, it is crucial to comprehend the relationship between climate change and pavement from a systematic perspective. Figure 2.7 illustrates an attempt to describe the interactions.

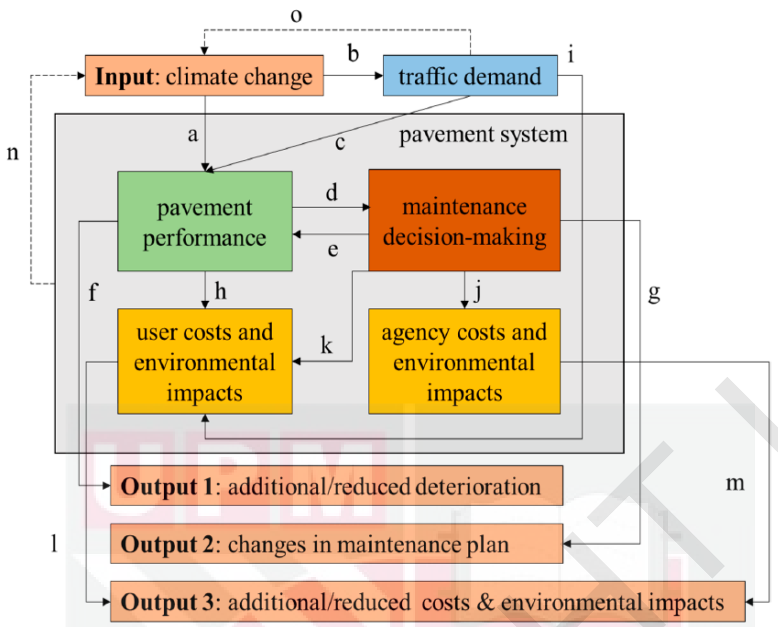


Figure 2.7 : Interactions: Climate, Performance, Maintenance, and Costs
(Qiao et al., 2020)

Figure 2.8 depicts these phases as well as some typical pavement inputs and outputs, along with their further explanation.

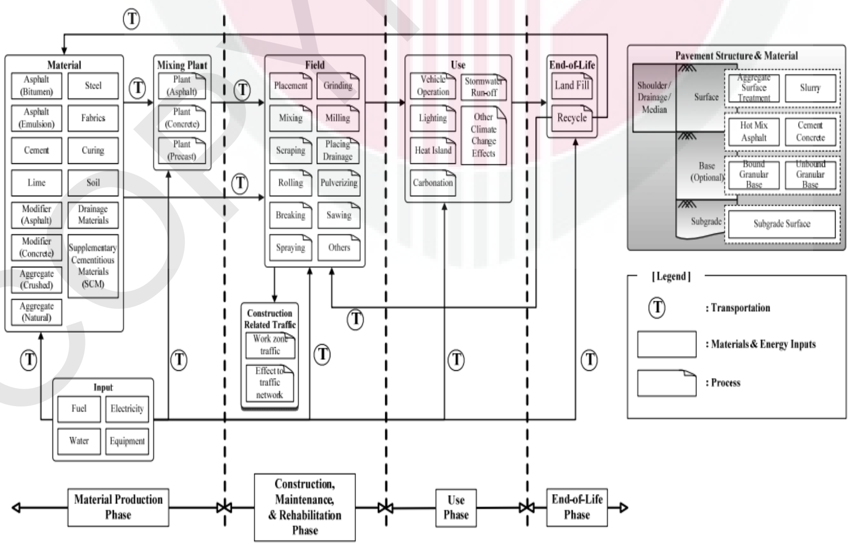


Figure 2.8 : Proposed Framework for Pavement LCA (Harvey et al., 2010)

2.9.2 Sustainability System

Behaviours or attributes that affect sustainability develop a sustainability ranking system. In its most basic form, a rating system may assign equal weight to the application of each best practice (for instance, assigning each one a point), in which case the rating system merely serves as a count of the best practices applied. Rating systems, which come in more complex forms, weigh best practices (typically in relation to their impact on a chosen definition of sustainability or a chosen set of priorities), and these systems can help decide which best practices will have the biggest impact given the available resources.

2.10 Modify Convention Pavement

It may be necessary to alter current pavement design and life cycle management procedures to adjust to changing climates and lessen their negative effects on the environment (Haslett et al., 2021). To lessen the environmental effects of pavements and related transportation on the macroclimate and microclimate, climate mitigation measures are urgently required. The effect of temperature on the mechanical behaviour of various types of pavement under vehicle loading must be thoroughly studied. The previous study used representative climate data for 24 hours in the summer to test the heat exchange theory between pavement and the outside environment. To lower pavement temperature and mitigate the UHI effect, cool pavement with a reflecting coating is crucial to relieve discomfort. In efforts to lessen the effects of urban heat islands, cool pavements have become more common. This adaption technique is usually implemented by applying a high-reflecting coating (high albedo coating) over already-existing pavements. Air temperatures close to pavement surfaces are observed to be reduced by the coating while improving solar energy reflection. The use of such a covering in Singapore resulted in a 17 ℃ drop in asphalt surface temperature. The surrounding constructed environment, however, may get warmer as a result of the reflected solar radiation, therefore this must be taken into account when applying the "cool" coating. The "cool" coating appears to be an effective method of climate adaptation even if it is intended to reduce climate change. Less rutting is anticipated by drastically lowering pavement temperature. Additionally, it has been shown that permeable pavements have a "cooling" effect, which can be exploited to reduce the urban heat island effect. This results from the asphalt concrete using heat as the latent heat of the vaporization of water, hence water is required for this process. Additionally, permeable pavements can drain stormwater faster and lessen the possibility of pavement floods. Additionally, the shade given by buildings and trees can be useful because it is efficient in lowering pavement temperature and, thus, can lower ambient temperature.

In Figure 2.9, two types of cool pavements—reflective pavement with a reflective surface (such as a coating) and permeable pavement with a permeable surface layer (e.g., pervious concrete, porous asphalt, or permeable concrete pavers)—are compared to the conventional pavement (dense graded asphalt or concrete pavement with a low albedo). Reflective pavements, when compared to conventional pavements, have a lower surface and air temperatures mainly by increasing solar radiation reflected (Figure 2.9 a and b), which can affect pedestrian thermal comfort, building energy use, and carbon emissions.

Permeable pavements, in contrast to impervious ones, collect water on their surfaces and permit infiltration into layers below, which lowers temperatures largely through evaporative cooling (latent heat flux); the porous structures of permeable pavements also significantly aid urban stormwater management. (Figure. 2.9 c)

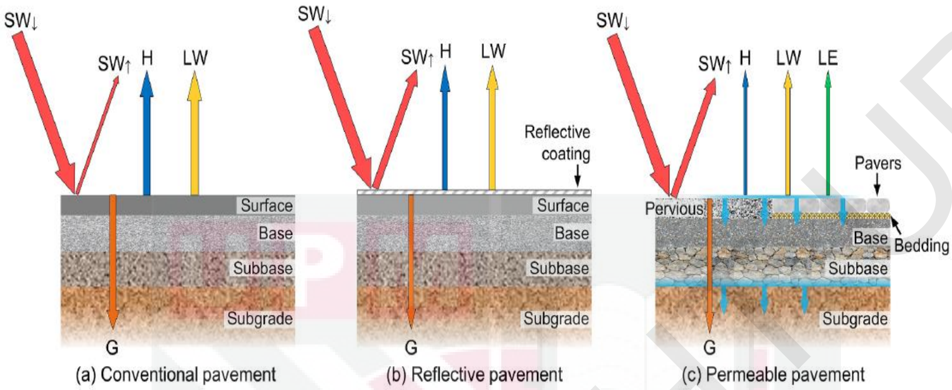


Figure 2.9 : Structures of Pavement Types (C. Wang et al., 2021a)

The following sections provide a comprehensive evaluation of the quantitative and qualitative pavement research that has recently been done on pavement techniques and climate change. Both conventional pavement and cooling pavement have illustrated the problems, projects planned to do it, and who is working on them. All these are explained in the three sub-sections that follow namely challenges, motivation, and stakeholders respectively.

2.11 Cool Pavement Overview Factors and Applications

One of the most significant pavement distresses in cold climates is freeze and thaw damage. Wintertime temperature drops on asphalt pavement might lower the binder's quality requirements. Lower pavement temperatures may limit the thermal strains that concrete pavements experience and the thermal cracking that occurs in flexible pavements (Anupam et al., 2020). To create a better riding surface, the paved surface must be cleared of ice and snow. For this reason, deicing agents and salts, snowplowing, or frequently both, may be utilized. Such techniques are uneconomical, have a negative impact on the pavement's strength, and might have an adverse environmental impact (Anupam et al., 2020). Repeated temperature curling causes transverse, longitudinal, and corner cracks in concrete pavements. It was discovered that a greater temperature differential was the primary cause of the stiffening and formation of cracks.

Effective mitigation strategies include the use of alternate materials or surfaces that can reject the incident solar radiation or the related heat gains in order to offset greater heat temperatures and lower surface temperatures (Santamouris & Young, 2020). According to this scenario, an urban area's energy balance may be changed to maintain a low ambient temperature as well (Wardeh, Kinab, Escadeillas, Rahme, et al., 2022). As a result, it has been thoroughly researched to adjust the thermal characteristics of urban pavements and thereby their energy balance as a UHI mitigation method (Kousis & Pisello, 2023b).

The term "cool pavements" refers to pavements that have been constructed using various technologies and materials to limit or minimize pavement temperature (Anupam et al., 2020). These changes fall under the broad umbrella of "Cool Pavements", which can be classified into: reflecting pavements, evaporative pavements, and energy storage or conversion pavements (Kousis & Pisello, 2023b).

2.11.1 Reflective Pavement Application

Because of its reflected quality, reflective pavement is cooler than other types of pavement techniques. Is typically bright in color and reflects a significant amount of incident sun radiation. Thus, it returns less sensible heat to the lower levels of urban canopies and lowers the air temperature above them (Calis et al., 2022). The bulk of the documented reflective paving solutions are created by adding reflective coatings to currently installed conventional pavements or by enhancing the texture of the pavement by changing its thickness and building materials (Qi et al., 2019). A quick and easy way to increase pavement reflectance without changing its mechanical characteristics is to apply reflective coating. A reflective pavement's reflectance is finely controlled over the solar radiation's wave range. Since the only area that human eyes detect differently is high visible radiation reflectance, it may result in glare problems or discomfort. Near-infrared radiation has a higher power than visible light, yet it cannot be seen by humans. The near-infrared portion of the incoming radiation is so substantially reflected by cold coatings, according to research. Additionally recently described as possible advanced cool pavement candidates are retro-reflective and photoluminescent materials (Kousis & Pisello, 2023b). Retroreflective pavements can reduce solar radiation by reflecting it in a certain direction. Retroreflective pavements can reduce potential inter-building effects by reflecting the incoming solar radiation in a certain direction (Pan et al., 2022a). On the other hand, photoluminescent pavements simultaneously re-emit some of the incoming radiation in addition to reflecting it, according to (Chiatti et al., 2021). In fact, a promising radiative cooling method that is anticipated to be instrumental in the reduction of UHI is the tailoring of a surface's emission spectra within particular confines, such as the air window, and combining it with high solar reflectance (X. Yu et al., 2021). Additionally, thermochromic components are evaluated for cool pavement applications and are discovered to adjust surface temperature in accordance with preferences, extending the pavement's lifecycle (Kousis & Pisello, 2023b).

2.11.2 Evaporation Pavement Application

Another well-liked Cooling pavement method is to make the pavement evaporative. Due to the water being caught by the pavement throughout its transition from liquid to vapor, evaporative cooling can be successful through latent heat flux buffering. Since their cooling impact depends on water availability, they are better suited for regions with frequent rain and high humidity. According to impact (Anupam et al., 2020) evaporative pavements can either be porous and pervious (allowing water to travel through them), permeable (allowing water to pass around them), or water-retaining (holding water in their top layers) (Kousis & Pisello, 2023b). As a cellular grid system, porous cooling pavement is typically produced. The system that has been designed consists of interlocking blocks with a circular space in the center that is filled with sand, gravel, soil, or grass. They can therefore store sufficient water for evaporative cooling. With a large void content and a typical construction of asphalt or concrete, pervious cooling pavements are a subtype of porous pavements. They may therefore percolate and hold more water than traditional porous pavements while also reducing surface run-off and deep drainage processes (Lu et al., 2019). To lessen aquaplaning and improve pavement friction, permeable asphalt-based mixtures, such as open graded friction courses, are frequently employed. They can, however, retain and move water in the lower layers surrounding the pavements because of the air gaps. Various other evaporating By creating a permeable surface layer on top of an impervious bottom layer, cooling pavements are made to retain water in their higher layers (Kousis & Pisello, 2023b).

2.11.3 Heat Harvesting Pavement Application

Road pavements take up a large portion of urban surfaces in contemporary cities and absorb a lot of solar energy. Pavements can therefore play a significant role in the use of solar energy and act as distributed energy generators in smart and sustainable communities. Pavement-integrated photovoltaic (PIPV), pavement-integrated solar thermal (PIST), and pavement-integrated photovoltaic thermal (PIPVT) modules are a few solar energy harvesting pavement modules that have evolved in recent years (Ma et al., 2022). Conventional pavements, such as those made of asphalt and cement, absorb more solar radiation in the summer than other materials. As a result, they could be used for heat-harvesting purposes to increase the amount of heat released into the atmosphere during the winter. The primary method used to create heat-transfer pavements involves installing water pipes below the pavement's surface to lower pavement temperature while simultaneously storing and using the equivalent transferred energy. As a result of reducing the quantity of heat released back from the pavement due to heat energy harvesting, the air temperature above the pavement may be lowered. The local microclimate boundary conditions, in particular the amount of solar radiation, ambient temperature, wind speed, pavement surface temperature, pavement material, the layout of the heat exchanger, and the system's circulating water flow rate, are the primary factors that control the heat transfer performance of energy harvesting applications (Kousis & Pisello, 2023b).

The first category consists of innovations that employ the mechanical energy that is delivered from moving cars to the pavement. Piezoelectric material embedded in the asphalt or speed bumps that can convert the motion and pressure created by a passing vehicle into energy can both be used to convert the load into power (Vizzari et al., 2021).

The second category includes innovations that make use of the pavement's solar exposure. Solar cells embedded in a semi-transparent covering allow sunlight to be turned into power (Vizzari et al., 2021).

Due to exposure to sunlight, asphalt's surface temperature can rise by about 70 °C, hastening some common road failures like rutting (permanent deformation of pavements) and asphalt oxidation (which results in changes in viscosity, component separation, embrittlement, and loss of cohesion). Asphalt solar collectors are a good way to take advantage of the sun's rays while lowering the temperature of the pavement. They are made up of pipes that are immediately buried in the asphalt and may collect thermal energy from a fluid (in this case, water). Heat is transferred from the pavement to the fluid as a result of the temperature difference between the fluid and the asphalt. Or, to put it another way, a cold fluid enters the system, and a hot fluid exits (Vizzari et al., 2021).

The energy obtained from the asphalt solar collectors could be used for snow melting systems or for the heating system of the adjacent buildings. The solar collectors can also be embedded in concrete pavements, but they are less performant because the concrete's solar absorption coefficient is lower than asphalt (Vizzari et al., 2021). The heating systems of the neighboring buildings or snow melting systems could both benefit from the energy produced by the asphalt solar collectors. Since concrete absorbs sunlight less efficiently than asphalt, it is possible to incorporate solar collectors in concrete pavements as well (Vizzari et al., 2021). The asphalt pavement, the pipes, the air in the atmosphere, and the fluid flowing through the network of pipes are all included in the energy balance of an asphalt solar collector. The energy is first balanced along the pavement-atmosphere contact in terms of heat exchange systems. In this instance, the heat flux is brought on by incident solar radiation, air-to-asphalt convection, and asphalt thermal radiation. In exchange, the heat flux alters the pavement's temperature, which triggers a conduction process from the road's exterior to inside. Conduction keeps going in the contact asphalt-pipe before a convection mechanism eventually takes place in the pipe-fluid interface (Vizzari et al., 2021).

For the asphalt solar collectors to capture energy from the pavements, heat fluid is necessary. However, the existence of a break in the pipes could jeopardize the entire system, allowing the fluid to leak and increasing the likelihood that the pavement will fail. Due to the temperature differential between the outside and the asphalt, there is a difference in pressure between the end of the chimney and the entrance into the pavement when the air conduits are linked to an updraft and a downdraft chimney. The end result is a continual breeze, which can raise the pavement's temperature by 10% during the winter or lower it by 10% during the summer (Vizzari et al., 2021). The drawbacks of using a porous layer as a solar thermal system is the porous layer's weak strength.

Moving on from the observations, the challenge for photovoltaic roads is the mix-design of an innovative semi-transparent layer with low power loss and distinguished by high aging resistance, while the challenge for porous solar thermal systems is to maximize the porosity (using porous concrete) while maintaining an adequate strength.

The semi-transparent layer appears to be crucial for both the thermal transfer in deeper layers and the photovoltaic efficiency. Therefore, from the perspective of research, the primary challenge relates to the design and optimization of the semi-transparent layer able to support the traffic load, ensure the vehicles' friction, permit the passage of sunlight, safeguard the solar cells, and maximize heat transfer to the porous layer (Vizzari et al., 2021). The solar thermal system with a porous layer and photovoltaic technology appear to offer the best chances for energy collection. Nevertheless, because these technologies continue to exhibit some serious problems, more research is needed. The following drawbacks of the photovoltaic road can be identified in light of the research review:

The use of epoxy as a binder in the top layer is not advised because it is negatively impacted by aging. The power loss of the solar cells due to the semi-transparent layer could be very high. The efficiency of the solar cells is reduced around noon because the pavement reaches the highest temperatures. And the optical and mechanical capabilities of the semi-transparent layer are impacted by this phenomenon (Vizzari et al., 2021).

2.11.4 Phase Change Material Application

Lower asphalt pavement temperatures can reduce the necessity for binder quality. Repeated temperature curling causes transverse, longitudinal, corner, and early fracture formation in concrete pavements. The main cause of cracking was discovered to be a higher temperature difference (Anupam et al., 2020). and as a result, decreased pavement temperature may limit the thermal loads that concrete pavements are subjected to (Anupam et al., 2020). In order to allow asphalt to absorb or release a significant quantity of heat under constant conditions and control the temperature of the road surface, phase change material (PCM) utilises its own latent heat (M. Yang et al., 2021).

Although reflective pavements and other typical cool pavement technologies significantly lower the pavement's temperature, they also exacerbate concerns with glare, the thermal load on foot traffic, and the temperature of neighboring buildings. In the absence of water, the temperature of evaporative pavements is higher due to their lower thermal inertia and solar reflectance. Therefore, it was necessary to create cool pavement technologies that had less effect on the environment (Anupam et al., 2020).

Phase change materials (PCMs) are being included into pavements to limit temperature extremes, and this is becoming a significant area of research. Both the higher and lower temperature extremities in pavements can be limited by including PCM. Latent heat can be stored by PCMs without any increase in temperature or significant volume changes. To reduce PCM leakage, pavements employ encapsulated PCMs. asphalt and concrete pavements both include PCMs (Anupam et al., 2020). According to studies, the addition of solid-liquid PCMs to pavements can lower the temperature of the pavement. It undergoes phase change by collecting heat energy from the pavement as the pavement temperature rises above the phase change temperature of PCM, which helps to lower the pavement temperature (Anupam et al., 2020). An efficient method of low temperature thermoregulation is the incorporation of liquid-solid PCM. It is possible to raise the pavement temperature and melt snow off the pavement surface by using the heat emitted during the solid-liquid phase change of PCMs.

Although heat energy can be stored in a material by changing its temperature (sensible heat storage), changing its phase (latent heat storage), changing its intermolecular bond (thermochemical energy storage), or by combining these methods, latent heat storage materials have a higher energy density per unit mass and are less sensitive to temperature changes. As a result, many various options for including PCMs in pavements have been studied. The difficulties and solutions related to the use of PCMs in pavements are shown in the ensuing sections (Anupam et al., 2020).

2.12 Pavement Selection Challenges

When applying the pavements, many restrictions appear. The researchers were able to find solutions for some of them, but not for the others. The difficulties noted in the literature are categorized into the following types in this section:

2.12.1 Design Issues

There are several challenges associated with the design of pavement. A majority of these challenges are around particular ideas. However, by taking into consideration their overall impact, it can be identified that design challenges concerning pavement fall into at least one of these four categories: (1) Social, (2) Materials (3) Structure, and (4) Environment.

2.12.1.1 Social Perspective

Social Challenges refer to the issues and challenges which might be in a way linked to social aspects such as people or the economy. While identifying the challenges in that regard, it was identified that social challenges are either lifestyle-related or economically-related. For the lifestyle challenges, their main concerns are due to the tremendous increase in the population which can impact cooling systems around the world and thus affect their lifestyle (Khosla et al., 2020). Another area of concern is associated with problems of contrast and glare which can impact human comfort due to solar radiation (Khosla et al., 2020). High air temperature on the ground level has a direct impact on pedestrians and causes thermal discomfort for human (Nasrollahi et al., 2020). Different kinds of cool pavements require more studies regarding their influence on pedestrians. Besides that, health risks happen due to the influence of building physics. Meanwhile, heat waves intensify the occurrence of UHI, leading to intense heat stress conditions reported in some mortality cases (Nasrollahi et al., 2020). More challenges are associated with the mechanism of mitigation strategies for cooling the air temperature, which in turn emphasizes the need to know how it will impact the human-bio meteorological aspect (Nasrollahi et al., 2020). One of these challenging strategies entails the cooling of pavements to limit the relative negative effects on human health (Pasetto et al., 2019). Aside from lifestyle and people, more social challenges are concerned with the economic aspect. In this respect, authors are economically challenged by the existence of low traffic volume which has an impact on fully permeable pavement design approaches (Nasrollahi et al., 2020). Others are challenged by the idea that slow-moving Traffic can impact structural design methods since there are currently no empirical methods that have been developed for totally permeable pavement designs. Researchers try to develop cool pavements to reduce the negative effects of UHI, thus saving the economy (Pasetto et al., 2019).

2.12.1.2 Material

Due to the increasing heat temperature and the global warming, most people to use a cooling system such as air conditioning which causes more energy consumption consequences through the release CO2 (Nasrollahi et al., 2020). To avoid heat and pollution emissions, efforts have been carried out to counterbalance urban warming by applying cool materials on the construction surface; the main challenge in using these kinds of materials is in ensuring the cooling efficiency of the cool pavements (Nasrollahi et al., 2020). In addition, there is a need to determine their influence on the thermal conditions of adjacent buildings in the urban area. Other challenges in selecting appropriate sidewalk materials are related to the pedestrians' comfort**.** Cooling material performance changes with time due to weathering and aging, which will be reflected in efficiency reduction or the opposite with others**.** Many applications have been done for cool material assessments to combat the UHI effect (Nasrollahi et al., 2020). The physical properties of the material have a significant influence on its performance. Therefore, when applying the finishing materials on the construction surface, careful consideration should be given on the thermophysical characteristics to avoid intensifying the UHI phenomenon. There are different thermal performances for a variety of pavements; the challenge is in selecting the best one with the lowest impact on the urban environment (Nasrollahi et al., 2020)**.**

2.12.1.3 Structure, Standards, Quality, Purpose

The design is considered one of the challenges that contribute in mitigating UHI as 50% of population is living in urban cities. This entails the design for urban layout as due to the high-rise building absorbs more solar radiation (Nasrollahi et al., 2020), and pavement structure design which impacts the cooling mechanism. Another challenge for design pavement structures and layers entails the purpose of the pavement (Nasrollahi et al., 2020). Likewise, strength issues are also considered an important factor for pavement design as some are not meant for heavy traffic use. More research is needed on cooling pavements as some of them have not been applied yet in the field. Many studies have been conducted to improve cool pavement performance**.** To have the best result for the cooling system by integrating urban climatology with the design process, there is a need to understand the relationship between different types of pavements and their impacts on UHI so as to present the best result (Nasrollahi et al., 2020)**.**

2.12.1.4 Environment

- Climate

Climate change challenge is considered one of the factors influencing pavement selection; the various climates for different regions render specific factors for choosing the most appropriate alternative. The increase in greenhouse gas emissions has led to global warming issues, and researchers are striving to find a solution (Ghenai et al., 2023). The global average temperature is increasing in urban centres due to some characteristics of the covering material. To counterbalance the heat island problem, different approaches are used and integrated such as vegetation related to environmental engineering with the design and planning of the city to achieve the best results to address the UHI effect. Poor urban design has a direct effect on the microclimate and contributes to the development of the UHI effect. To provide thermal comfort green areas are integrated with cool strategies but this time in urban open spaces (Detommaso et al., 2021).

- Effect of Pavements on the Environment and UHI

Artificial pavement covers a large portion of the urban area. Dark surfaces, higher heat storage capacity, and large thermal inertia of conventional pavements contribute to the development of the UHI phenomenon. Recently, scientists found a cool pavement solution to reduce the UHI effect; this is why more studies are needed to see the relationship between different types of pavements and their impacts on UHIs (Nwakaire et al., 2020b). The challenge is that the different types of pavements have varying characteristics; thus, the cooling mechanism for every single pavement has a different effect on the air temperature (Ko et al., 2022). Today, various experiments are being conducted in the lab and field to improve cool pavement policies and limit their negative effect on the environment (Pasetto et al., 2019). The contrast among diverse pavement types is obvious since each type has a different response to the UHI effect; thus, there is a need to assess several types of pavements. When searching for cooling pavements, we must recognize the object specification to record it as a reference.

2.12.2 Impact of Pavement

This section focuses on the effects of pavements on different sectors either during the implementation phase or upon completion of the project. There are many serious challenges for scientists in counterbalancing the impact of urban heat (Santamouris & Yun, 2020). These issues are classified according to impact type namely: (1) UHI-related, (2) People-related, (3) Health-related, (4) Environment-related, (5) Economy-related, and (6) Structure-related.

2.12.2.1 UHI-Related Issues

Higher air temperature in the urban area compared to that in the suburban area is called the UHI effect. Heating released from conventional pavements contributes significantly to the development of the UHI phenomenon (Sen & Roesler, 2017). Furthermore, impermeable pavement characterized by dense fabric negates the cooling of the resulting evaporation. In the summer time, high emissions and sensible heat from the dark and dense surfaces intensify the UHI effect in cities (Farhadi et al., 2019). To reduce the UHI threat, several mitigation strategies have been developed namely: reflective, evaporative, or harvesting methods. Cool pavement is one of the solutions to reduce the UHI effect and currently many researchers are focusing on this topic area (Pasetto et al., 2019). Few data in the literature reported a relationship between various types of pavements and the UHI effect**.**

2.12.2.2 People-Related Issues

Concerns have emerged about the impact of the cool pavement technique on the ground level. It is clear that people-related challenges are linked to either visual issues or human comfort (Al-Humairi et al., 2021). The effect of reflect radiation on visual perception causing a glare effect needs careful examination, including in different climates. Most of the studies on reflective pavement focused on how to apply the paving technique and material development; there is a lack of studies on optical properties and their relation to the coloured reflective pavement (Xie et al., 2019). Research on spectral reflectance of reflective pavement coating is still in its infancy, and limited research has been done about reflective pavement issues in different spectral region influence (Xie et al., 2019). Another area of concern is the effect of UHI on human comfort. Different pavement materials on the roads and sidewalks pose different effects on pedestrians' comfort; very few studies have been conducted on the effect of pavements on pedestrians level. Many mortality cases have been reported of the direct impact of heat waves on outdoor pedestrian's thermal comfort. Very few studies are available about the effect on the human-biometeorological aspect. The UHI phenomenon is the main reason for the significant effect of heat stress on people; hence, more research attention is needed on outdoor thermal comfort (Farhadi et al., 2019). Through the computation of thermal indexes, we must assess the variation in thermal comfort(Battista et al., 2019). Past research efforts had not adequately focused on the comfort of people in an outdoor environment with limited access to a cool spot or cold drinks. There are very few studies on the effect of cool pavement on outdoor thermal comfort (Sen et al., 2022). The rapid development of cities due to the 50% increase of people living in urban areas had increased the absorption surface as well as the impact on thermal conditions, thus reducing people's well-being and quality of life. Moreover, increased concerns about cool pavement materials require further investigation to discover more about the material's effect on pedestrians' thermal comfort. Cooling pavements have shown some negative effects on the thermal comfort of pedestrians, as shown by some simulation study (Sen et al., 2022).

2.12.2.3 Health-Related Issues

Human health is a big factor in choosing the most appropriate pavement due to the direct impact of the latter on the former. More investigation is needed to modify material properties, emissivity, and dynamics so as to reduce the direct influence of solar radiation on people's health. Furthermore, there is a need to develop policies and solutions to mitigate the UHI effect by improving the performance of cool road pavements (Pasetto et al., 2019). Elevated temperatures lead to significant health problems and consequently death (Farhadi et al., 2019). Many studies had reported an increase in mortality due to heat waves (Shao & Kim, 2022). In some countries, heat is the key factor leading to increased mortality over time. A cool pavement technique is one of the suggested solutions to reduce the potential of health risks.

2.12.2.4 Environment-Related Issues

Besides the direct impact on people's health, pavements also affect the environment. Greenhouse gas emissions have become a global concern and the challenge is to reduce the release into the environment (Litardo et al., 2020). People’s quality of life and comfort now depends on the climate condition of the urban environment. As such, most of the previous studies focused on a wide area to discover the effect of cooling strategy air temperature (Anupam et al., 2020). The literature state that rigid pavement contributes to the development of UHI, which is then distributed to the surrounding environment. Cool pavement is one of the cooling strategies contributing to the reduction of negative environmental effects, and of which require more experiments to develop the relevant policies (Pasetto et al., 2019) to mitigate heat island temperature vegetation and environmental engineering combined with urban planning to achieve a balance in urban climate. Various types of cool pavements have different impact on the thermal condition of adjacent buildings depending on the solar reflectance which will affect the urban environment. Evaporative pavement is one of the cooling strategies used to reduce pavement impact on the outdoor thermal environment; unfortunately, very few studies had evaluated this technique. There is a lack of data on cool mitigation strategies at the microclimate level using numerical simulation (Gupta et al., 2021).

2.12.2.5 Economy-Related Issues

Conventional pavement leads to high environmental temperatures. To counterbalance the increase in air temperature, people tend to use air-conditioning for a long time which leads to higher energy consumption and thus higher energy bills. Many countries have tried to find solutions to reduce greenhouse gas emissions and to cool the weather so as to consume less energy and save money (Gupta et al., 2021). To address this challenge many types of research are needed to modify the mechanical system and material properties in order to limit the negative environmental effect and reduce the UHI phenomenon, thus leading to improved socioeconomic life. Cool pavement is one of the solutions for mitigating this phenomenon and for improving the economy via the development of relevant policies (Pasetto et al., 2019). We need to select the right type of cooling pavement which meets the environmental requirements to avoid extra costs, such as the need to spray water on the permeable pavement every 2 days to stay cool when there is no rain (Jianlong Wang et al., 2023).

2.12.2.6 Structure-Related Issues

Structural challenge is associated with the mechanism of cool paving mitigation strategies, as high air temperature influences the structure's performance and city buildings (Kousis & Pisello, 2023a). Countries with historical buildings face the challenge of high air temperature which endangers the buildings. Pavement design and material are the factors that determine the suitability of the cooling pavement; hence, more studies are needed to identify the specifications for all types of pavements. Furthermore, there is a need to study the building environment adjacent to the pavement such as tall buildings and wide roads in order to choose the best alternative that can reduce the pavement's impact on the adjacent building. Research into the challenges and factors influencing cool pavement techniques is still at the preliminary stage (Xie et al., 2019). There is a lack of information on the impact of various structural strategies on the neighbourhood; some studies numerical simulations to determine the different design structures at the microclimate level.

2.12.3 Pavement Research

The following sub-sections review the challenges associated with pavement structure in terms of the experimental, design, missing studies, and performance evaluation. Additionally, they clarify the pavement challenges related to UHI and people.

2.12.3.1 Experimental Performance

Cool pavement techniques are considered new technology and still in the development phase; some of them have been applied in the field and others have been thoroughly studied in the lab. The challenge in applying cool pavement is the lack of thermal condition information; practical data to be used as reference is non-existent leading to the rare application of cooling strategies (X. Yu et al., 2021). Furthermore, there is scarce application of cool materials in the micro-climate, and most of the provided data include lab experiment limitations. New strategies are applied to examine the quality of structures because highways and road designs must be able to cater heavy traffic. Moreover, there is a need to determine the reactiveness of mitigation strategies in different urban climates in order to reduce losses and the negative environmental effects. Researchers have carried out simulations under similar boundary conditions and observed changes in the material due to weathering and aging. Most previous studies have conducted city-wide investigations by using numerical weather prediction models. Some others investigated heat mitigation strategies at the microclimate scale using numerical simulations. Geographical intricacies at the city and regional scales are not accurately reproduced, which is a challenge with simulation research. Furthermore, offline models largely ignore interactions between the land and the atmosphere. These factors make it challenging to use the results of offline investigations as a reference at the local and regional levels (Mohammad Harmay et al., 2021). Investigating mitigation strategies in the field is still encouraged to enable real life usage.

2.12.3.2 Pavement Evaluation

To rank and select the appropriate pavements, we need to evaluate the pavement's performance. Very few works had evaluated pavements in the field and some have not even been used in a real city (Abaas, 2020). Performance evaluations rely on pavement requirements to show the best production. Besides that, the pavement's material has a significant effect on its performance; this area needs more research especially since pavement materials have a direct effect on the pedestrian**.** The benefit of such evaluation is that it enables the estimation of the potential risks of the countermeasure and thus reduce them. The collection of pavement data is not restricted by itself, but is rather widened to include a variety of subjects (climatology, epidemiology, social sciences, building physics, horticulture, and engineering).

2.12.3.3 Design Development

The pavement design is one of the key challenges in its implementation in a real city; there is a need to identify the purpose of the road to ensure that the structure design fits the requirements since certain pavement designs have not been developed (Morales-Inzunza et al., 2023). Furthermore, focus should be given on the usage of the materials and the impact of the air temperature on the environment. The finishing material has a significant effect considering their thermal characteristics(Plati, 2019).

2.12.3.4 Lack of Studies, UHI concept, Mitigation Strategies

The UHI phenomenon is considered a major problem in the world today. Many studies have been conducted to understand this phenomenon. However, there is still a lack of knowledge and understanding on the topic (Elizondo-Martínez et al., 2020). This phenomenon was initially studied in 1960, with several works focusing on major cities in developed countries; however, there is very little data on medium cities, and no data at all on other types of cities. To counterbalance the UHI effect, mitigation strategies were developed and applied in various areas. Firstly, there is a need to establish a standard and official definition for cooling pavement. Another key challenge is establishing the practicality of various cooling strategies (Qi et al., 2019). There are also missing data on the general rules for mitigation strategies in the effort to reduce the UHI effect, and the ways to make it sustainable for cities.

2.12.3.5 Relation between Pavement and People

The literature states that the right selection of pavements hardly pose any effect on people, either in providing a comfortable environment and safe driving, or the opposite. Some pavements reflect solar radiation thus causing a glare effect; based on recent studies, it is difficult to determine the lighting implication of reflective coatings. Research into the optical characteristics of reflective pavement coatings is still in its early phases, and the relationship between the lightness of the coatings and their spectral reflectance is also still developing (Xie et al., 2019). Moreover, more studies are required to identify the cooling pavement effect on the human-biometeorological aspect. The effect of evaporative permeable pavements on the ambient temperature has been the subject of several investigations. Other previous efforts had focused on road paving, with very few focusing on the sidewalk effect. There is a need for further investigation on the thermal and visual effect of the cooling system on pedestrians so as to avoid glare and discomfort heating emissions from the implementation of the pavement (Xie et al., 2019). Finally, to reduce mortality cases during the summer, there is a need to intensify efforts to reduce the paving material effect as well as the UHI phenomenon.

2.12.3.6 Relation between UHI and Pavements

In terms of environmental concerns, little research has been done on the relationship between pavements and the UHI effect, and thus more work is required to clarify the thermal performance of the reflectiveness and permeability of pavements. To specify the type of pavement that is suitable for certain areas, more research on urban geometry and regional atmospheric conditions is required. The top pavement layer's physical characteristics, which affect the pavement's surface temperature, had been the focus of many existing studies; however, pavement structure also affects the mitigation measures adopted, necessitating a separate set of research (Gong et al., 2023b).

2.12.4 Pavement Resources

The following sub-section presents the challenges of pavement resources before, during, and after the project building. These include the design of the project, provision of materials to build the structure, and changes to the physical properties in conjunction with the pavement’s aging.

2.12.4.1 Lack of Recourses

Cooling pavements have different mechanisms to keep the pavement surface cool. As previously mentioned, the material and design of the pavement should be considered when selecting the appropriate pavement. Furthermore, some of them need to be sustainable to ensure reduction in air temperature. Permeable pavements need water either from rainfall or scheduled sprinkling every couple of days; experiment results state that about 1-2 days are needed to keep the permeable pavement surface cool (Guan et al., 2021). Besides that, green coverage in some areas are conditioned by providing it water.

2.12.4.2 Special Materials

The material influences pavement performance. More research is needed to clarify the physical properties as well as to examine the quality and strength of the structure in order to keep developing pavement designs and making them available in the market. Additional studies are needed on how to modify material properties by decreasing heat absorption of surfaces with reflective pavement or dynamically controlling permeable and harvesting pavements (Ma et al., 2022). Recent studies reported that 40% of energy demand is for civil usage; hence, appropriate cooling pavement mitigation strategies are needed to help reduce urban heat (Battista et al., 2019). Moreover, due to urbanization and city expansions, more environmentally-friendly highways and roads need to be constructed.

2.12.4.3 Inadequate Strategies

It must be noted that some techniques that reduce heat temperature and cools the environment in the summer are not able to reduce the cold during winter. When selecting the best pavement, the impact on the indoor and outdoor environmental quality as well as energy consumption must be taken into consideration. The additional cost to sustainable performance will also affect the decision-making in selecting the best pavement (Khahro et al., 2021).

2.13 Motivation for Developing Strategies to Counter UHI

This section presents the motivations for researchers to investigate pavement problems as well as the efforts conducted to find the solutions. It also looks into studies on the development of cool pavement techniques and the improvement of their performance that will help counterbalance the UHI problem. The motivations are discussed in several sub-sections as follows:

2.13.1 Improvement Research

Motivations associated with research and urban heat are scattered over many categories in the academic literature. One area of interest is the continuous efforts for research improvement. Three sub-areas are observed namely: (1) policy development, (2) improvement of thermal comfort, and (3) improvement of climate conditions. Each research improvement motivation is discussed below.

2.13.1.1 Policy Development

With increased research on UHI development, there is a need to identify more details about the definition and classification of cooling strategies as part of the policy development to improve the proposed frameworks (Qi et al., 2019). Moreover, development policies also motivate research efforts to analyse the performance of cool pavements. Governments and the scientific community are working together to develop policies and other measures that will reduce the UHI effect and its adverse environmental effects (Pasetto et al., 2019). Significant efforts have been made to mitigate the effects of rising urban temperatures, leading to the development of effective mitigation solutions. Other motivations were observed by using an alternative to determine the effects of pavement-watering. Another interesting motivation was observed by accelerated pavement testing to develop a mechanistic-empirical design method for permeable interlocking concrete pavements. Others were motivated by their pursuit to improve the efficiency of UHI mitigation efforts (Shao & Kim, 2022). Research incentives are also increased by factors such as the quick development of mitigating methods to lessen the effects of the phenomenon and the avoidance of problems resulting from the increase in the global average temperature (Mohammad Harmay et al., 2021).

2.13.1.2 Improvement of Thermal Comfort

This section discusses research motivations aimed at improving thermal comfort. Researchers argued on the importance of cooling strategies in providing thermal comfort for people, especially in urban areas (Battista et al., 2019). Further motivations were inspired by the opportunities to develop urban planning and design since they can significantly improve outdoor thermal comfort conditions (Díaz-Borrego, 2022). Improvements to the general public's life quality also motivate studies on thermal comfort. The most significant motivation entails cooling techniques that serve to enhance outdoor thermal conditions and lessen the effects of heat islands in hot regions (Qaoud et al., 2023).

2.13.1.3 Improvement Urban Liveability

This category addresses urban liveability. It was reported that performing mitigation strategies in the urban area can help improve the urban environment as well as the people's life quality (Sahlol et al., 2021). Studies aim to improve the general quality of the public by identifying a set of measures and verifying their effects using cool community techniques to solve heat island mitigation measures, as well as benefits for the people. One of the cooling techniques namely permeable pavement seeks to enhance community liveability by lowering vehicle miles driven and promoting more walking and cycling.

2.13.1.4 Improvement of Climate Condition

Further research motivations are related to climate condition. One important aspect is the effort to limit the effects of global warming and climate change using cool strategies which contribute to improving climate conditions. Research has demonstrated the potential to improve the climatic conditions in cities by applying cooling pavements. Designers, builders, operators, and owners are among those who are motivated to develop a sustainable built environment and improve both economic and environmental performance. Improvements in climate urban environment can be achieved by changing some characteristics of the urban centers to reduce changes in the global average temperature (Díaz-Borrego, 2022).

2.13.2 Solutions to the Obstacles: Effective Strategies

For the purposes of better comprehending the subject and providing the facts from many viewpoints, study any prospective problems that might have an impact on this research field.

2.13.2.1 Effect and Cause Investigation

The UHI phenomenon is considered a significant global issue. Many studies have been conducted to quantify the intensity of urban heat island as well as to illustrate the impact on energy usage. Numerous researchers have attempted to limit the negative effects by developing cooling strategies that decrease heating emissions and save energy inside the building (Litardo et al., 2020). Other works focused on providing thermal comfort for pedestrians by cooling the ambient temperature. Another motivation entails the effort to decrease the effect of visual perception issues of solar radiation due to high albedo (Rossi et al., 2018).

2.13.2.2 Solution Investigation

The techniques used to counterbalance the UHI effect in the microclimate based on the urban design are presented below.

- Cooling Strategies Investigation

Efforts are still ongoing in investigating the different adaption strategies in all seasons and in various climate regions to understand the effects of cooling strategies on outdoor human thermal comfort (Yu Liu et al., 2022). Pavement structure is illustrated in review papers to understand the whole concept of pavements. Furthermore, other comprehensive experiments had aimed to show a specific thermal behavior of the pavement surface characterized by different textures and colors to decrease human discomfort (Pasetto et al., 2019). Other experiments in the field and laboratory focused on cooler coatings that are useful for reducing air pollutants. To show more benefits of the adaption strategies, researchers tend to combine cooling pavement with other cooling strategies (e.g., water ponds, trees, and green surfaces) (Detommaso et al., 2021). Numerous papers had focused on the thermal performance of various HMSs in the landscape of a real urban environment.

- Microclimate Investigation

There is an increasing research trend on the effects of different heat mitigation strategies on the microclimate. Most were motivated to investigate the surface and air surface temperature of cool paving materials in microclimatic conditions with the consideration of both the design and the aged values of solar reflectance. This issue is especially significant in large cities, which are densely populated and have a high proportion of elderly residents. For this reason, numerous attempts have been made to investigate various urban microclimate mitigation measures (Abaas, 2020).

- Urban Design Investigation

Urban design is one of the factors that impact outdoor thermal comfort (Xiao et al., 2023). Many works have investigated this issue and attempted to improve it. Other motivations include the need to develop offline models and perform simulation research on the diminishing effects of pavements on the urban thermal environment.

2.13.3 Required Research to Mitigate UHI Phenomenon

Numerous types of research and experiments have been conducted worldwide either in the field or in the lab to gain more knowledge about UHI and the methods to solve this problem. However, there is still a lack of information in this area (Elizondo-Martínez et al., 2020). For these reasons, researchers need to find solutions to avoid or mitigate the increased UHI effect by examining the characteristics of various pavement types. Likewise, more efforts are needed to modify pavement material properties to improve surface emissivity and dynamically control the surface, as well as to determine the health and socioeconomic impacts of UHI. Countries and cities have specific characteristics; hence, there is a need to find the right solution for each city. Moreover, the different climates and seasons around the world are one of the reasons to conduct further work to understand and ensure the right solution to solve the problem (Qin et al., 2022).

2.13.4 Analysis Research

To avoid intensifying the UHI phenomenon, various studies have been conducted to find effective solutions, i.e., by analyzing various criteria and alternatives as well as their performance and experimental results.

2.13.4.1 Change Analysis

To counterbalance the UHI effect, researchers have been analyzing the phenomenon to see if there is a noticeable change on places and environments. In the literature review, it was found that many efforts have been performed to analyze the UHI effect in the summer time over the last three decades as well as the mitigation strategies and their responses to the urban climate change (Abaas, 2020). Besides that, analyses have also been carried out to determine how adaption strategies affect UHI in dense and old neighbourhoods. Other studies had compared the results of experimental and theoretical works to critically and comprehensively establish scientific knowledge.

2.13.4.2 Performance Analysis

Different types of cooling pavements show different performance. In the literature, the UHI phenomenon had been identified, and mitigation methods had been analysed and described. The performance of cool pavements was analysed by measuring the outdoor meteorological conditions, and checking outdoor and indoor thermal comfort (Abaas, 2020). In addition, researchers had studied cooling strategy performance in the same area using different factors. Many experiments with photo-catalytic coatings have been done in the field and in the lab to analyze pavement performance and evaluate its efficiency in decreasing air pollutants emission into the environment (Qin et al., 2022). To assess the thermal comfort index for a different type of pavement and better comprehend and utilize urban outdoor thermal environment indices, an analysis of the water absorption properties of the pavement was also conducted.

2.13.5 Previous Studies Contribution of Research

The literature shows us that several decades ago, extensive studies had been done on the UHI phenomenon and the mitigation strategies. This had left a fingerprint on development knowledge and contribute to improving solution methods.

2.13.5.1 Construction material impact on UHI

As mentioned above, paving material has a significant effect on UHI intensity, which provide further motivation to do field experiments to determine the material effects on this phenomenon (Senevirathne et al., 2021). Furthermore, a series of simulation experiments in the laboratory have been conducted to discover the thermal behaviors and performances of paving materials. Discrepancies were found in their thermal behaviors under the same simulation conditions. More research was done on the reflective material on roads or pavements in real cities to reduce surface temperature and contribute to counterbalancing the impact of UHI (Ferrari et al., 2020). Others were motivated to conduct simulation works which revealed that the heat flux of different pavement layers has varying thermal diffusivity and inertia. Thermal interactions between buildings and their surroundings have a considerable impact on the temperature inside the urban canopy, according to numerical model applications. The performance of materials relies on their capacity to mitigate the negative effects of UHI; the enveloping materials were classified using the solar reflectance index (SRI).

2.13.5.2 UHI Mitigation Strategies Developed

The high prevalence of UHI leads to the development of mitigation methods. Cooling pavement is one of the cooling strategies described and applied in various urban regions. Furthermore, a large scale of cool paving has been conducted in major traffic. Researchers have clarified that the best performance of cooling strategies can be achieved by combining the existing strategies (Mohammad et al., 2021).

2.13.6 Advantages of Cooling Pavement

Cooling pavement usage has a positive effect in mitigating UHI. The effect of cool pavement on the urban environment has been studied. Moreover, a decrease in energy consumption due to cooling weather has been observed. More effort was focused on solving some negative effects on the thermal comfort of pedestrians by adding trees, or vegetation to improve thermal comfort in city centers (Qin et al., 2022). Numerous experiment results have been documented and published in articles which could be used by future studies as a reference.

2.13.7 Assessment Research

To select the appropriate solution to counterbalance the UHI effect, researchers had attempted to generate a general idea about the target area in order to assess the variations in ground surface temperature, air temperature, water content, and wind speed to be able to design and choose the right strategy. Other studies had assessed cooling strategies for facing heatwaves or for creating cooler environments (Huang et al., 2023). By selecting the most suitable paving for combatting climate change, will be able to assess the benefits of the implemented strategy. In addition, assessing the negative outputs of mitigating strategies and comparing them helps in making the right decision to limit environmental emissions.

2.13.8 Previous Evaluation Research

The literature presented various cooling techniques for decreasing the UHI effect; some of them had already been used in real life and other understudies. There is a need to evaluate the performance of these different scenarios to help the contractor in selecting the most appropriate alternative for the environment.

2.13.8.1 UHI Mitigation evaluation

To have the best result of mitigating strategies the evaluation performance by comparing outputs with the situation without using the techniques. Many of the works doing overall studies on the UHI countermeasures to evaluate their effectiveness. Furthermore, evaluate the different types of strategies for UHI mitigation during the daytime and their influence on thermal comfort (Farhadi et al., 2019). The motivation to implement mitigation strategies is to reduce heat weather on summer days, other side studies try to understand work strategy in the cold climate.

2.13.8.2 Experiment Evaluation

To examine mitigation strategies and obtain accurate results about their performance, many of the methods had been carried out on real cities. Numerous models and field measurements had been presented. Six different scenarios had been conducted and examined to evaluate the effects of different mitigation strategies. Additionally, the effects of pigments and coatings on optical properties and thermal performance had also been evaluated (Xie et al., 2019). Some cities had carried out large projects on the roads and pavements, and reported their evaluation. A simulation model has also been tested in the representative site of a city is to investigate the effects of possible mitigation strategies. Moreover, numerical analysis of various solutions had been performed to determine the effectiveness of urban mitigation strategies (Battista et al., 2019).

2.14 Stakeholders

The outcomes from the experiments will help engineers, designers, architects, and contractors to do their best work via the provision of information needed during the project implementation and be considered as a reference for new experiments. In addition, the outcomes serve as recommendation to complete unfinished projects. It is useful for a construction company to achieve the requirements in providing a comfortable environment by improving material usage so as to minimize electric consumption, reduce hot emissions to the environment, and successfully provide thermal comfort for humans.

2.14.1 Mitigation Strategies Contribution

The purpose of using mitigation strategies is to: (1) provide cool air quality indoors and outdoors, (2) provide a nice environment for the people, and (3) reduce energy consumption.

2.14.1.1 Environment Improvement

Various strategies have been used in diverse climates to improve urban surface temperature and decrease the contribution of pavement surface in intensifying the prevalence of UHI. A study has been done on the colored coating of reflective pavement to achieve balance between the reduction of optical effect and the increase of radiation reflection to counterbalance the UHI effect (Xie et al., 2019). Another study found that reflective cool pavement is not an exceptionally effective strategy for reducing the UHI effect as it does not take into consideration the thermal interaction between the building environments. Such outcomes can help architects, urban designers, and planners to understand more about the effect of green and grey areas on the environment of open spaces in cities (Huang et al., 2023). Furthermore, architects and landscapers can learn more about surface reflectance, thus assisting them in designing public areas that contribute less to the UHI problem.

2.14.1.2 People’s Comfort

A decreasing effect on the environment means less effect on the people; researchers have used the same techniques and policies to provide thermal comfort for people in the urban area. Moreover, human life quality outdoors is improved when designers, planners, and architects thoroughly understand about green and cool pavement applications (Sahlol et al., 2021). Understanding about reflective surfaces in open areas such as parking lots and patios can help reduce negative effects on pedestrians. Improvements on the finishing surface material can also limit the negative effects on humans on top of preventing glare (Xie et al., 2019).

2.14.1.3 Material Improvement

To decrease pavement material effects on the environment and humans, researchers have investigated material behaviors in various seasons. As a requirement of the EU's commitment to lessening energy consumption, efforts have been made to provide reliable implementation techniques by modifying reflective coating materials (Ghenai et al., 2023). To optimize the design of reflective cool pavement coating and reduce aesthetic issues and glare, all the relevant results have been compiled (Xie et al., 2019).

2.14.1.4 Energy Saving

There are various strategies for assessing energy usage costs which result in optimized surface temperature in urban areas and energy savings. A cooling environment provides thermal comfort at the pedestrian level as well as air quality at the room level, thus leading to less air-conditioning usage and lower energy consumption (Jalali et al., 2023). To meet the EU commitment to reduce energy consumption over the 2020-2030 period, more effective and safe road illumination has been made available for all users thanks to the availability of trustworthy implementation methodologies and reference data.

2.14.2 Urban and Pavement Design

The section will be helpful for planners and designers in sketching cities and selecting the best pavement design based on the factors explained below.

2.14.2.1 Urban / Cities Design

Based on the results of significant field or lab experiments, architects, engineers, and designers can use them as reference for planning or designing (1) cities and (2) pavements (C. Liang et al., 2020). Architects and landscapers can use the information when designing public area spaces. The findings would benefit urban planning, particularly for assessing pavements prior to actual application. City architects, designers, and planners would be able to understand the effects of pavements on the environment and people as well as the most effective design combinations (Plati, 2019). They would know not to depend on only one cooling source such as air-conditioning due to the additional energy consumption, but rather to combine countermeasures on the urban scale. To create livable cities, designers need to determine the effects of paving materials on people in all seasons and provide reliable data for landscapers and urban designers. The results of efforts on existing issues might help both urban planners and designers in selecting the most suitable pavement for the climate condition. Moreover, research has provided a framework that can be used as a model for cities, but of which needs some modifications to fit each city and climate (Abu Dabous et al., 2020). Cities and their leadership have also developed a "master plan" that will lead to improved communities and cities in the future.

2.14.2.2 Pavement Design

For pavement design, numerous works have examined pavement structures and the possible modifications whenever needed (P. Liu et al., 2022). Researchers must know the purpose of the building pavement, i.e., if it is meant for heavy traffic and thus be careful when designing it. While finishing the pavement material, quality parameters in standards are collected to achieve the EU commitment of reducing energy consumption by 2020 and 2030 (Rossi et al., 2018). Designers must be able to assess the modification of pavement materials in urban areas due to changes in climate conditions in order to meet the requirement to provide a cool environment. Furthermore, the research results could be used as reference for optimizing reflective cooling pavement designs and evaluating the optical and thermal performance of pavement materials so as to avoid glare and mitigate UHI (Xie et al., 2019).

2.14.3 Investigation Required to Mitigate UHI Effect

Many efforts had focused on clarifying the UHI phenomenon and finding solutions to counterbalance this problem through field or lab experiments. However, there is still a lack of information causing the need for more studies.

2.14.3.1 Lack of Specification

One of the studies recommended doing more work on aggregate properties in the pavement layers and usage methods, as well as regarding the stabilization of the sub-base aggregate with cement, geogrids, or geocells (Litardo et al., 2020).

2.14.3.2 Lack of Study

Mitigation strategies have been developed to reduce heat during summer. However, during winter, people need more heating; as such, more studies are needed to examine the strategies in different climates (H. Yu et al., 2023). Further investigation is also needed in different neighbourhoods to identify the performance with variable changes.

2.14.3.3 Other Policies to Improve Cooling Pavement Performance

Besides cooling pavement, two more blue and green strategies help in providing cool weather particularly when integrating cooling pavement with the green or blue area. Therefore, studies recommended investigating the implementation of different forms of water in urban areas (H. Yu et al., 2023). The analysis period should be extended to give more time in evaluating the adaption strategies on pavement types that depend on water as a resource (Yu Liu et al., 2022). Furthermore, there is a need to investigate the impact of reflective surface on human thermal comfort at the ground level. Thermal interactions between buildings and the environment with reflective pavement cases must also be investigated. In the end, we conclude that numerous research have been done and alternative measures for mitigation have been described, which can be used as reference for future research (Q. Wang et al., 2019).

2.14.4 Future Directions of UHI Mitigation Strategies

UHI mitigation strategies are still in the developmental stages. However, they have been applied in actual areas based on the provided knowledge as reference. Although some mitigation strategies have already been used on the field, scientists advise to keep focusing on more developments (Miao et al., 2023). Experimental results showed the good performance of UHI mitigation techniques which contribute to sustainable urban planning in cities. One of the studies refers to the possible implementation of mitigation strategies for a specific project (Battista et al., 2019). The derived results may be useful for architects, designers, and urban planners in developing urban designs in open spaces to provide thermal comfort for people.

2.15 Critical Review Summary of Previous Studies

To summarize the literature review is separated into strengths and weaknesses elements. The strengths present the motivations to develop future studies including: improving the knowledge and understanding of other factors that contribute to the UHI phenomenon. Suggest design strategies for more Resilient urban planning. Investigate the efficacy of different heat mitigation strategies. additional research is needed on how to modify surface emissivity and dynamically control surface and material properties. Discuss and evaluate UHI phenomenon. Identify, analyze, and examine UHI mitigation techniques. Cool pavements definition may be further refined. Get the medium terminology for energetic and environmental urban sustainability.

Weaknesses presented in previous studies challenges include: Urban design and development. Lack of information on the UHI concept, mitigation Strategies, and combined mitigation strategies. Factors affect on performance of mitigation strategies. Limited utilization of UHI mitigation strategies. Scarce studies and practical application of mitigation strategies. Impacts UHI on Historic buildings. And cool pavements are still in the preliminary stages more research is required.

2.16 Review MCDM Methods in the Literature

Previous studies have used the MCDM approach as a solution in selecting the best alternative for complicated scenarios and obtaining multiple criteria. Below are the MCDM methods mentioned in the literature for the construction sector.

To address the lack of a quantitative evaluation technique to aid decision-makers in choosing resilient and sustainable systems, a new integrated framework was presented. To lessen the effects of climate change and growing urbanization, the following ten indicators were suggested: cost, social acceptability, pollution control, annual runoff volume control, resilience, flood volume, flood duration time, hydraulic performance index, and annual runoff volume control, all of which were weighted using the modified AHP and the design schemes ranked using the TOPSIS technique in order of preference by similarity to the ideal solution (C. Liang et al., 2020). The proposed approach used the AHP and multi-attribute utility theory (MAUT) to rank and prioritize huge networks of pavement sections while including several objectives under the sustainability-related criteria. The suggested framework gives the decision-maker a choice in choosing the decision criteria, allocating weights, and defining intensities of the various objectives and criteria, which is a big challenge in the absence of the decision-makers' expertise and judgment (Abu Dabous et al., 2020). The Analytical Hierarch Process (AHP) was employed to determine which building material satisfies the criteria for the most sustainability. These factors were obtained from rating scales, earlier research, and the opinions of specialists (Sahlol et al., 2021). Since novel engineering solutions were studied to move towards more sustainable pavement management methods, a multicriteria decision analysis method was applied to evaluate the preference order of potential scenarios. A thorough and integrated model for life cycle costing and assessment of pavements was then developed (Santos et al., 2017). The analytic hierarchy process was conducted to develop an asphalt pavement recycling decision system since there is no quantitative evaluation method and calculation program available for selecting an optimal recycling method for existing asphalt pavements. Many factors had been considered when conducting life cycle environmental assessment to improve pavement performance, cost, and environmental evaluation; all these are reflected in the alternative ranking (Cao et al., 2019). Another study assessed the usefulness of features like noise mitigation, skid resistance, and stormwater and runoff quality control. In addition to mechanical performance, porous asphalt's durability was also shown. The multiple-response problem optimization was converted into a single-response problem optimization using a novel multi-criteria decision-making (MCDM) technique (Slebi-Acevedo et al., 2020). The methodology suggested a decision support system based on sustainability. Indicators for the economy, society, and environment were chosen to be used in the assessment of sustainability. The alternatives' definition and the creation of the evaluation matrix came next. Each indicator with an assigned weight was used to evaluate how well each alternative performs. Finally, the priority sequence of the alternatives being compared was ranked using the MCDM approach. The influence of the adjusted parameter weights on the ranking of the alternatives was determined using the sensitivity analysis method (Santos et al., 2019). The use of TOPSIS which helps in ranking the alternatives per the ideal solution and chosen based on cost, carbon emissions, and energy consumption criteria, helped in the selection of the best course of action (Heidari et al., 2020b). Five pavement choices were ranked according to four primary parameters using the FAHP methodology. Fuzzy comparison matrices were created using expert judgment and simulation data from stormwater management models (SWMM) (Y. Zhu et al., 2021). Both the fuzzy analytic hierarchy (AHP), which determined the weights, and the VIKOR model, which ranked the alternatives by taking into account the relevant criteria, were merged to prioritize the options for pavement repair. The criteria were determined based on the opinions of specialists (Babashamsi et al., 2016). The development of the Multi-Criteria Decision Analysis (MCDA) approach made it possible to evaluate the effectiveness of several roofs and choose a flat roof that would promote sustainable growth. The selection process was supported by the Analytic Hierarchy Process (AHP) and the Technique for Order of Preference by Similarity to the Ideal Solution (TOPSIS). The main purpose of expert advice is to improve and balance the suggested indicators (Guzmán-Sánchez et al., 2018). More studies are needed in the attempt to apply the objective-based AHP method to establish the relative maintenance priorities of the pavement sections and build up on the existing AHP methodologies to study pavement management system (PMS) (Ahmed et al., 2017). A model of multi-criteria decision-making was used. The three sustainability characteristics (economic, environmental, and social) were merged using the AHP-VIKOR model to determine the best sustainable pavement option. A sensitivity study was performed to see how weights affected the outcome of the decision (Zheng et al., 2019). Multi-criteria decision making was used to assess the effectiveness of seven potential low impact development (LID). For a thorough examination of LID situations, 16 criteria were evaluated using the AHP approach and integrated into the TOPSIS evaluation matrix (Koc et al., 2021). When creating a multi-criteria value model to enable the prioritization of maintenance and rehabilitation interventions in the pavements of road networks according to technical, economic, and social aspects, the application of the measuring attractiveness by a categorical-based evaluation technique (MACBETH) approach was proposed as an alternative to AHP. The foundation for both AHP and MACBETH is qualitative pairwise comparisons (Marcelino et al., 2019). A comprehensive framework was developed to compare the costs of installing asphalt and concrete pavements while also taking into account the time required for construction, the embodied energy, and fuel usage. A methodology was developed for making multiple decisions that use superiority and inferiority ranking to determine the best alternative (Marzouk & Ashmawy, 2021). A hybrid approach to multi-criteria decision-making (MCDM) was presented which combined the AHP weighting system with the ELECTRE II, ELECTRE III, and ELECTRE IV ranking systems to rank the options. The final ranking for determining road maintenance priorities was achieved by combining the data with the Copeland technique, in which the roads were assessed and ranked based on eight criteria (Sayadinia & Beheshtinia, 2020). To convert the multiple response optimization problem into a single optimization problem, three MCDM techniques were used. The CRITIC approach was used to determine the relative weights for each criterion, and the TOPSIS and WASPAS methodologies were used to rank the alternatives according to preference and to find the best additions for the mixture's overall performance (Slebi-Acevedo et al., 2022). To examine the pavement management decision-making problem, a decision support framework was developed to rank and prioritize huge networks of pavements based on the decision factors found. Sensitivity analysis was used to assess how the various criteria affect the ranking process (Abu Dabous et al., 2020). To choose the best approach for an asphalt concrete overlay atop flexible pavements, life cycle cost (LCC) and multi-criteria decision-making (MCDM) assessments were carried out to assess the effectiveness of currently known reflective cracking mitigation approaches (Golestani et al., 2018). A multi-criteria decision support model was created to help with the choice of courses in European nations. It is based on the analytic hierarchy process (AHP) and the technique for order of preference by similarity to ideal solution (TOPSIS) and includes several additional complements, including fuzzy logic, Monte Carlo methods, the GRG algorithm, and distance-based aggregation. In a five-step procedure, the decision-making problem was defined, questionnaires were processed, criteria were weighted, alternatives were evaluated, and sensitivity analysis was performed (Jato-Espino et al., 2018). For pavement alternatives, a framework for life-cycle sustainability assessment (LCSA) based on uncertainty was presented to capture the uncertainties related to the economic, environmental, and social pillars across the life cycle (Zheng et al., 2020). To address the issue of non-economic criteria neglect, a three-step hybrid methodology was suggested. Using the DEMATEL technique and assessment laboratory, the causal links of the primary factors influencing the pavement type selection were ascertained. A fuzzy analytic network process (ANP) was then used to establish the relative weight and significance of the various criterion and subcriteria. A fuzzy approach (TOPSIS) was used to rank pavement choices based on how closely they resemble the optimum solution (Pasha et al., 2020). To help decision-makers, this article sought to rank the most significant variables influencing pavement performance using the Analytic Hierarchy Process (AHP). In this study, 29 criteria were rated (Sirin et al., 2021). The distance from the average solution (EDAS), the technique for ordering preferences by similarity to ideal solution (TOPSIS), and the weighted aggregated sum product assessment (WASPAS) as well as three MCDMs were used in the study to rank the chosen additives based on four criteria: mechanical, hydraulic, environmental, and economic (Gupta et al., 2021). An innovative strategy was implemented for choosing urban flood mitigation solutions that are based on a multi-criteria analysis to reduce flood risk, minimize costs, and maximize benefits. The steps included: choosing the best criteria to evaluate alternatives, defining the relative weight of each criterion, scoring each option separately based on each criterion, and combining weights and performances to determine the total score for each option (Alves et al., 2018). Compromise ideal treatment train layouts and sizing combinations of green infrastructure treatment trains were found using the Technique for Order of Preference by Similarity to the Ideal Solution (TOPSIS). To validate the results from TOPSIS, a sensitivity analysis was done by taking into account various weighting strategies for various performance indicators (Jayasooriya et al., 2019). To assist decision-makers in the road sector in selecting the most optimal option and addressing both qualitative and quantitative performance, the AHP and Hellwig method approaches were merged to provide an efficient and productive methodology (Skrzypczak et al., 2020). To officially evaluate the sustainability of pavement engineering alternatives, the author developed a framework and investigated the use of multicriteria decision-making procedures based on the hierarchy process (AHP) and choosing by advantages (CBA). Firstly, the variables were outlined to take into account sustainable pavement management. Finally, a comparison analysis was conducted on the outcomes from the AHP and CBA (Torres-Machi et al., 2019). The study showed how to use AHP as a selection technique for dust palliatives. A comparison of the contenders was done to choose the most suitable among them based on additional criteria. Setting comparison criteria and creating pairwise comparison matrices require expert judgment. For the AHP approach, the maximum number of choices is ten (Melese et al., 2020). To enhance conversation with the decision-makers, the Interactive Multi Objective Optimization-Dominance Rough Set Approach (IMO-DRSA) which is a novel methodology was proposed (Augeri et al., 2019). The development of a decision support system framework for pavement management with an integrated pavement life cycle costs-life cycle assessment model sought to improve the sustainability of the decision-making process for road pavement maintenance (Santos et al., 2018). The TOPSIS and WASPAS multi-criteria decision-making methods were used to evaluate the most common additives employed in porous concrete pavements. Furthermore, the Fuzzy AHP and entropy weighting procedures were integrated and compared. Different additives were combined to determine the best mechanical and safety performance (Elizondo-Martínez et al., 2020). The low-cost pavement management system (PMS) conceptual framework was also made available. The Analytical Network Process (ANP) was used to determine the priority ranks of the PMS indicators, and a sensitivity assessment test was used to validate each rank (Khahro et al., 2021).

2.17 Overview MCDM Methods

In a situation where there are competing criteria, the objective of a multiple criteria decision making (MCDM) problem is to rank and choose among a range of choices. Simultaneous consideration of both qualitative and quantitative criteria is possible using MCDM approaches. There are numerous methods for evaluating MCDM challenges that are based on weighing criteria or evaluating alternative styles.

In MCDM, The first approach corresponds to human approach, which include analytic hierarchy process (AHP) is a widely used method. Thomas L. Saaty (Saaty, 1990) invented this technique, which is dependent upon human preferences (Haktanır & Kahraman, 2024). Inconsistency is a significant disadvantage of AHP in criteria weighting. Only after the pairwise comparison matrices passed the consistency test can the computed priorities in AHP be considered realistic. The DMs offer the values of the elements in the pairwise comparison matrix based on their experiences and skills. The elements are expressed on a numerical scale. Because of these limits in terms of experiences and skills as well as the complexity of the choice problem, the pairwise comparison matrix may therefore be inconsistent (Guillén-Mena et al., 2023). According to AHP, there are $n*(n-1)/\ 2$ comparisons, where n is the number of criteria (Saaty, 1990). As there are more criteria, the number of comparisons can go up gradually. As a result, pairwise comparisons cause inconsistent results (Koczkodaj & Urban, 2018). Additionally, when the number of criterion increases from two to ten, there are 45 comparisons (Ebrahimian et al., 2015). Additionally, when the number of comparisons rises, a significant amount of inconsistency is added. As a result, the number of pairwise comparisons increases in line with the discrepancy. Furthermore, when taking into account the interplay and dependency between high-level and low-level elements, many choice issues cannot be organized hierarchically.

The second approach refers to the mathematical approach, which includes several methods technique for order of preference by similarity to ideal solution (TOPSIS). Typically, TOPSIS uses the Euclidean distance between individual attributes and the ideal solution to estimate the costs and benefits of each attribute (Tüysüz & Kahraman, 2024). Another issue arises from using two distinct references to compare alternatives. TOPSIS, for instance, calculates each alternative's ratio of positive to negative ideals. The option that is most opposite the negative and most similar to the positive is considered the best one. However, this ratio does not guarantee the closeness of the ideal solution (X. Wang, 2009). Due to this, not all evaluations of alternative relation qualities can be revealed by the closeness degree based on Euclidean distance (Kuo, 2017). Furthermore, the only possible ideal solutions are the maximum and minimum values. Between the highest and lowest value is the optimal range for blood pressure measurements. It has been suggested that TOPSIS be improved by measuring weight distance, and the max-min normalization technique has been used to address normalization in an impressive way—the larger the better, and the smaller the better (Hsu et al., 2014). velikekriterijumska optimizacija i kompromisno resenje (VIKOR) is one of the most often used MCDM strategies. By ranking options, this technique simultaneously finds solutions for agreement. A minimum distance from the ideal solution is required as the agreement solution. A balance between individual and group agreement, the evaluations' minimum set of criteria from the perfect solution, and the summing of all criteria from the evaluations' assessments form the basis of these three ranking lists (Oliveira et al., 2023). Using precise and discrete measures, every assessment and weight in the VIKOR approach is calculated. When addressing the verbal perspectives of experts in real-world decision-making situations, this kind of data is not ideal. VIKOR may lead to a situation where an alternative with high measures for most criteria and low value for one criterion is not selected as the optimal alternative, even though it offers significant advantages over other techniques for decision situations. Therefore, VIKOR cannot accurately represent the state of the alternatives and may produce irrational and inconsistent results (Tazzit et al., 2023).

TOmada de Decisão Iterativa Multicritério (TODIM) is one of the earliest MCDM techniques based on the Prospect Theory (G. Yang et al., 2023). The purpose of the TODIM is to pairwise compare the options in terms of gains and losses for each criterion. After passing the gains and losses to the prospect function, the partial dominances are obtained. The ultimate domination is then formed by adding the partial dominances. This final dominance essentially determines the rank order of the options. Only discrete numbers are handled by the TODIM method in its conventional formulation. While TODIM has been extensively modified to handle various forms of data, there hasn't been much effort put into adapting it to handle heterogeneous data. The TODIM approach was expanded to handle fuzzy, interval-valued, and crisp numbers simultaneously (Divsalar et al., 2023).

2.18 Theoretical Model Development

MCDM is a branch of operational research that focuses on finding the best outcomes in complex situations with various criteria. Despite all efforts, there are still unresolved problems with MCDM approaches' handling of imprecise and ambiguous situations brought on by decision makers' (DMs') hesitation. To address these problems, numerous MCDM techniques are expanded under various fuzzy set contexts. Many different kinds of fuzzy sets, such as intuitionistic fuzzy sets (IFSs) (Ebrahimnejad et al., 2015) and hesitant fuzzy sets (HFSs) (Gitinavard et al., 2016), are designed to manage ambiguous and imprecise information. The dual hesitant fuzzy sets (DHFS), which combine the benefits of intuitionist and hesitant concepts, were introduced by (Zhang et al., 2017). DMs can indicate their reluctance by using HFSs, which allow the membership grade to be linked to more than just two alternative values (Zhang et al., 2017). DHFS offers membership (GM) and nonmembership levels, just like IFSs (GNM). But rather than a single number, these grades are represented by a numeric range. When illustrating real-world issues, this feature is precise and flexible. For instance, in a company, some DMs give the GM and GNM of alternative A that satisfies criterion x 0.6 and 0.3, respectively. Some may choose to put (0.8, 0.2), whereas others may put (0.7, 0.2). These DMs are inconsistent with one another. As a result, the difficulty in defining a common GM and a GNM is caused by the presence of a set of potential values rather than the presence of an error margin (IFS) (HFS). The DHFS elements (0.6, 0.8, 0.7, 0.3, 0.2) in this case differ from the IFS numbers (0.8, 0.2 or 0.7, 0.2), and the HFS values (0.6, 0.8, 0.7) in that they reflect the desired degrees.

For group decision-making problems where determining the h and g functions is challenging, DHFS is particularly beneficial (Yu, Li, et al., 2016). The fuzzy decision by opinion score method (FDOSM) (Salih et al., 2020) has been demonstrated to be particularly effective in overcoming various issues in MCDM in the context of MCDM approaches. FDOSM chooses the best answers for each criterion in an opinion matrix, relying on the knowledge of professionals (DMs) to arrive at logical judgments. FDOSM is restricted to explicitly weighting the criterion, though. To determine the relative importance of each pavement criterion, it is necessary to use an outside method, such as the fuzzy-weighted zero-inconsistency (FWZIC) method (Zhang et al., 2017). It has been suggested to use FWZIC to determine the subjective weights of the criteria with zero inconstancies (Zhang et al., 2017). To solve ambiguous and imprecise difficulties, FDOSM and FWZIC have been merged with a variety of fuzzy sets, including Pythagorean fuzzy sets, T-spherical fuzzy sets, and q-rung Orthopair fuzzy sets (Alsalem et al., 2021) (Albahri et al., 2022). This article creates a new, unified MCDM framework inside the context of DHFS, driven by the aforementioned problems. It is expected that the usage of this MCDM technique including DH-FWZIC and DH-FDOSM can integrate the pavement criteria identified into one single and holistic framework for decision-making purposes.

2.19 Summary of Chapter

This chapter had reviewed the studies related to our scope of research which is essential to achieve the research objectives. A systematic literature review for pavement techniques along with decision-making methods was conducted to clarify and outline the challenges, motivations, and stakeholders in pavement selection. In the literature review studies found out that ranking and prioritizing the alternatives are the main challenges in the selection best pavement techniques. Following the literature review, it was concluded that no study has yet presented an evaluation framework for selecting the most optimal pavement techniques. For these reasons, a multi-criteria decision-making method was used as a recommended solution that can deal with this issue. MCDM techniques and definitions are illustrated in this chapter along with the protocol to present all MCDM methods that have been used to build the pavements. The next chapter will propose new MCDM weighting and ranking methods that could successfully help address the issues in literature (e.g. inconsistency, imprecise and ambiguous information).

CHAPTER 3

METHODOLOGY

3.1 Introduction

Based on the objectives of this research, this chapter presents the research methodology, identifies the pavement alternatives and evaluation criteria to develops a new formulation. The main aim is to develop a novel pavement technique methodology for weighting the evaluation criteria and ranking the alternatives of pavement selection decision makers based on the dual hesitant fuzzy-weighted zero-inconsistency (DH-FWZIC) method and the dual hesitant fuzzy decision by opinion score method (DH-FDOSM), respectively. The necessary steps have been created to move seamlessly between the objective stages to achieve the objective of this research. Three main objective phases make up the research methodology chapter. The first one is the identify the selected alternatives along with the evaluation criteria for building the metric matrix. This is followed by the development of a new weighting method (DH-FWZIC) for weighing the criteria according to the alternatives and a new selection method (DH-FDOSM) for selecting the best alternative. Finally, an evaluation and comparison analysis is conducted to evaluate the proposed new MCDM method. All these stages are shown in the methodology flowchart in Figure 3.1. Below is an explanation of the stages in the study methodology.

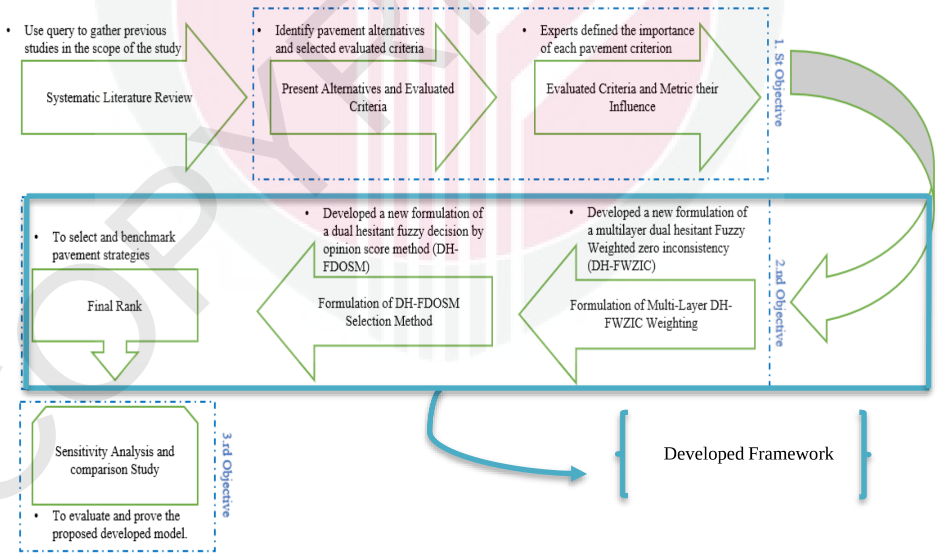


Figure 3.1 : Methodology Flowchart

3.2 Systematic Literature Review Protocol

The systematic review protocol begins with the selection of the sources of information followed by the search strategy which entails the inclusion and exclusion criteria, and ends with a full paper reading to obtain the final set of articles to be used as references for the data collection. Figure 3.2 demonstrates the main stages of the systematic literature review.

3.3 Research Information Sources

Four data sources (Web of Science, Science Direct, Scopus, and Springer) are used to get the latest published articles over a five-year period (i.e., 2015-2020). Several keywords are combined to build the query including ("heat island" OR "Urban heat" OR "Urban heat-island" OR "UHI" OR "Urban warming") AND (pollution OR thermal) AND (mitigate* OR adapt*). These are used in the search engine of the four data sources. The highest number of extracted articles comes from Web of Science followed by Science Direct, Springer, and Scopus.

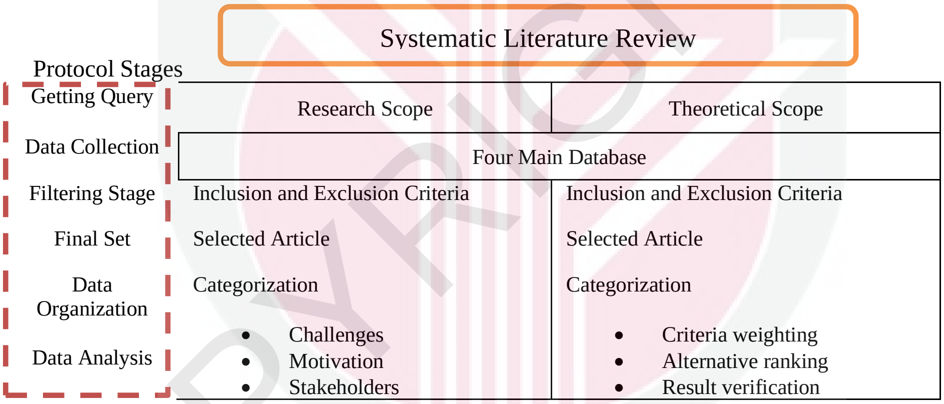


Figure 3.2 : Systematic Literature Review Process

3.3.1 Inclusion and Exclusion Criteria

All the articles derived from the previous step are screened using specific criteria such as the language used and the type of article. Articles with case studies as well as practical, simulation, experimental, and numerical assessments are kept in order to use their results for the comparative study. Articles that do not talk about the study topic are excluded.

3.3.2 Selected Articles

The final set of selected articles is ready once the filtering process is complete. A quick scan of the titles and abstracts is carried out to exclude all irrelevant articles. Next, all duplicated articles are screened and excluded. Finally, a deep review is conducted on the filtered articles, entailing a full-text reading, as shown in figure 3.3.

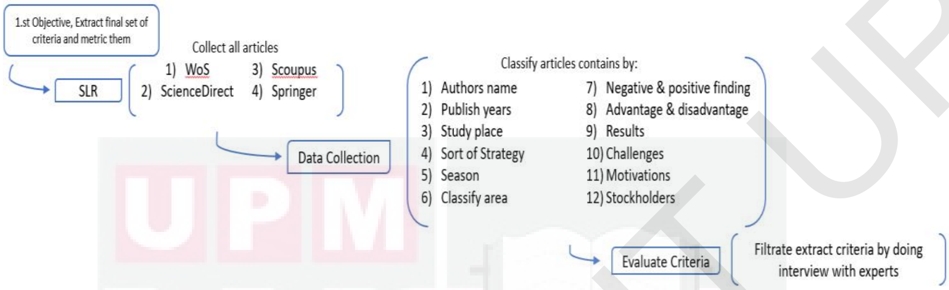


Figure 3.3 : Filtering Evaluate Criteria

3.3.3 Data Organization

Extracted information from the selected articles is organized by using Mendeley and Excel software. Each paper is read as a full text. The collected and extracted data are organized and categorized according to title, name of authors, year of publication, article type, place of study, mechanism type, pavement type, season, classified area, developing or development city, type of findings, type of methodology used, interview, simulation, field experimental, laboratory, objectives, and limitations. Furthermore, the challenges, motivation, stakeholders, and future study also make up the main classification of the articles. This helps in identifying the research gap. In appendex A shows how the articles are clasified according to the descriptions above.

3.4 Theoretical Information Sources

In this part, another query is created to collect articles which use the theoretical methods by decision-makers, published over the 2016-2021 period. The query is: ("MCDM" OR "MADM" OR "Multi Criteria Decision Making" OR "Multi Attributes Decision Making" OR "Multi Criteria Decision Analysis") AND (pavement OR paving OR pav*). The same protocol is applied when collecting relevant articles from the four databases (ScienceDirect, Web of Science, Scopus, and Springer). They are then filtered using the inclusion and exclusion criteria. The final set entails 47 papers out of 1317, including 16 duplicates and 1 that is not written in English.

3.5 To identify Pavement Alternatives and Related Criteria

The first step in MCDM as shown in Figure 3.4 is to identify evaluated pavement criteria.

According to the systematic literature review results, there are many pavement types used worldwide (Anupam et al., 2021). Some of these pavement techniques were built traditionally and classified into two different types of structure design, material, and environmental impact which are flexible and rigid pavements. Some modifications and changes have been done to those two types of pavements to adjust their environmental as well as social and economic impacts. These changes include modifying the structure design or using a material to fabricate a new structure road to have positive effects on the three tenets of sustainability (environmental, social, and economic). "Cooling pavement" is the term used to identify these new structure roads. In this study, focus is on the types of pavements commonly used and of which have more studies, information, or data to be able to distinguish between pavement alternatives (Anupam et al., 2021; Xu et al., 2021). This study obtains two main groups of alternatives including four pavement techniques namely flexible/asphalt, rigid/concrete, reflective, and evaporative pavement techniques. And 30 evaluated pavement criteria separated to three layers. In first layer three general evaluation criteria (GEC) namely: environmental, economic, and social, and two specific evaluation criteria (SEC) namely: initial cost, and region's environment. Under these criteria, there are other sub-criteria which must be investigated to determine their impact on pavement performance and how they are affected by the pavement. Second layer criteria: UHI, Local Environment, Pavement Limitation, Aged, Physical Properties, Maintenance, Implementation, Energy Usage, Strength, Human Comfort, Road Safety, Urban Surface, Air Temperature, Urban Design, Day and Night Difference, Season, and Shading. Last layer criteria: Climate, Water, Wind, Reflective, Absorb, Permeability, Cost, and Frequency. This methodology path has been published in Q1 journal "IEEE Transaction on Fuzzy Systems" (Ismael et al., 2023).

All alternatives and criteria are defined and identified in Chapter 4. Section 4.2 demonstrates the alternatives' definitions whereas Section 4.3 explains the candidate evaluation criteria.

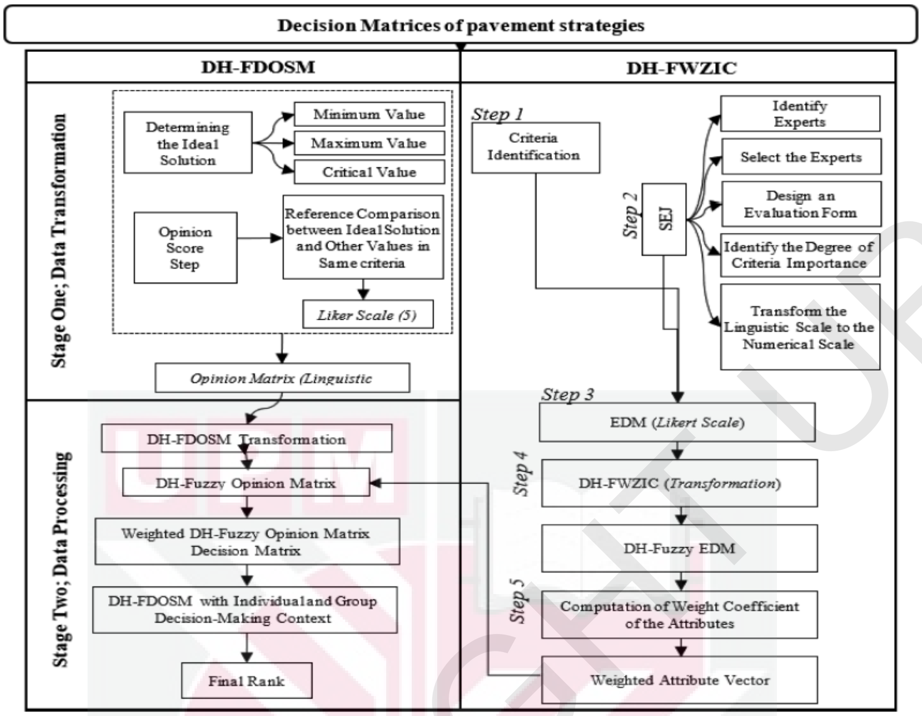


Figure 3.4 : Phases of the Proposed Method (Ismael et al., 2023)

3.5.1 Reviewing and Starting Steps

Pavement technique definitions were taken from the literature studies and identified as alternatives. Previous studies have been reviewed and analyzed in the literature chapter. The in-depth definitions and explanations for the candidate alternatives had also been presented. The relative evaluation criteria and sub-criteria had been collected and identified as well, along with a systematic review protocol. The scope of study is limited to the most common pavement technologies to avoid any missing data. The inclusion and exclusion criteria are applied to screen and filter the articles. Critical analysis is conducted on the final set of articles to identify the gaps and main challenges in evaluating and ranking the alternatives.

3.5.2 Alternative Definition

Four pavement types are identified and selected in this study to determine the differences between them based on 30 criteria and sub criteria. The definitions of the alternative and criteria are made by referring to previous studies. Firstly, two main category derivatives from the pavement techniques are identified to be with or without cooling techniques. Flexible/asphalt and rigid/concrete are those to be without cooling technique group, while the reflective and permeable types are those to be with cooling techniques group.

3.5.3 Criteria Definition/step 1

The extracted criteria from the literature are explored and explained as the full definition to help decision-makers in understanding and evaluating the pavement criteria of the alternatives. All criteria are sorted into groups according to impact field and target area. The evaluation criteria are examined and divided into two major categories: the general evaluation criteria (GEC) which present all criteria without consideration of the area and region, and the specific evaluation criteria (SEC) which is more specific to a region and particular area. In addition, the GEC has three layers of criteria. As shown in the Table (3-1), The first layer of the GEC is A1 (environment), B1 (economy), and C1 (social). The second layer consists of eleven criteria: A1-1 (UHI), A1-2 (local environment), A1-3 (pavement limitation), B1-1 (aged), B1-2 (physical properties), B1-3 (maintenance), B1-4 (implementation), B1-5 (energy usage), C1-1 (strength), C1-2 (human comfort), and C1-3 (road safety). The last layer of the GEC consists of eight criteria: A1-3-1 (climate), A1-3-2 (water), A1-3-3 (wind), B1-2-1 (reflective), B1-2-2 (absorb), B1-2-3 (permeability), B1-3-1 (cost) and B1-3-2 (frequency). Next, the first layer of the SEC consists of two criteria: A2 (initial cost) and B2 (region's environment). Its second layer consists of six criteria: A2-1 (urban surface), A2-2 (air temperature), A2-3 (urban design), A2-4 (day and night difference), A2-5 (season), and A2-6 (shading). All these alternatives and criteria are used in this study to create the evaluation decision matrix of the pavement techniques.

Table 3.1 : Evaluation Criteria Codes

General Criteria	
A1	Environment
B1	Economy
C1	Social
A1-1	Urban Heat Island (UHI)
A1-2	Local Environment
A1-3	Pavement Limitation
A1-3-1	Climate
A1-3-2	Water
A1-3-3	Windy
B1-1	Aged
B1-2	Physical Properties
B1-2-1	Reflective
B1-2-2	Absorb
B1-2-3	Permeability
B1-3	Maintenance
B1-3-1	Cost
B1-3-2	Frequency
B1-4	Implementation
B1-5	Energy Usage
C1-1	Strength
C1-2	Human Comfort
C1-3	Road Safety

Specific Criteria	
A2	Region's Environment
B2	Economy / Initial Cost
A2-1	Urban Surface
A2-2	Air Temperature
A2-3	Urban Design
A2-4	Day & Night Difference
A2-5	Season
A2-6	Shading

The way was used to classify the second and third layers criteria is by determine which criteria are belong to another criteria. Such as Climate, water, and windy effects on pavement performance. Reflective, absorb, and permeability all are pavement properties. Cost and frequency which are determine the maintenance cost and how often.

3.6 Evaluate Criteria and Metrics Affecting Pavement Performance

According to (Alsalem et al., 2021), MCDM involves decision-making in situations with multiple criteria. Instead of relying on deductive analysis, the present study will employ qualitative analysis methods. Prior studies by (Alsalem et al., 2021), (Ibrahim et al., 2023), and Qahtan et al. (2022) have effectively employed structured interviews with three respondents to develop MCDM models. For instance, these studies have examined the prioritization of COVID-19 vaccine doses, sustainability assessment of palm oil industry 4.0 technologies, and sustainable transportation modeling, respectively. Four respondents will participate in structured interviews as part of this study's data collection procedure.

Four experts shown in Table 3.2 are used to process the framework beginning with scoring the pavement criteria to build the expert decision matrix (EDM). For this study, a few definitions had been developed to ensure the expertise of the experts, as shown below:

Years of Experience: Experts must have a minimum of 10 years of experience in the field of civil engineering, specifically in the area of road and pavement construction.

Degree Qualification: Experts must hold a minimum of a bachelor's degree in civil engineering.

Certification Level: Experts must possess at least a fundamental engineer (FE) level. FE certificate is the first of the two exams engineers must pass in order to become licensed professional engineers (PE) obtain by National Council of Examiners for Engineering and Surveying (NCEES) institute.

Table 3.2 : Demographic of Experts

Expert	Company	Position	Year of Experiance
E1	A&M University	Associate Professor	16 Year
E2	AECOM	Project Manager	14 Year
E3	LJA Engineering	Project Engineer	10 Year
E4	SLB	Project Engineer	13 Year

3.6.1 Structured Expert Judgment/Step 2

The criteria for experts are those who are highly knowledgeable and experienced in the construction scope. The collection data form was designed and organized to be ready to collect data. The experts determine the form's reliability and validity. The importance and significance level of each evaluated criterion is determined using the Likert scale as shown in Table 3.3. The numerical representation scale column (1 to 5) meets the linguistic representations column with five levels (very low importance, low importance, medium importance, high importance, and very high importance) to get their equivalent fuzzy representation (DHFNs) membership degree $\tilde{h}$ and non-membership degree $\tilde{g}$ (Calache et al., 2021). Whereby 1 = very low importance (VLI), 2 = low importance (LI), 3 = (MI) medium importance, 4 = high importance (HI), and 5 = very high importance (VHI). The language terms' numerical equivalents are shown in Table 3.3.

Table 3.3 : Linguistic Terms and Their Corresponding DHFNs

Linguistic scoring scale	Numerical scoring scale	DHFNs $\tilde{h}$	$\tilde{g}$
Very Low Importance (VLI)	1	0.10	0.85
Low Importance (LI)	2	0.23	0.65
Medium Importance (MI)	3	0.50	0.50
High Importance (HI)	4	0.75	0.20
Very High Importance (VHI)	5	0.90	0.05

(Calache et al., 2021)

3.6.2 Building Expert Decision Matrix (EDM)/Step 3

This step uses the results from Step 2 to build the expert decision matrix (EDM) for each expert. Pavement criteria are intersected by an expert panel, with each expert scoring the overall relevance of each pavement criterion. The results of this step (i.e., EDM) are used to feed the next step for further analysis.

3.7 Developed a New Formulation of a Multilayer Dual Hesitant Fuzzy Weighted Zero Inconsistency (DH-FWZIC)/Step 4-5

A new formulation of the DH-FWZIC for weighting the pavement evaluation criteria of the EDM is developed in the next step.

3.7.1 DHFS Membership Function Application/Step 4

The four Expert Decision Matrices (EDM) data in this step are transformed to DHFS-EDM by applying the Dual Hesitant Fuzzy Sets (DHFS) membership function. It is challenging to give each criterion a specific preference, so the transformation process is essential. To solve or reduce the uncertain and imprecise information caused by the experts' hesitancy, the fuzzy sets are utilized instead of crisp numbers.

Calache et al. (2021) and B. Zhu et al. (2012) defined the DHFSs as an extension of the HFSs. Given a fixed set U, a DHFS D in X is represented as $\widetilde{D} = \{x, \tilde{h}_{\widetilde{D}}(x), \tilde{g}_{\widetilde{D}(x)} \mid x \in U\}$, in which $\tilde{h}_{\widetilde{D}}(x)$ and $\tilde{g}_{\widetilde{D}(x)}$ are in the range [0,1] denoting the degrees of membership and non-membership of the element $x \in U$ to set D, respectively, under the conditions: $0 \leq \gamma, \eta \leq 1$ and $0 \leq \gamma^{+} + \eta^{+} \leq 1$, for all $x \in U$ $\gamma \in \tilde{h}_{\widetilde{D}}(x), \eta \in \tilde{g}_{\widetilde{D}}(x), \gamma^{+} \in \tilde{h}_{\widetilde{D}}^{+}(x) = \cup_{\eta \in \tilde{g}_{\widetilde{D}}(x)}$ Max $\{\eta\}$.

The following DHFS arithmetic operations are adopted from Calache et al. (2021) and Du (2021). For the DHFS aggregation operation (DHFA), Equation (1) is utilized:

$$\text{DHFA}\left(\tilde{d}_1, \tilde{d}_2, \ldots, \tilde{d}_n\right) = \oplus_{j=1}^{n} \left(\tilde{d}_j\right)$$
$$= \cup_{\tilde{\gamma}_j \in \tilde{h}_j, \tilde{\eta}_j \in \tilde{g}_j} \left\{\left\{1 - \prod_{j=1}^{n}(1 - \tilde{\gamma})\right\}, \left\{\prod_{j=1}^{n}(\tilde{\eta})\right\}\right\} \quad (1)$$

For the DHFS division operation, Equation (2) is used.

$$= \begin{cases} d_1 \oslash d_2 & \cup_{\tilde{\gamma}_1 \in \tilde{h}_1, \tilde{\gamma}_2 \in \tilde{h}_2, \tilde{\eta}_1 \in \tilde{g}_1, \tilde{\eta}_2 \in \tilde{g}_2} \left\langle \frac{\tilde{\gamma}_1}{\tilde{\gamma}_2}, \frac{\tilde{\eta}_1 - \tilde{\eta}_2}{1 - \tilde{\eta}_2} \right\rangle, \text{if } 0 \leq \frac{\tilde{\gamma}_1}{\tilde{\gamma}_2} \leq \frac{1 - \tilde{\eta}_2}{1 - \tilde{\eta}_2} \leq 1 \\ \langle 1,0 \rangle, & \end{cases} \quad (2)$$

The linguistic rating scale and corresponding DHF numbers are shown in Table (3-3) (DHFNs). In this phase, DHFNs are used in place of the numerical scoring scales that correspond to the linguistic scoring scale (Step 2).

Equation (3) (Alsalem et al., 2021) is used to defuzzify the DHFNs and transform them into crisp values as seen below:

$$S(d_j) = \frac{1}{\#\tilde{h}} \sum_{\tilde{\gamma}_j \in \tilde{h}_j} \tilde{\gamma}_j - \frac{1}{\#\tilde{g}} \sum_{\tilde{\eta}_j \in \tilde{g}_j} \tilde{\eta}_j \quad (3)$$

3.7.2 Evaluation Criteria's Weight Coefficients Calculation

After discovering the fuzzified paving criterion data, the next step is to utilize these data to calculate the weight coefficients for the final criterion as follows:

a) Equations (1) and (2) are used to calculate the fuzzified data ratio. Equation (4) below shows the process in its symbolic form.

$$\tilde{E}_{ij} : \tilde{C}_{ij} = \frac{\text{Im}\,(\widetilde{E1}/C1)}{\sum_{j=1}^{n} \text{Im}(\widetilde{E1}/C_{1j})} \quad (4)$$

where $Im(\widetilde{E1}/C_{1j})$ is the fuzzy number of $Im(E1/C1)$

b) In this extension of multi-layer dual hesitant fuzzy weight zero-inconsistency (DH-FWZIC), the defuzzification is implemented on the DH-EDM to convert all fuzzy values ($\tilde{E}_{ij}$: $\tilde{C}_{ij}$) to crisp values (E_{ij}: C_{ij}) by using Equation (3) before calculating the mean values due to the DHFS fuzzy environment.

c) The final weight values of the pavement criterion are calculated using the mean, and Equation (5) represents this process symbolically. The weight allocated to each criterion for rescaling should be decided by the total of all the criteria weights.

$$W_j = \left(\sum_{i=1}^{m} E_{ij} : {}^{C_{ij}}/_{m}\right) \text{, for } i = 1, 2, 3, .. m \text{ and } j = 1, 2, 3, .. n. \quad (5)$$

3.8 Developed a New Formulation of a Dual Hesitant Fuzzy Decision by Opinion Score Method (DH-FDOSM)

FDOSM is developed into DH-FDOSM, i.e., an extended version (Salih et al., 2020) that can assist in selecting and benchmarking the pavement techniques to rank the pavement alternatives. Two steps show how the DH-FDOSM formulation is conducted.

Step one: Data Transformation Unit

The decision matrices are transformed into opinion matrices as follows:

The ideal solution in the decision matrices of each criterion or sub criterion is selected if obtainable by using Equation (6)

$$A^* = \{[(max_i\, v_{ij}\, |j \in J), (min_i\, v_{ij}\, |j \in J)(Op_{ij} \in I.J)|i = 1.2.3 \ldots\ldots m\} \quad (6)$$

The max represents the ideal solution of the benefit, and by contrast, the min represents the ideal solution of the cost, whilst the $Opij$ reflects the ideal solution of the critical criteria. The literature review chapter had explained and defined each of these criteria. Next, the differences between the ideal solution and all the pavement technique values under that criterion are compared. A five-point Likert scale is used for the comparison process. Equation (7) describes the comparison process.

$$Op_{\text{Lang}} = \left\{\left((\tilde{v}_{ij} \otimes v_{ij}|j \in J)\,.\,\middle|\,i = 1.2.3 \ldots\ldots m\right)\right\} \quad (7)$$

where ⊗ refers to the comparison process between the ideal solution and the value of alternatives in the same criterion. The outcome of this step is opinion matrices (equation

(8) filled with linguistic terms by the selected experts (four paving experts) is ready to be transformed into a fuzzy opinion matrix by equation (8).

$$Op_{\text{Lang}} = \begin{array}{c} A_1 \\ \vdots \\ A_m \end{array} \begin{bmatrix} op_{11} & \cdots & op_{1n} \\ \vdots & \ddots & \vdots \\ op_{m1} & \cdots & op_{mn} \end{bmatrix} \tag{8}$$

Step Two: Data Processing Unit

Four opinion matrices resulting from the previous stage are transformed into fuzzy opinion decision matrices in this stage. Table 3.4 shows the linguistic terms in opinion matrices replaced with DHFNs (Alsalem et al., 2021). The linguistic representation column starts with the best level scale (No Difference) and ends with the lowest level scale (Huge Difference) in the opposite way of Table 3.3 which impact on $\tilde{h}$ and $\tilde{g}$ value in the opposite way as well.

Table 3.4 : Linguistic Terms and Their Corresponding DHFNS

Linguistic scoring scale	DHFNs	
	$\tilde{h}$	$\tilde{g}$
No Difference (ND)	0.90	0.05
Slight Difference (SD)	0.75	0.20
Difference (D)	0.50	0.50
Big Difference (BD)	0.23	0.65
Huge Difference (HD)	0.10	0.85

(Calache et al., 2021)

The result of Step One is four opinion matrices transformed into fuzzy opinion decision matrices. The table below shows how to replace opinion matrices with DHFNs.

In this study, individual and group decision-making (GDM) contexts are provided as two benchmarking pavement technique situations. To comprehensively assess and benchmark the pavement techniques, the obtained weights of each pavement evaluation criterion are used in the DH-FDOSM. Using either the dual hesitant fuzzy weighted averaging (DHFWA) operator, as indicated in Equation (9) (Calache et al., 2021), or the dual hesitant fuzzy weighted geometric (DHFWG) operator, as given in Equation (10) (D. Yu et al., 2016), each fuzzy opinion matrix can be aggregated. Both operators are used in the current study to rank pavements.

$$\text{DHFWA}\left(\tilde{d}_1, \tilde{d}_2, \ldots \tilde{d}_n\right) = \oplus_{j=1}^{n}\left(\omega_j\, \tilde{d}_j\right)$$
$$= \cup_{\tilde{\gamma}_j \in \tilde{h}_j, \tilde{\eta}_j \in \tilde{g}_j} \left\{\left\{1 - \prod_{j=1}^{n}(1-\tilde{\gamma})^{\omega_j}\right\}, \left\{\prod_{j=1}^{n}\left(\tilde{\eta}\right)^{\omega_j}\right\}\right\}. \tag{9}$$

$$\text{DHFWA}\left(\tilde{d}_1, \tilde{d}_2, \ldots \tilde{d}_n\right) = \oplus_{j=1}^{n}\left(\tilde{d}_j^{\,\omega_j}\right)$$
$$= \cup_{\tilde{\gamma}_j \in \tilde{h}_j, \tilde{\eta}_j \in \tilde{g}_j} \left\{\left\{\prod_{j=1}^{n}(\tilde{\gamma})^{\omega_j}\right\}, \left\{1 - \prod_{j=1}^{n}\left(1 - \tilde{\eta}\right)^{\omega_j}\right\}\right\}. \tag{10}$$

The findings are then combined using Equation (3) to defuzzify it and produce a score value for each pavement technique. The generated scores are ranked, with the best pavement technique having the greatest score. The benchmark results must be aggregated in order to account for the differences in benchmark values of the paving technique among DMs. Therefore, the GDM context with DH-FDOSM is used in this investigation. Equation (11) is used to determine the final GDM score using the arithmetic mean. The best paving technique is the one with the highest score value.

$$\text{Group DH} - \text{FDOSM} \ = \oplus S^{*} \tag{11}$$

where ⊕ represents the arithmetic mean and S* represents the final rank of each expert.

3.9 Framework Validation

There are three methods used to validate the framework. First is through sensitivity analysis to evaluate the developed framework's robustness and identify potential weaknesses that may require further refinement or calibration. Second is by using comparison study to enable testing of the framework against alternative frameworks or methods currently in use. Third is through focus group discussion to get feedback from a group of individuals who have experience or expertise related to the developing multi-criteria decision-making framework for pavement selection strategy.

3.9.1 Sensitivity Analysis

Sensitivity analysis is a valuable tool for improving our understanding of complex models. By examining the impact of changes in input parameters on the model's output, sensitivity analysis can provide insights into how the model works and which parameters are most important in determining its results. Moreover, by identifying weaknesses in the model's framework, modifications can be made to improve its accuracy. Additionally, sensitivity analysis can provide a measure of the uncertainty associated with the model's results, which can increase confidence in its ability to predict outcomes. Finally, by highlighting the key drivers of the model's outcomes and the uncertainties associated with them, sensitivity analysis can aid in the communication of results to stakeholders. In summary, sensitivity analysis is a powerful tool that can enhance our understanding of models, improve their accuracy, increase our confidence in their results, and facilitate communication with stakeholders.

3.9.2 Comparison Study

Comparison studies are valuable in several ways. First, they serve as a benchmark for evaluating the performance of a developed framework. By comparing it to established frameworks or approaches, researchers can gain insights into how well their framework performs and identify areas that require further refinement or improvement. Second, comparison studies provide validation for the developed framework. By demonstrating its effectiveness in comparison to other approaches, confidence in the framework's ability to produce accurate and useful results is strengthened. Third, such studies help identify the strengths and weaknesses of the developed framework. By comparing its performance to other approaches, researchers can pinpoint areas where it excels or falls short, allowing for targeted refinement and improvement. Lastly, comparison studies facilitate communication between researchers and stakeholders. They provide a common reference point for understanding the developed framework's capabilities and limitations, enabling stakeholders to make informed decisions and engage in meaningful discussions. Overall, comparison studies play a crucial role in benchmarking, validation, identification of strengths and weaknesses, and enhancing communication surrounding a developed framework.

3.9.3 Focus Group Discussion

Focus Group Discussions (FGDs) offer several advantages for validating a framework. Firstly, FGDs gather a group of individuals who provide diverse perspectives on the framework being studied. This enables the identification of common themes, areas of agreement or disagreement, and potential issues or concerns that may have been overlooked by other validation methods. Secondly, FGDs yield rich data by capturing participants' attitudes, beliefs, and experiences related to the framework. By actively listening to participants' discussions and probing further, researchers can gain a comprehensive understanding of how the framework is perceived and used in practice. Thirdly, FGDs facilitate discussion and interaction among participants, fostering an environment where areas requiring further refinement or clarification can be identified. The collective brainstorming and exchange of ideas within the group can reveal valuable insights. Lastly, FGDs serve as a means to validate assumptions made during the framework's development. By prompting participants to share their experiences, researchers can assess whether the assumptions hold true in practice. This validation process ensures the framework's applicability and effectiveness. In summary, FGDs provide the benefits of gathering multiple perspectives, generating rich data, facilitating discussion, and validating assumptions, thereby enhancing the overall validation of the framework.

3.10 Summary of Chapter

This chapter illustrated the research methodology used to successfully achieve the research objectives. Four sections demonstrate the research methodology. Each section represents one or more of the research objectives. The first objective identified specific definitions for the alternatives and evaluated the criteria identified via the systematic literature review explained in the previous chapter. This is followed by an evaluation of the criteria and metrics that influence pavement performance.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

The results of the systematic literature review, which is part of the first objective, are presented in this chapter. Four alternatives are divided into two groups. The classification, definition, and clarification are presented in Section 4.3. Meanwhile, the 30 evaluated criteria are explained in Section 4.4. In Section 4.5, the decision matrix evaluation results are constructed and the DH-FWZIC is applied to obtain the weight of the selected criteria and sub-criteria based on the four paving experts to assess the degree of importance of all the collected criteria. After that, the DH-FDOSM is implemented to rank the pavement alternatives based on the contexts of individual decision-making and group decision-making. Finally, Section 4.6 evaluates the robustness of the developed framework via the sensitivity analysis, comparative research, and model validation.

4.2 Systematic Literature Review (SLR) Results

The next sub-sections present the results of the systematic literature review for both research and theoretical scope.

4.2.1 Research Scope Results

This section presents the results of the SLR of the first query. A total of 4,021 articles are obtained, in which 1024 are from Web of Science, 1956 from Science Direct, 802 from Scopus, and 1367 from the Springer database. After applying the inclusion and exclusion criteria, and subtracting 56 duplicate articles, the total number of articles remaining is 261. Finally, the articles are filtered to 45 articles concentrating on the UHI phenomenon associated with counterbalance policies such as cool pavements to reduce emissions to the surrounding areas. All these steps are illustrated in Figure 4.1.

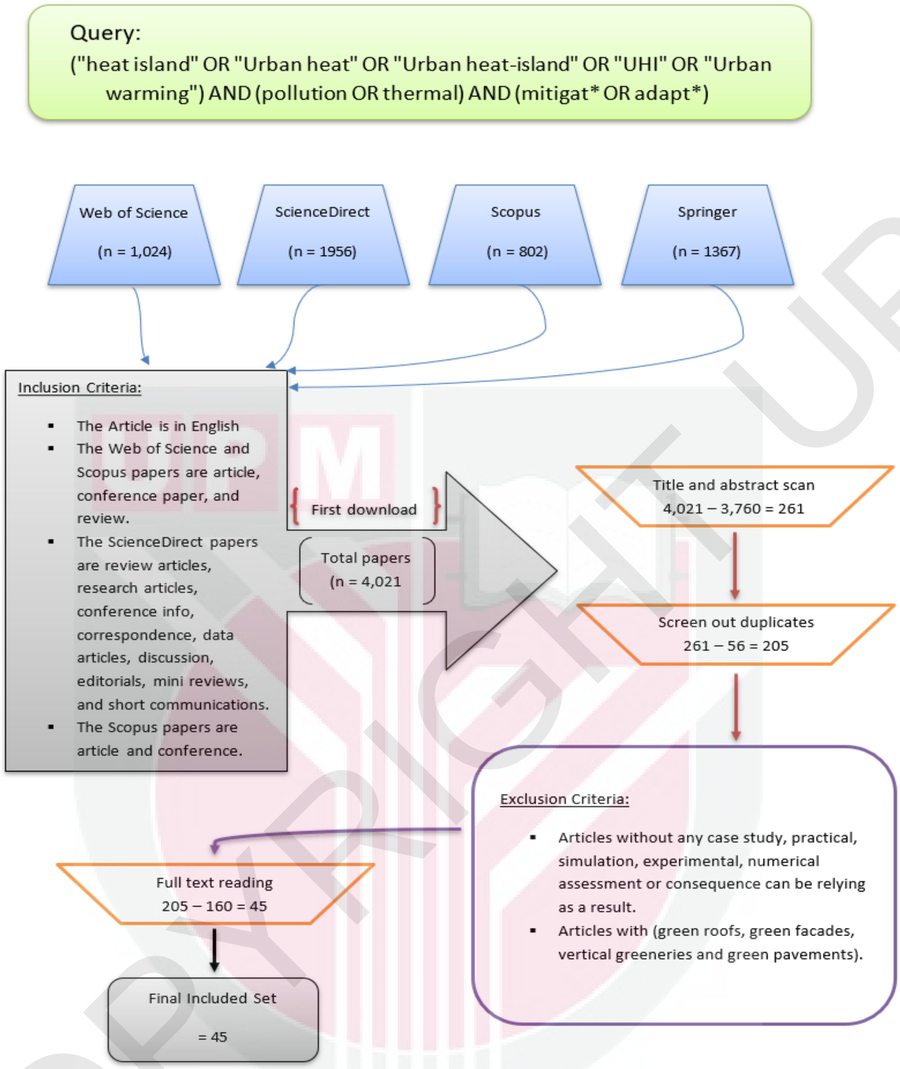


Figure 4.1 : Research Scope Systematic Literature Review Flowchart

4.2.2 Theoretical Scope Results

In this part, another query is developed to collect articles which use the theoretical methods by decision-makers, published over the 2016-2021 period. The query is: ("MCDM" OR "MADM" OR "Multi Criteria Decision Making" OR "Multi Attributes Decision Making" OR "Multi Criteria Decision Analysis") AND (pavement OR paving OR pav*). The same protocol is applied to collect the related articles from the four databases (ScienceDirect, Web of Science, Scopus, and Springer), which are then filtered using the inclusion and exclusion criteria. The final set of papers entails 47 articles out of 1317 including 16 duplicates and 1 that is not written in English. Figure 4.2 demonstrates the systematic literature review flowchart of the theoretical scope.

Query: -

("MCDM" OR "MADM" OR "Multi Criteria Decision Making" OR "Multi Attributes Decision Making" OR "Multi Criteria Decision Analysis") AND (pavement OR paving OR pav*)

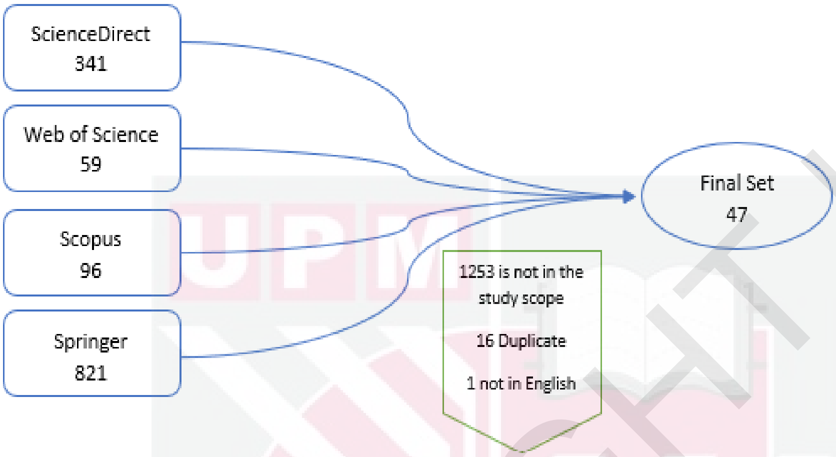


Figure 4.2 : Theoretical Scope Systematic Literature Review

4.3 Alternatives Definitions

As mentioned before, four types of pavements are studied in this investigation. Each pavement is considered as an alternative based on its design, building technique, and mechanical working. These pavements are grouped into two namely: without cooling technique, and with cooling technique. Below are the definitions and explanations of the four different pavement techniques. This classification result sections onwards have been published in Q1 journal "IEEE Transaction on Fuzzy Systems" (Ismael et al., 2023).

4.3.1 Without Cooling Techniques

Pavements without cooling techniques are also known as impermeable pavements. They are further sub-divided into two traditional types of pavements namely flexible/asphalt pavement and rigid/concrete pavement. Both are commonly used around the world. Below are the definitions of these pavements.

4.3.1.1 Flexible Pavement

Also called Asphalt Concrete (AC), Hot Mix Asphalt (HMA) is mostly used to cover main roads and street surfacing which are considered significant sources of UHI. Densely graded texture and low albedo contribute to increased surface temperature which can reach up to 60℃ in summer, thus leading to the development of the UHI phenomenon (Mohajerani et al., 2017). This result section onwards has been published in Q2 journal "IOP Conf. Series: Materials Science and Engineering" (Ismael et al., 2023).

4.3.1.2 Rigid Pavement

This type of pavement is built of portland cement concrete (PCC). Its rigidity and high modulus of elasticity makes it highly durable compared to other pavements and as such, it is used more for heavy load roads. The concrete materials have strong thermal inertia and dark surface color, which allow the structure to absorb solar radiation and maintain high temperatures, thus contributing to environmental warming and the UHI effect. The worst case ever recorded was in Phoenix, Arizona where the temperature reached 138°F (58.9°C) (Ibrahim et al., 2018).

4.3.2 With Cooling Techniques

One of the cooling strategies developed to counterbalance the UHI problem is the application of cooling pavements. The three essential techniques are reflective, evaporation, and harvesting, which are either applied on new pavements or existing ones.

4.3.2.1 Reflective Pavement

This type of pavement reflects solar radiation into the atmosphere to keep the pavement surface cool. The surface has a reflection of 25% or more and can be considered as a reflective surface by making it lighter, i.e., either by painting it with light-color coating or mixing it with light-color materials (Md Tukiran et al., 2015; Al-Humairi et al., 2021**;** Wang et al., 2021). There are two types of reflective pavement:

- Asphalt reflective pavement

  This entails a thin layer of hot bitumen with finely graded aggregate applied on the aged pavement. Many methods can be used such as chip seal, slurry seal, and painting or micro-surfacing with light-color. A slurry seal is costly and decreases chip seal albedo with age (Qin, 2015; Al-Humairi et al., 2021**;** Wang et al., 2021).

- Concrete reflective pavement

  By modifying the mix design, light-colored aggregates and whitish cementitious materials are combined. Some additives such as fly ash increase concrete durability, but at the same time reduce pavement albedo due to the dark color of the material (Qin, 2015; Al-Humairi et al., 2021).

4.3.2.2 Evaporation Pavement

Roads, parking lots, and walkways are examples of paving structures that are able to store water in sub-layers for evaporative cooling. By utilizing thermal energy to evaporate stored water and limit thermal absorption, water-holding in the layers of the pavement keeps the pavement surface cool (Qin, 2015; Al-Humairi et al., 2021**;** Anupam et al., 2021).

- Permeable Pavement Concrete

  Permeable pavers, also known as permeable modular pavers, are made out of a layer of fired-clay or concrete bricks. Permeable pavers do not work as pervious and porous pavers; it permits rainwater to move around the paver rather than through it. Water that accumulates in the surface layer and/or lower layers can evaporate, and the pavers' spacing lugs or tiny perforations which act as evaporation channels help to evaporate the water. The area ratio of the lugs are typically between 8% and 20%. The temperature development of permeable pavers has also been observed. This pavement's temperature is comparable to that of concrete pavement, although it is warmer during the day and colder at night than asphalt pavement (Qin, 2015; Al-Humairi et al., 2021).

- Pervious Pavement Asphalt / Concrete

  A unique form of concrete called a pervious paver has a high porosity level that allows water to run through it rather than around it. Large, single-graded aggregates are coated with concrete paste or an asphalt binder to create pervious concrete. This concrete features a sizable space between the pieces for drainage. Because of how easily the pavement systems drain, the majority of percolating water is not held inside the pervious pavers. The pervious pavements have a larger solar absorptive capacity than conventional pavements and lower thermal inertia which makes the pervious pavements warm as dark asphalt pavements on sunny summer days and in the absence of water. According to additional research, pervious pavements can cool more quickly than regular concrete and have lower overnight temperatures, making them potentially cooler pavements (Qin, 2015; Al-Humairi et al., 2021**;** Anupam et al., 2021).

- Porous Pavement

  Internal pores in porous pavers act as water permeation channels. To hold moisture, these pavers typically have a cellular grid system with holes filled with mud, sand, gravel, or grass. This filler covers anywhere between 20% and 50% of the pavement area. This technique may have a very small cooling impact when dirt, soil, or gravel is utilized as the infill and may be thermally similar to concrete pavement. When grass is utilized as an infill, it encourages transpiration and its roots move moisture from deeper soil to the top where it can evaporate and cool the pavements. These porous pavers often come in the form of open-celled paving grids with grass, plastic Geocells with grass, and reinforced turf or grass paving (Qin, 2015; Al-Humairi et al., 2021 Anupam et al., 2021).

4.3.2.3 Heat Harvesting Pavement

Harvesting pavement is used to lower pavement surface temperature. Concrete pavements are less favored than asphalt pavements because asphalt absorbs more solar radiation. The embedded asphalt solar collectors use the absorbed heat to extract it for use in renewable energy. Combining asphalt solar collectors with a piping system and embedding a generator in the pavement will make the pavement cooler by removing the absorbed heat from the surface layer of the pavement. This technique is performed by installing pipes to conduct fluid in the pavement layers. The most typical pipe fluid is water. A roadside water tank is a convenient place to store the energy captured for future use or as a renewable energy source. The reservoir beneath the pavement may be used to store the heat that was collected to help melt snow in the winter. The pipe's composition, the pavement's materials, how the pipe is set up, and the fluid's flow rate all have an impact on how well the pipe collects heat or how well the pavement cools. The energy efficiency of heat-harvesting pavements has received a lot of research attention from experimental studies, theoretical research, and numerical simulations. Without a pipe, water can also be routed via the pavement. A multilayer asphalt pavement system with two impermeable layers around a center porous layer can conduct water. Laboratory testing shows that this pavement construction can harvest and maintain cool pavement energy (Qin, 2015; Al-Humairi et al., 2021; Xu et al., 2021).

4.3.2.4 Phase Change Material Pavement

A heat-fusion substance that melts and solidifies at a specific temperature is known as a phase change material (PCM). Solid-solid, solid-liquid, solid-gas, and liquid-gas phase shifts are all examples of PCMs. However, due to volumetric stability, only solid-liquid change is appropriate for PCMs in building use. Concrete can either have PCM applied directly or microencapsulated. Unlike other typical building materials such as wallboard, ceilings, and roofs, pavement slabs hardly ever employ PCM. However, any traditional construction material can use the same latent heat storage principles. Theoretically, conventional pavements have a lower heat capacity than PCM-embedded concrete, which results in conventional pavements having larger thermal inertia. In comparison to traditional pavements, this concrete can maintain a lower surface temperature. Latent heat has a huge energy storage and release capacity. When the temperature is relatively low at night, the heat stored is released. The thermal performance of the PCM-doped coating tile has been compared to that of the common coating, and it was discovered that the PCM-doped tile may reduce heat by 3℃ to 8℃ at the heat's peak hours. In addition to the doped approach, PCM was absorbed into the pores of light aggregates, which have been employed to add the PCM-impregnated aggregates to the concrete mix. With the use of this technique, the PCM is prevented from appearing at the cement-aggregate interface, which has been demonstrated to be deleterious to the cement's ability to hydrate and the final strength of PCM-impregnated concrete (Qin, 2015; Al-Humairi et al., 2021; Anupam et al., 2021).

To select the most appropriate pavement, the many criteria that influence pavement performance as well as how the pavements affect other criteria must be taken into consideration.

4.4 Criteria Definitions

- Urban Heat Island (UHI): The UHI is a worldwide problem that jeopardizes the functionality and liveability of our cities and urban ecosystems. The concept of UHI has been well studied and documented, although knowledge on the subject is still fairly restricted. This has altered recently as a result of more attention being paid to global warming and its effects on the climate, the preponderance of hotter cities, and advancements in measurement and analytic technologies. The considerably higher temperatures in our cities compared to the countryside surrounding them is known as the "heat island effect" (Mohajerani et al., 2017). This result section onwards has been published in Q1 journal "IEEE Transaction on Fuzzy Systems" (Ismael et al., 2023).

  - Urban Surface: The warming of urban surface which entails material types that cover most of the constructions such as streets and buildings is a major contributing factor to urban heat island or the UHI phenomenon (Cortes et al., 2016).

  - Air Temp: This refers to the pedestrian level which is from the ground surface raising to 1.5m (Tsoka et al., 2018). Surface reflectance amount has a direct effect on the surface air temperature increase albedo by 0.30 of asphalt and concrete pavements, which may lead to a significant reduction of the air temperature at the human level, reaching 2.0 °C during the hot summer (Tsoka et al., 2018).

  - Urban Design: It is important to emphasize the varying spatial configurations of the study areas, which should be taken into account when determining the different magnitudes of air temperature cooling as a result of cool pavement applications. Urban morphology features like orientation and H/W ratio can significantly affect how much of the canyon surfaces are exposed to direct solar radiation, changing the canyon's overall temperature (Tsoka et al., 2018).

  - Aged: Aged pavement affects reflectance value by either increasing or decreasing it, depending on the material content (Kyriakodis & Santamouris, 2018; Tsoka et al., 2018). For example, the reflectance of the new asphalt material is less compared to the aged asphalt pavement. Take into consideration experimental measurements of albedo variables due to aging (Tsoka et al., 2018).

  - Physical Properties: The layers on the pavement surface are one factor causing the development of heat islands. The pavement materials' physical features such as color, surface texture, and material characteristics had been examined for their ability to cool the structure (Md Tukiran et al., 2015). The physical characteristics of permeable paving materials such as pore characteristics and rainfall conditions have a significant impact on water absorption. The best results are achieved whenever the liquid water stays a long time in permeable paving materials after rainfall or artificial irrigation. Accordingly, the more liquid water absorbed by the permeable paving materials, the higher the moisture content and the longer the duration of the evaporation process for a cooling effect (Junsong Wang et al., 2018).

- Environment: In comparison to typical products, the included technologies result in lower heat storage and lower surface temperatures, which dramatically reduce sensible heat transfer to the environment through convection phenomena (Tsoka et al., 2018). In addition to environmental factors including rain, wind, and sunlight, all are considered during experimental assessments of albedo which entail changes due to weathering (Tsoka et al., 2018). In addition, increasing energy demand during the summer months increases the amount of air pollutants produced by power plants. Rising energy and environmental costs have harmful consequences for cities with larger ecological footprints (Santamouris, 2015).

- Day and Night difference: The primary cause of the convective heat transfer between the pavement surface and near-surface air throughout the day is the absorption of net shortwave solar radiation. Since the surface temperature is the same temperature as the surrounding air at night and the net shortwave solar radiation is almost zero, the convective heat transfer is also virtually zero (Junsong Wang et al., 2018). Concrete pavement has a substantially lower surface temperature than grass and gravel throughout the day because it can hold more heat. However, the surface temperatures of concrete pavement are higher at night, while those of green turf and gravel typically decrease quickly after sunset (Phelan et al., 2015).

- Season: Some cool pavement techniques such as pavement evaporation or shade, for example, are intended to enhance the summer thermal environment but make the winter a little bit colder. Therefore, methods that can only improve evaporation or provide tree shading during the hot summer months are preferred. In the hot summer, conventional impermeable pavements—particularly new black impervious asphalt pavements—produce high surface temperatures of up to 65°–80°C. The impacts of various cool pavement technology on outdoor human thermal comfort are assessed using the outdoor human thermal comfort index in both summer and winter climates (Li, He, et al., 2016).

- Human Comfort: This indicates human comfort outdoors at the pedestrian level. During summertime in hot climates, the high temperatures of pavements and near-surface air can generate severe adverse environmental effects similar to the human index (HI) effect, including decreased human comfort and health issues (Li, He, et al., 2016).

- Strength: The pavement's strength is determined by its design. A fundamental component of pavement design entails determining the equivalent single axle load that a certain pavement will experience over its lifetime (Ibrahim et al., 2018). The structural properties of interest include stiffness, strength, endurance, fatigue, and rutting performance; this list deviates from the presumptions of empirically based designs that use "structural coefficients" of generic material types without taking into account actual mechanical properties (Li, Jones, et al., 2016; Al-Humairi et al., 2021). Flexible pavements are made to flex under loads as horizontal tensile and compressive strains are created in the layers of the pavement. High flexural strength and a greater load distribution area are two advantages of rigid pavements. Therefore, rigid pavements prevent the layers from deforming (Mohajerani et al., 2017).

- Driving Safety: This indicates people's safety on the road. Cool pavement offers higher tire-road resistance, lighter nighttime driving visibility, and therefore better-driving safety than traditional dense pavements following rain. However, additional elements that contribute to driving safety include pieces of dirt on the road, traffic speed, and road resurfacing, in addition to driver visibility and tire resistance (Qin, 2015).

- Economy and Energy use: Energy is needed to heat the aggregate and binder during mixing in the plant to temperatures ranging from 121.1°C to 176.6°C to produce heat mix asphalt (HMA) (Ibrahim et al., 2018). Highly reflective materials can help enhance energy efficiency and traffic safety at night while reducing the UHI effect during the day. High reflectivity coating can decrease energy usage for roadways or outdoor lighting systems aside from thermal concerns (Rossi et al., 2018). High intensity UHI requires more energy for cooling (Taleghani, 2017).

- Initial Cost: This indicates the project cost which is represent capital expenditure (Capex). The selection of pavement type is influenced by a variety of factors, one of which is the initial cost. Because of its low initial prices and rapid building times, asphalt pavement is widely used. Although ultra-thin white topping and roller-compacted concrete pavements have shorter project durations as compared to traditional concrete pavements, asphalt pavements offer less construction time (Al-Humairi et al., 2021). Additionally, pavement owners and manufacturers consider the usage of cool pavements as an additional expense and performance risk (Qin, 2015).

- Maintenance: This indicate to ongoing expenses during running the project which is represent operation expenditure (Opex). The open porous construction is prone to clogging, hence additional expenses are required to remove the clogging dirt in the cavity (Qin, 2015). Concrete pavement requires less upkeep during its lifetime and is more durable than asphalt pavement. For rigid pavement, maintenance is required for flaws such as joint failure, longitudinal cracks, and transverse cracks. Due to its rigidity, it offers a solid surface that is resistant to shoving, ruts, and washboards. Additionally, this pavement reduces the likelihood of potholes (Ibrahim et al., 2018).

The final cost for the project's conclusion will be the combined amount of the Capex and Opex, which we'll refer to as Total Expenditure (Totex), as follows:

$$\boxed{\text{Totex} = \text{Capex} + \text{Opex}}$$

- Implementation: This indicates how easy work is needed to build the pavement. In roadway networks where several utility activities (such as those involving water, power, sewage, pipelines, etc.) are anticipated after initial construction, asphalt pavements are favored. Full replacement of Portland concrete slabs is more costly than the rehabilitation of asphalt concrete (Qin, 2015). Conventional pavements satisfy the requirements of marketing because of their affordable price and practical design.

- Shading: It appears that increasing pavement shading through the use of trees or other means is a highly effective method for lowering pavement surface temperature and physiological equivalent temperature (PET), benefiting human thermal comfort during hot weather by roughly 17% to 28% in the three locations examined (Li, He, et al., 2016). At 16:00, 35.3℃ was reported for the non-shaded pavement and 32.5℃ for the shaded pavement, by nearby buildings and trees with cool pavement cases. At 16:00, 39.3℃ was reported for the non-shaded pavement and 34.5℃ for the pavement by nearby buildings and trees with conventional pavement (Kolokotsa et al., 2018).

- Pavement limitation

  Pavement performance controlled by the weather climate using cool pavement techniques could help people feel more comfortable throughout the warm summer months. During the cold winter months, they could also have some unfavourable consequences. The winter results did show that there are some concerns regarding the cool pavements. For example, in Sacramento, California, the summers are warm and the winters are cold. Some cool pavement techniques such as evaporation pavement used to improve summer thermal settings may make the PET a little bit colder in winter. But other cool pavement techniques, like reflective pavement, can make people feel more comfortable in the heat of the summer and improve human thermal comfort in the cold of the winter. Therefore, it is preferable to choose a method that can help lower summer high temperatures but not winter low temperatures, such as evaporation and tree shading only in summer (Li, He, et al., 2016). Other factors are water and wind which contribute significantly to the UHI phenomenon. One of the most significant natural factors affecting the UHI effect is wind speed. Higher wind speeds can improve cooling systems, increase air circulation, lower city temperatures, and disperse pollutants (Mohajerani et al., 2017).

4.5 Decision Matrix Evaluation Results

To build the evaluation decision matrix, the study firstly defines and identifies both pavement techniques along with the pavement evaluation criteria as shown in Sections 4.3 and 4.4, respectively. The results are used to intersect the identified pavement technique with the identified pavement's criteria. Additionally, the study specifies the amount value of each pavement technique according to the selected criteria. Consequently, the pavement techniques' evaluation decision matrix is created. The results of the decision matrix are presented below in Table (4.1). Table (4-2) shows the same evaluation decision matrix containing the codes for the alternatives and criteria; all these codes are explained and identified in Section 3.5.3. A total of 30 pavement criteria are used to evaluate each pavement technique, and those criteria are evaluated based on the literature. This result section onwards has been published in Q1 journal "IEEE Transaction on Fuzzy Systems" (Ismael et al., 2023).

The evaluated decision matrix table shows some of the criteria such as windy on the flexible, rigid, and reflective pavement and water on the reflective pavement which are not applicable to the pavement technique, thus the reason why they are evaluated as N/A. UHI, local environment, absorb, cost, frequency, implementation, energy usage, urban surface, air temperature, day and night ratio, and initial cost are assessed as high to low. Aged, reflective, permeability, strength, driving safety, urban design, and shading are assessed as low to high. The climate and water criteria are evaluated based on their flexibility, rigidity, and permeability. Whilst the wind on permeability is evaluated on a yes/no basis. Human comfort is evaluated on a comfort/discomfort basis.

Climate and season are considered critical criteria for the advantage of using permeable pavement in the tropical area because the water factor is provided, which can help improve pavement performance to cooler ambient temperatures so that we can evaluate the water factor with permeable pavement as high.

While in the Mediterranean area zone which is a dry and hot climate, the reflective pavement performance is high compared to the others. Seasonal changes cause the pavement techniques to have different effects on the same area throughout the year. In the summer days, permeable pavement can make the surrounding area comfortable for people in contrast to reflective pavement which lowers thermal comfort for humans. In cold weather, reflective pavement provides thermal comfort, but permeable pavement reduces it due to the cooler impact. Finally, it is concluded that the selection of the best pavement performance as per the specific criteria is not that difficult compared to selecting the best pavement performance among all the evaluation criteria defined in the literature. Therefore, the decision matrix is used as an input for developing a new formulation of the multi-layer dual hesitant fuzzy weighted zero-inconsistency (DH-FWZIC) and the dual hesitant fuzzy decision by opinion score method (DH-FDOSM) as a solution to this challenge and to help contractors and organizations.

Table 4.1 : Evaluation Decision Matrix Results (Extracted From Multiple citations)

General Criteria		Without cooling technique		With cooling technique	
		Flexible Pavement (Asphalt)	Rigid Pavement (Concrete)	Reflective Pavement	Permeable Pavement
Environment	Urban Heat Island (UHI)	High Impermeable pavements are recognized as one of the biggest contributors to the urban heat island (UHI) effect of cities	High Impermeable pavements are recognized as one of the biggest contributors to the urban heat island (UHI) effect of cities	Low Have greater albedo than conventional pavements and thus help decrease the surface temperature and the sensible heat release.	Low Holding water at the pavement surface layers thus they tend to stay cool and may contribute significantly to reducing the urban temperature and mitigating UHI.
	Local Environment	High Impact / Less friendly Hazardous emissions from mixing, heating, and placement.	High Impact / Less friendly 100% recyclable, eliminating the need to dispose of old material.	Friendly / Low impact Reduces the surface and ambient temperature and contributes to counterbalancing the impact of the phenomenon	Friendly /Low impact Pavement may contribute significantly to reducing the urban temperature and mitigating the urban heat island
	Pavement Limitation				
	Climate	No	No	Yes	Yes/Summer
	Water	Yes	Yes	N/A	Sprinkling &Rainfall: Yes
	Wind	N/A	N/A	N/A	Yes decreases surface temp. faster under windy conditions.
Economy	Aged	High[91] Albedo Increase (5% - 15.6%)	Low Decrease by 43% due to dirt, tire wear, and exposure darkening the pavement	Low Albedo reduction (40% - 15%)	Low Reduce the vapor
	Physical Properties				Lower thermal inertia
	Reflective	Low Reflectance 4.2	Low Reflectance 42.7	High Reflectance 12.5 (increasing albedo by 0.25 allows a surface temperature decrease of 10 °C)	Low Reflectance 17.5
	Absorb	High Absorb 95.8 Albedo 0.1	High Absorb 57.3 Albedo 0.25	Low Absorb 87.5	High Absorb 82.5

Table 4.1 : Continued

	Permeability	Low Higher density 2238 kg/m3	Low Density 2100 kg/m3	Low	High Water Through on
	Improvement and Maintenance				
	Cost	Low/Cost Full replacement of Portland concrete slabs is more expensive than asphalt concrete rehabilitation.	High/Cost Full replacement of Portland concrete slabs is more expensive than asphalt concrete rehabilitation.	Low/Cost Found light-colored surface requires little or no additional cost in comparison to conventional pavements.	High/Cost Additional costs are needed to dislocate the clogging dirt in the cavity because the open porous structure is prone to clogging.
	Frequency / No. of M&R	High /Frequency Need resurfacing every 5 years.	Low/ Frequency Less maintenance over its lifetime.	High/ Frequency More maintenance is needed.	High/Frequency At least one time yearly dislocate the clogging dirt in the cavity because the open porous structure is prone to clogging.
	Implementation	Low Asphalt pavement is dominant because of its short construction lengths.	Low Shortened project lengths, but they still lag significantly behind asphalt pavements.	Low Low cost and convenient construction make them meet the requirement of marketing.	High Pavement owners and producers may perceive the use of cool pavements as an extra cost and performance risk.
	Energy Usage	High Rigid concrete pavement outperforms asphalt pavement in terms of safety and economic	Low Rigid concrete pavement outperforms asphalt pavement in terms of safety and economic	High outdoor Low indoor 75% energy saving	Low Energy saving
Social	Strength	High In the pursuit of high strength and durability.	High In the pursuit of high strength and durability.	High[79] Adding fly ash to react with calcium hydroxide increases concrete durability.	Low traffic volume
	Human Comfort	Discomfort	Discomfort	Comfort in open space & winter Discomfort for humans (an increase of every 0.1 albedo of the surfaces led to 1.2 °C higher mean radiant temperature)	Comfort/No Noise, avoid glare Discomfort / Humidity
	Road Safety	Low	High	Low/night	High

Table 4.1 : Continued

Specific Criteria		Without cooling technique		With cooling technique	
		Flexible Pavement (Asphalt)	Rigid Pavement (Concrete)	Reflective Pavement	Permeable Pavement
Environment	Urban Surface	High Highest recorded temperature is 47.3°C at Sarawak, Malaysia / Humidity weather. The worst case of asphalt pavement surface temperature was reported in U.S 70°C [29] at Phoenix, Arizona / sweltering and dry weather.	High Highest recorded temperature is 38.1°C at Sarawak, Malaysia / Humidity weather. The worst case of concrete pavement surface temperature was reported in U.S 138°F (58.9°C) at Phoenix, Arizona / sweltering and dry weather.	Low Cool asphaltic and concrete pavements in Athens, Greek / Hot and dry weather could reduce the surface temperature by up 12 K	Low Highest recorded temperature is 39.8°C at Sarawak, Malaysia / Humidity weather. Experiment shows the PCC specimen has 18% surface temperature lower than PCPC specimen under 5-hour thermal radiations.
	Air Temperature	High Since the surface temperature of asphalt pavement is always greater than the air temperature, the near atmosphere is always being heated	High Near air surface temp. of the PCC specimen during the testing was 22%-30% higher than PCPC specimen[100].	Low “cool asphaltic and concrete pavements” could reduce the air surface temperature by up to 1.9 K	Low Near air surface temp. of the PCC specimen during the testing was 22%-30% higher than PCPC specimen.
	Urban Design	Low Able to cause an increase in the air Temp. of 3.5’C – 5’C[26] in the canopy layer, Rome Italy Rome has a warm-temperate subtropical climate.	Low Able to cause increase in the air Temp. of 3.5’C – 5’C[26] in the canopy layer, Rome Italy Rome has a warm-temperate subtropical climate.	High Raising the pavement's albedo in an urban canyon can have negative effects as it increases the amount of solar radiation reflected into the surrounding walls of the buildings and can increase air temperature.	High
	Day & Night Difference	High High UHI at Night	High Heat released at night[80] Higher UHI / Night	Low Decrease 1.5-2 @3am & 3-4@3pm Day concrete<green Night concrete>green Decrease 1.8’Cnight &4’Cday	Low When dry, it is hotter and thus releases more sensible heat than conventional pavement during noontime High with provide water

Table 4.1 : Continued

	Season	Low the average surface temperature of the reflective asphalt over the cooling period is by up to 7.5 ◦C lower than the corresponding surface temperature of the conventional asphalt.	Low	Performing Summer High Human thermal Summer Low Winter High	High Low / winter might make the cold winter slightly colder
	Shading	High Cool pavement has in all cases lower temperature than the conventional pavement either under shaded or under unshaded spots	High The weather in Attica, Greece is predominantly Mediterranean Reduction 4.8'C.	High The weather in Attica, Greece is predominantly Mediterranean Reduction 2.8'C[11]	High Cool pavement has in all cases lower temperature than conventional pavement either under shaded or under unshaded spots
Economy	Initial Cost	Low Asphalt pavement is dominated because of its low initial costs and its short construction lengths.	High Roller- compacted concrete pavements have shortened project lengths, but they still lag significantly behind asphalt pavements.	Low Light-colored surface requires a little or no additional cost in comparison to conventional pavements.	High Pavement owners and producers may perceive the use of cool pavements as an extra cost and performance risk.

Table 4.2 : Evaluation Decision Matrix Results / Codes

	Criteria Layer 1	Criteria Layer 2	Criteria Layer 3	Without cooling technique		With cooling technique	
				Flexible/Asphalt Pavement	Rigid/Concrete Pavement	Reflective Pavement	Permeable Pavement
GEC	A1	(A1-1)		High	High	Low	Low
		(A1-2)		High Impact	High Impact	Low Impact	Low Impact
		(A1-3)					
			(A1-3-1)	No	No	Yes	Yes
			(A1-3-2)	Yes	Yes	N/A	Yes
			(A1-3-3)	N/A	N/A	N/A	Yes
	B1	(B1-1)		High	Low	Low	Low
		(B1-2)					
			(B1-2-1)	Low	Low	High	Low
			(B1-2-2)	High	High	Low	High
			(B1-2-3)	Low	Low	Low	High
		(B1-3)					
			(B1-3-1)	Low	High	Low	High
			(B1-3-2)	High	Low	High	High
		(B1-4)		Low	Low	Low	High
		(B1-5)		High	Low	High	Low
	C1	(C1-1)		High	High	High	Low traffic volume
		(C1-2)		Discomfort	Discomfort	Comfort	Comfort
		(C1-3)		Low	High	Low	High
SEC	A2	(A2-1)		High	High	Low	Low
		(A2-2)		High	High	Low	Low
		(A2-3)		Low	Low	High	High
		(A2-4)		High	High	Low	Low
		(A2-5)		Low	Low	High	High
		(A2-6)		High	High	High	High
	B2			Low	High	Low	high

(Ismael et al., 2023)

4.5.1 Criteria Weighting Results

This section discusses multi-layer DH-FWZIC, and the many steps conducted to perform this method. The results for the weighted criteria created by DH-FWZIC in this step are inconsistent. Firstly, the collected weighted criteria are defined and categorized in Chapter 3, Section 3.5.3/Step 1, whilst the collected data from the candidate experts are summarized in Section 3.6.1/Step 2. Four paving experts assessed the importance of the pavement technique criteria, collected through the designed assessment form. All the expert assessment numbers are transformed into an equivalent numerical scale. Finally, the EDM is constructed for each expert. The DHFS membership function is then applied to convert all the crisp numbers of the EDM into the DHFS-EDM. The ratio values of the pavement's criteria for each layer are determined by using equations (2) and (3). Equation (4) is then used to determine the fuzzy weight by computing the mean of the experts' preferences for all the criteria of each layer. Finally, the final weights of the 30 criteria for all layers are determined using equation (5). Table (4.3) below shows the weighting results of the entire criteria. This result section onwards has been published in Q1 journal "IEEE Transaction on Fuzzy Systems" (Ismael et al., 2023).

The weight for all three layers and the final weights are explained here. At layer 1, A2 0.2644 has the highest importance weight, whereas B2 has the lowest importance value at 0.1215. At layer 2, for the Al sub-criteria, the Al-1 criterion has the highest weight of 0.4191 and A1-3 has the lowest weight value of 0.1832. For the B1 sub-criteria, B1-4 has the highest value of 0.2419 and Bl-1 has the lowest value of 0.1101. For the Cl sub-criteria, both Cl-1 and Cl-3 have the same highest value of 0.3707, and the last sub-criterion Cl-2 has the lowest value of 0.2586.

For the A2 sub-criteria, both A2-2 and A2-5 have the highest value of 0.2239, while A2-3 has the lowest value of 0.0734. At layer 3, for the Al-3 sub-criteria, the order from highest value to the lowest is Al-3-1, Al-3-2, and Al-3-3. While in the Bl-2 sub-criteria set, the order is Bl-2-1, Bl-2-3, and Bl-2-2. Finally, in layer B1-3, the weight values of the sub-criteria Bl-3-1 and Bl-3-2 are 0.5019 and 0.4981, respectively.

The final weighting value of the criteria is obtained by multiplying the weight of the criteria at layers 1, 2, and 3. B2 shows the highest important value (0.1215), which indicates the value of layer 1 without sub-criteria at layers 2 and 3. And the value of (0.0089) is the lowest which is for A1-3-3. Finally, to evaluate the identified pavement techniques accurately, the entire final weight values are transformed to the DH-FDOSM step.

Table 4.3 : Criteria Weighting Results

Criteria layer 1		Criteria Layer 2		Criteria Layer 3		Final Weights
A1	0.2514	A1-1	0.4191			0.1054
		A1-2	0.3977			0.1000
		A1-3	0.1832	A1-3-1	0.4319	0.0199
				A1-3-2	0.3748	0.0173
				A1-3-3	0.1932	0.0089
B1	0.2254	B1-1	0.1101			0.0248
		B1-2	0.2287	B1-2-1	0.3645	0.0188
				B1-2-2	0.3083	0.0159
				B1-2-3	0.3271	0.0169
		B1-3	0.2287	B1-3-1	0.5019	0.0259
				B1-3-2	0.4981	0.0257
		B1-4	0.2419			0.0545
		B1-5	0.1906			0.0430
C1	0.1373	C1-1	0.3707			0.0509
		C1-2	0.2586			0.0355
		C1-3	0.3707			0.0509
A2	0.2644	A2-1	0.2123			0.0561
		A2-2	0.2239			0.0592
		A2-3	0.0734			0.0194
		A2-4	0.1274			0.0337
		A2-5	0.2239			0.0592
		A2-6	0.1390			0.0368
B2	0.1215					0.1215

(Ismael et al., 2023)

4.5.2 Selection Results

To benchmark the identified pavement techniques, the discussion and results reported in this section are based on the contexts of individual decision-making and group decision-making. Four DMs evaluated the decision matrix and then converted it into an opinion matrix using the five scales. Equation (6) is used by the DMs to determine the ideal pavement technique for each criterion. Then, the opinion matrix is generated by comparing the ideal pavement value to the other values for each criterion using linguistic terms and then converting the generated opinion matrix to dual hesitant fuzzy numbers (DHFNs). The opinion matrix of the four DMs is transformed into a fuzzy opinion matrix based on Table (3.3). The DH-FDOSM method is applied on the generated fuzzy opinion matrix to create individual and group decision-making contexts, as presented in Table (4-4). This result section onwards has been published in Q1 journal “IEEE Transaction on Fuzzy Systems” (Ismael et al., 2023).

Table 4.4 : Selection Results

Ranking results based on DHFWA operator										
Experts	DM1		DM2		DM3		DM4		GDM	
Alternatives	Score	Rank	Score	Rank	Score	Rank	Score	Rank	Score	Rank
Flexible/Asphalt Pavement	0.4736	1	0.5931	1	0.5290	1	0.5081	1	0.5010	1
Rigid/Concrete Pavement	0.3106	2	0.3935	2	0.2675	2	0.3745	2	0.3365	2
Reflective Pavement	-0.1647	4	-0.0969	4	-0.2088	4	-0.0611	3	-0.1329	4
Permeable Pavement	0.0501	3	-0.0158	3	0.0571	3	-0.0985	4	-0.0018	3
Ranking results based on DHFWG operator										
Experts	DM1		DM2		DM3		DM4		GDM	
Alternatives	Score	Rank	Score	Rank	Score	Rank	Score	Rank	Score	Rank
Flexible/Asphalt Pavement	-0.0029	1	-0.0001	2	0.0778	1	0.0029	2	0.0194	1
Rigid/Concrete Pavement	-0.0744	2	0.0655	1	-0.0095	2	0.0712	1	0.0132	2
Reflective Pavement	-0.4902	3	-0.5214	4	-0.5089	4	-0.3773	3	-0.4745	3
Permeable Pavement	-0.5037	4	-0.4866	3	-0.4539	3	-0.5261	4	-0.4926	4

(Ismael et al., 2023)

The pavement that obtains a high score is preferred over the one with a low score. Table (4.4) shows that some of the scores have negative values, which means that the non-membership value exceeds the membership value, illustrating the DHF concept. For the ranking of the alternatives obtained by the DHFWA operator, a consistent ranking for the 1st, 2nd, and 3rd DMs is observed for all alternatives (flexible/asphalt, rigid/concrete, reflective, and permeable pavements), with the first, second, fourth, and third rankings, respectively. These findings show that the proposed method is effective in overcoming the DMs' hesitancy and narrowing the differences in their preferences. However, the fourth DM swapped the rankings for reflecting and permeable pavements with the third and fourth rankings, respectively. The remaining two alternatives (flexible/asphalt pavement and rigid/concrete pavement) are kept at the same ranking results given by DMs l, 2, and 3.

For the rankings obtained by the DHFWG operator, the flexible/asphalt and rigid/concrete pavements swapped their ranking results (first and second ranks) for the 1st and 4th DMs. Here, the flexible/asphalt pavement is ranked first by the 1st and 3rd DMs, while rigid/concrete pavement is ranked first by the 2nd and 4th DMs. This is reflected on the reflective and permeable pavements which swapped their ranking results between the third and fourth ranks. The reflective pavement is ranked fourth by the 2nd and 3rd DMs, while permeable pavement is ranked fourth by the 1st and 4th DMs.

Finally, the group decision making (GDM) gathers all the experts' perspectives and generates a unified ranking for the alternatives. For the GDM rankings obtained based on the DHFWA operator, the flexible/asphalt pavement achieves the first rank with a score value of (0.5010), followed by rigid/concrete pavement with a score value of (0.3365), and permeable pavement with a score value of (-0.0018), ranking second and third, respectively. The reflective pavement has the lowest rank with a score value of (-0.0018). By contrast, for the GDM rankings obtained based on DHFWG operator, flexible/asphalt pavement remains on the same ranking result (first rank) as in the GDM rankings based on the DHFWA operator with a different score value of (0.0194), followed by rigid/concrete with a score value of (0.0132), and reflective pavement with a score value of (-0.4745). The fourth and lowest rank is received by permeable pavement with a score value of (-0.4926). The rankings produced using the DHFWG operators reflect the DMs' preference information well, as proven by Krejčí and Stoklasa (2018). Finally, the results from the phases proposed model in chapter three figure 3.4 can be used to select the best pavement technique.

4.6 Framework Evaluation

The main goal of this section is to evaluate the developed framework in three main sections. Section 4.6.1 presents the sensitivity analysis to validate the newly proposed weighting method. In section 4.6.2 a comparison study with other MCDM approaches is performed to compare both weighting method DH-FWZIC with DH-AHP and ranking method DH-FDOSM with DH-TOPSIS, DH-VIKOR, and DH-TODIM. While section 4.6.3 presents the framework validation which was presented to a group of construction professionals from W. T. Byler. Co., Inc. This result section onwards has been published in Q1 journal “IEEE Transaction on Fuzzy Systems” (Ismael et al., 2023).

4.6.1 Sensitivity Analysis

The variable weights given to the different criteria have a direct effect on the ranking results of the candidate pavement techniques. Therefore, the reliability of the proposed method is determined by examining the effect of changing the weights of criteria on the benchmarked results. In this section, the sensitivity analysis assessment is used to examine the effect of the most important criterion on the ranking results. A total of 30 criteria are used to evaluate the identified pavement techniques and it is found that the most important criterion is B2 (w=0.1215) based on multi-layer DH-FWZIC as shown in Table (4.5). Nine scenarios have been created by using equation (12) based on the relative value of criteria weights.

$$w_c = (1 - w_s) \times \left(\frac{w_c^{\circ}}{w_c^{\circ}}\right) = w_c^{\circ} - \Delta_{x\alpha_c} \tag{12}$$

Table 4.5 : Criteria Weights Scenarios

Criteria	DH-FWZIC	S1	S2	S3	S4	S5	S6	S7	S8	S9	α_c
A1-1	0.1054	0.1199	0.1049	0.0900	0.0750	0.0600	0.0450	0.0300	0.0150	0.0000	0.1199
A1-2	0.1000	0.1138	0.0996	0.0853	0.0711	0.0569	0.0427	0.0284	0.0142	0.0000	0.1138
A1-3-1	0.0199	0.0226	0.0198	0.0107	0.0142	0.0113	0.0085	0.0057	0.0028	0.0000	0.0226
A1-3-2	0.0173	0.0196	0.0172	0.0147	0.0123	0.0098	0.0074	0.0049	0.0025	0.0000	0.0196
A1-3-3	0.0089	0.0101	0.0089	0.0076	0.0063	0.0051	0.0038	0.0025	0.0013	0.0000	0.0101
B1-1	0.0248	0.0282	0.0247	0.0212	0.0177	0.0141	0.0106	0.0071	0.0035	0.0000	0.0282
B1-2-1	0.0188	0.0214	0.0187	0.0160	0.0134	0.0107	0.0080	0.0053	0.0027	0.0000	0.0214
B1-2-2	0.0159	0.0181	0.0158	0.0136	0.0113	0.0090	0.0068	0.0045	0.0023	0.0000	0.0181
B1-2-3	0.0169	0.0192	0.0168	0.0144	0.0120	0.0096	0.0072	0.0048	0.0024	0.0000	0.0192
B1-3-1	0.0259	0.0295	0.0258	0.0221	0.0184	0.0147	0.0110	0.0074	0.0037	0.0000	0.0295
B1-3-2	0.0257	0.0292	0.0256	0.0219	0.0183	0.0146	0.0110	0.0073	0.0037	0.0000	0.0292
B1-4	0.0545	0.0621	0.0543	0.0465	0.0388	0.0310	0.0233	0.0155	0.0078	0.0000	0.0621
B1-5	0.0430	0.0489	0.0428	0.0367	0.0306	0.0245	0.0183	0.0122	0.0061	0.0000	0.0489
C1-1	0.0509	0.0580	0.0507	0.0435	0.0362	0.0290	0.0127	0.0145	0.0072	0.0000	0.0580
C1-2	0.0355	0.0404	0.0354	0.0303	0.0253	0.0202	0.0152	0.0101	0.0051	0.0000	0.0404
C1-3	0.0509	0.0579	0.0507	0.0435	0.0362	0.0290	0.0217	0.0145	0.0072	0.0000	0.0579
A2-1	0.0561	0.0639	0.0559	0.0479	0.0399	0.0319	0.0240	0.0160	0.0080	0.0000	0.0639
A2-2	0.0592	0.0674	0.0590	0.0505	0.0421	0.0337	0.0253	0.0168	0.0084	0.0000	0.0674
A2-3	0.0194	0.0221	0.0193	0.0166	0.0138	0.0110	0.0083	0.0055	0.0028	0.0000	0.0221
A2-4	0.0337	0.0384	0.0336	0.0288	0.0420	0.0192	0.0144	0.0096	0.0048	0.0000	0.0384
A2-5	0.0592	0.0674	0.0590	0.0505	0.0421	0.0337	0.0253	0.0168	0.0084	0.0000	0.0674
A2-6	0.0368	0.0418	0.0366	0.0314	0.0261	0.0209	0.0157	0.0105	0.0052	0.0000	0.0418
B2	0.1215	0.000	0.1250	0.2500	0.3750	0.5000	0.6250	0.7500	0.8750	0.9998	0.1382

(Ismael et al., 2023)

The following equation terms are explained. Ws indicates the most important criterion. Wc indicates the weights calculated by the multi-layer DH-FWZIC method. While w_c° indicates the total weights generated by the multi-layer DH-FWIC, and Δ_x indicates the changing range applied to the criteria weights, which represent the upper and lower limits of the most important criteria.

The elasticity coefficient (α_c) in that equation is determined to calculate the changing for each criterion according to the most important one. Moreover, to determine the higher and lower limitation numbers for the most important criterion, the new ranking results from changing the criteria weights in the generated scenarios are compared to the one attained from the multi-layer DH-FWZIC method. Table(4-5) shows the results of calculating αc for each criterion. The limit values of the B2 criterion are -0.1215≤ X ≤0.8785. The specified limit values are categorized into nine sequences. Each scenario leads to the formation of nine scenarios and the production of nine new weight values (Table 4.5).

Figure 4.3 presents the effects of the changing criteria weights on the ranking results of the pavement techniques (i.e., flexible/asphalt pavement [Pl], rigid/concrete pavement [P2], reflective pavement [P3], and permeable pavement [P4]) based on the DHFWA operator. The criteria weights have a significant effect on how pavement techniques are ranked in certain scenarios. The pavement technique ranking results based on the multi-layer DH-FWZIC method indicate its effectiveness in most scenarios. The outcome for the new ranking of four pavement techniques is compared to the original ranking generated based on the multi-layer DH-FWZIC. In the first five scenarios (Sl-S5), flexible/asphalt pavement remains first but then falls to the second rank in S6-S9. Rigid/concrete pavement remains in the same ranking under multilayer DH-FWZIC (rank = 2) in five scenarios (Sl-S5), but escalates to the first rank in four scenarios (S6-S9). In nine scenarios, reflective and permeable pavements rank third and fourth, respectively, under multilayer DH-FWZIC.

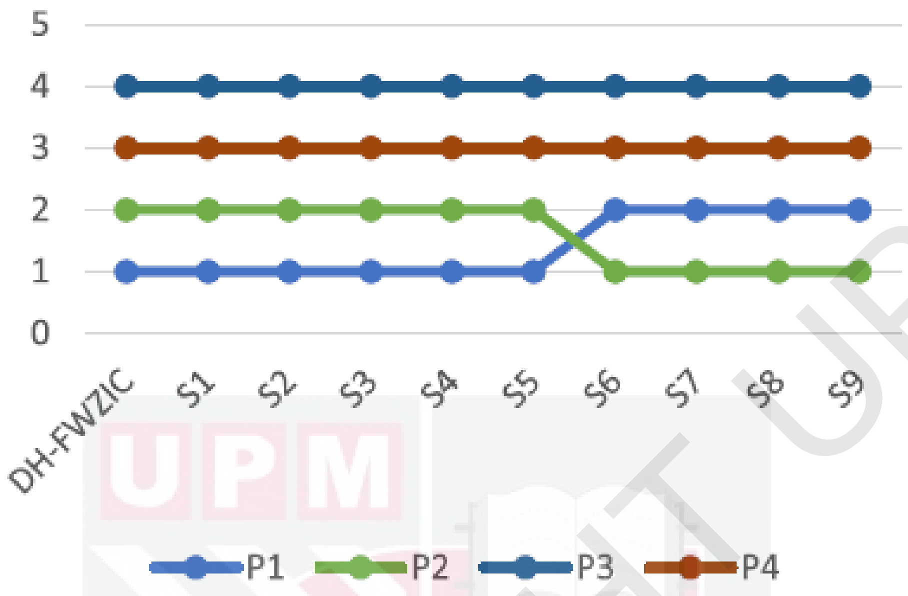


Figure 4.3 : Sensitivity Analysis Based on DHFWA Operator (Ismael et al., 2023)

Figure 4.4 depicts the new ranking results due to changes in the weighting of criteria when the DHFWG operator is used to rank pavement techniques.

In the first two scenarios (Sl and S2), the flexible/asphalt pavement earns the same ranking as the multilayer DH-FWZIC (rank = 1), but falls to the second rank in the remaining scenarios. By contrast, rigid/concrete pavement is ranked second in two scenarios (S 1 and S2) and raises to first in the remaining scenarios. In four scenarios (Sl-S4), reflective pavement is ranked high at three, but falls to the fourth rank in the remaining scenarios. By contrast, permeable pavement has the lowest rank at 4 as a multilayer DH-FWZIC in S1-S4, but elevates to the third rank in the remaining scenarios.

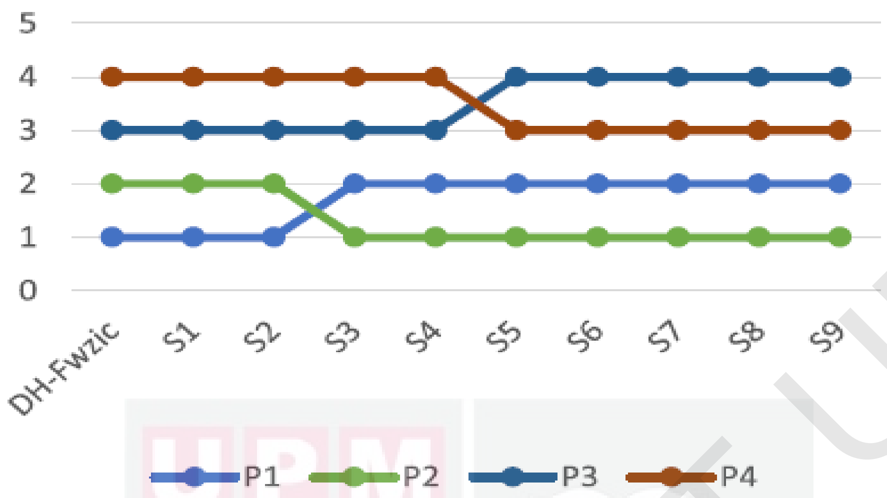


Figure 4.4 : Sensitivity Analysis Based on DHFWG Operator (Ismael et al., 2023)

These results indicate that the weights assigned to the criteria have a considerable effect on the determination of the final ranking results. For instance, the Al-1, Al-2, and A2-2 sub-criteria have the second, third, and fourth highest weights, respectively, under multilayer DH-FWZIC i.e., Table 4-3. However, these three sub-criteria significantly drop in the remaining scenarios of S6-S9. Consequently, the ranks of the first and second alternatives (flexible/asphalt pavement and rigid/concrete pavement) are interchanged see Figure 4.4.

Finally, the spearman correlation coefficient (SCC) is used to perform a statistical analysis of the associations between both the ranking results of the multi-layer DH-FWZIC and the ranking results of the nine scenarios. The results of the DHFWA operator show a strong association between the multi-layer DH-FWZIC and the nine scenarios ranks, as shown in Figure 4.5.

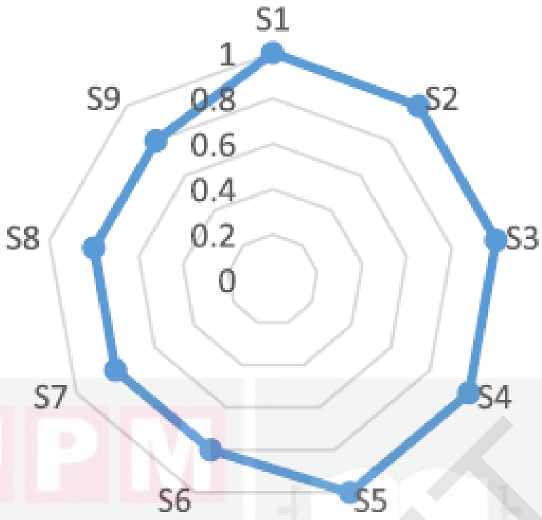


Figure 4.5 : Ranks Correlation Based on DHFWA Operator (Ismael et al., 2023)

A strong relationship (SCC = 1.0) in five scenarios (S-S5) out of the nine scenarios is revealed. The remaining scenarios (S6-S9) obtain 0.9 SCC value. This means that the mean value for all the scenarios is 0.911. The overall results indicate a strong and positive correlation.

Figure 4.6 shows the results of the DHFWG operator, i.e., a strong association between the multi-layer DH-FWZIC and the nine scenarios ranks.

The ranking of pavement techniques reveals a moderate relationship between multilayer DH-FWZIC and the first four scenarios (SCC = 1.0 in Sl and S2) which drops to (SCC = 0.8 in S3 and S4). An (SCC = 0.6) is recorded for the remaining scenarios (S5-S9) which exhibits a moderate relationship with multilayer DH-FWZIC. The mean value for all scenarios is 0.733, indicating a moderately positive correlation.

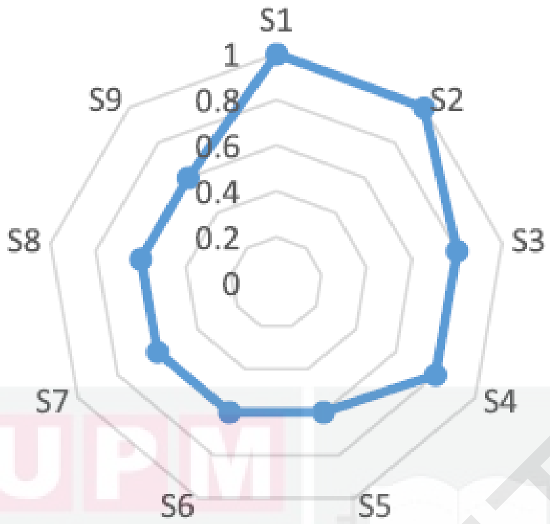


Figure 4.6 : Ranks Correlation Based on DHFWG Operator (Ismael et al., 2023)

4.6.2 Evaluation and Comparison Analysis Study

A comparison study is conducted for the proposed methods of DH-FWZIC and DH-FDOSM with other well-known DH-based MCDM approaches. This is to demonstrate how the DH-FWZIC and DH-FDOSM suggestion methods are stable and superior over other MCDM approaches.

The first comparison is with the analytic hierarchy process (AHP), known as the MCDM weighting method. There are two issues with the initial version of AHP, i.e., its imprecise and ambiguous information. Therefore, AHP is extended under the DHFS environment into DH-AHP (Qiu, 2017) to address these issues. However, other substantial deficiencies appear when comparing DH-AHP to DH-FWZIC, including the inconsistency problem caused by the comparison numbers (how many comparisons are to be made) and unnatural comparison (comparing uncorrelated criteria such as sound and smell) in DH-AHP. All these complicate the work for the experts. Moreover, DH-AHP also requires more time for pairwise comparison and is more complex in terms of obtaining expert feedback. In DH-AHP, high dependency occurs among the criteria (adding or eliminating a criterion necessitates a redo of pairwise comparison). Table (4-6) summarizes these points.

Due to all the comparison points mentioned above, Table VII demonstrates that DH-FWZIC is preferable to DH-AHP in terms of weighing criteria. DH-FWZIC solved all the previously mentioned issues (n = 6/6), whereas DH-AHP just solved the imprecise and ambiguous information (n = 1/6).

Table 4.6 : Comparison between Weighting Methos

Comparison issues		DH-FWZIC	DH-AHP
Inconsistency problem	Comparison numbers	Zero comparison	[n(n-1)/2]
	Unnatural comparison	Similar quantities	Different quantities
Time consumption		Low	High
Dependency among criteria		Independent	Dependent
Experts' feedback		Easy	Complex
Imprecise and ambiguous information		Solved	Solved

(Ismael et al., 2023)

The second comparison is a technique for ranking the alternatives by similarity to the ideal solution (TOPSIS) (Yorulmaz et al., 2021), VlseKriterijuska Optimizacija I Komoromisno Resenje (VIKOR) (Ren et al., 2017), and TODIM (an acronym in Portuguese for interactive multicriteria decision making) (D. Liang et al., 2020), all of which are widely known MCDM ranking methods that have been successfully applied to a variety of applications. The common issues of the original versions of these methods are that they are imprecise and ambiguous. As such, they are extended using the same DHFS as in DH-FDOSM into dual hesitant fuzzy TOPSIS, VIKOR, and TODIM, specifically DH-TOPSIS (Zeng et al., 2018), DH-VIKOR (Ren et al., 2017), and DH-TODIM (D. Liang et al., 2020). These extensions including DH-FDOSM have successfully solved the issues of imprecise and ambiguous information. However, DH-FDOSM is superior among these methods in terms of managing missing data (i.e., N/A values in the decision matrix), immeasurable criterion (e.g., color), weighting the criteria implicitly, normalization (unifying different measures of data in the decision matrix), ideal solution (optimal value under the same criterion), and distance measurement, i.e., the distance between the ideal solution and other alternatives. Furthermore, compared with DH-FDOSM-based DHFWA, the DH-FDOSM-based DHFWG accurately reflects preference information. Whereas the remaining ranking methods do not consider DHFWA and DHFWG. These points are summarized in Table (4.7).

As shown in Table VIII, the DH-FDOSM-based DHFWG has solved the entire issues, whereas DH-TOPSIS, DH-VIKOR, and DH-TODM solved only one out of seven, i.e., the imprecise and ambiguous information.

Therefore, the combination of DH-FWZIC and DH-FDOSM for weighting the pavement criteria and ranking the pavement technique in order of preference is more practical and functional compared to the other MCDM solutions. This is why it is used in this article.

Table 4.7 : Comparison between Ranking Methods

Comparison issues	DH-FDOSM DHFWA	DH-FDOSM DHFWA	DH-TOPSIS	DH-VIKOR	DH-TODIM
Missing data	✓	✓	X	X	X
Immeasurable criterion	✓	✓	X	X	X
Weighting the criteria implicitly	✓	✓	X	X	X
Normalization	✓	✓	X	X	X
Ideal solution and distance measurement	✓	✓	X	X	X
Imprecise and ambiguous information	✓	✓	✓	✓	✓
Reflect preference information well	X	✓	N/A	N/A	N/A

(Ismael et al., 2023)

4.6.3 Focus Group Discussion

The MCDM model developed in this study was presented on 29 March 2023 to a group of construction professionals from CPChem and W. T. Byler. Co., Inc. which is located in Texas, USA. Six participants have been selected who have a civil engineering degree and 10 years of construction experience as a minimum. The attendees included the construction manager (2), project manager (1), cost engineer (1), scheduler (1), and assistant project engineer (1) from the company. The demographic of participants in Table (48).

Table 4.8 : Demographic of Participants

Participants	Name	Company	Position	Year of Experience
P1	Wassem Ghanem	CPChem	Construction Manager	19 Year
P2	Tye Holloway	W. T. Byler	Construction Manager	17 Year
P3	Jeffrey Lopez	W. T. Byler	Project Manager	14 Year
P4	Seth Barrick	W. T. Byler	Cost Engineer	14 Year
P5	Russell Sitton	W. T. Byler	Scheduler	13 Year
P6	Fernando Lopez	W. T. Byler	Assistant Project Engineer	10 Year

The presentation was well-organized and received a high level of engagement from the participants. The attendees expressed great interest in the model and demonstrated a high level of acceptance, commending its usability, practicality, and accuracy. Their positive response served as a strong validation of the MCDM model below in Figure 4.7.

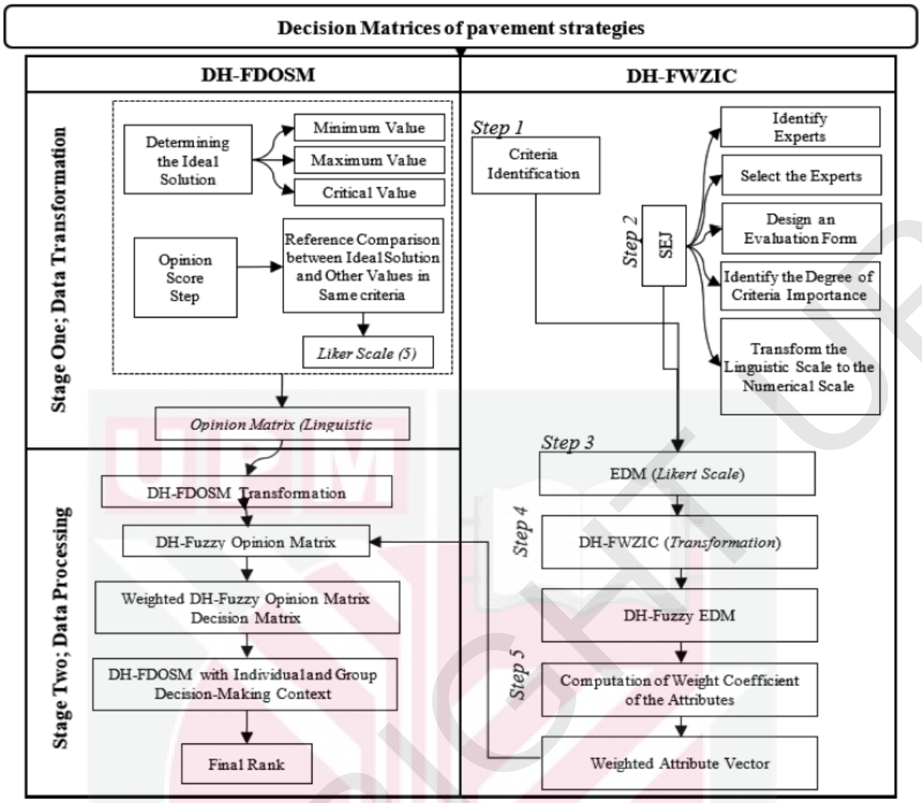


Figure 4.7 : The Model Presented to CPChem and W. T. Byler Co. Inc

The summary of participant results for the five questions of the framework evaluation is presented below in Figure 4.8.

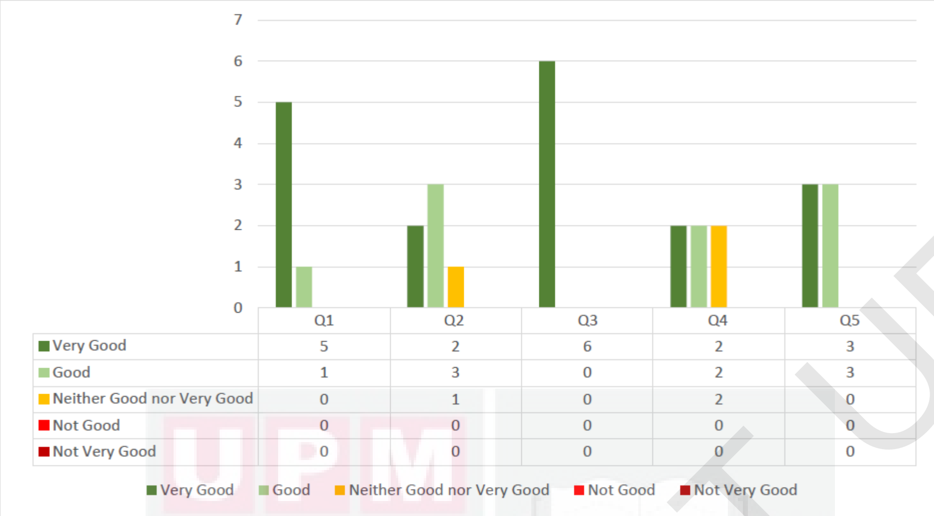
Q1 To what extent do you believe the developed framework effectively addresses the selection of pavement technique based on environmental, economic, and social factors?

Q2 To what extent do you believe the developed framework is suitable for application in practice?

Q3 To what extent do you believe the developed framework provides a clear and comprehensive guide for addressing the selection of pavement technique based on environmental, economic, and social factors?

Q4 To what extent do you believe the developed framework can be easily implemented within existing organizational structures and processes?

Q5 To what extent do you believe the developed framework has the potential to improve outcomes in practice?

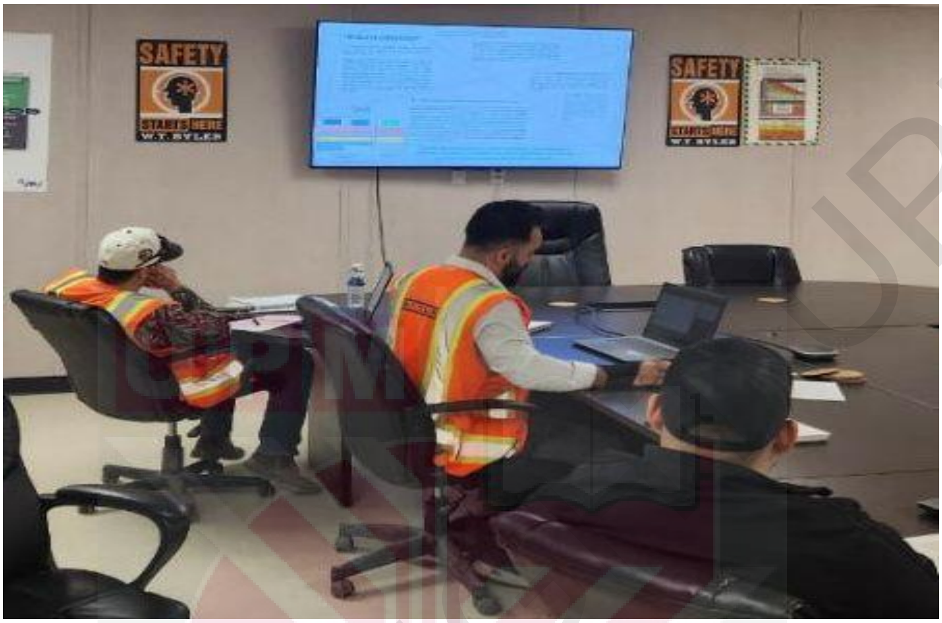


	Q1	Q2	Q3	Q4	Q5
Very Good	5	2	6	2	3
Good	1	3	0	2	3
Neither Good nor Very Good	0	1	0	2	0
Not Good	0	0	0	0	0
Not Very Good	0	0	0	0	0

Figure 4.8 : Summary of Participant Results

And the conclusion of the participant's response was the statement made on the issue was clear and concise, highlighting a comparison and identifying a better path forward along with its associated benefits. The research conducted was not only interesting but also well-organized, providing useful information. As times are changing, the content is informative and useful in identifying the changes that need to take place. The pavement solution seems particularly suitable for regions with high populations and warmer climates. The content is well researched and composed, making it both informative and interesting. The framework includes well-described factors and scenarios, which will help in determining the best applications and regions where these pavements will be most effective.

The focus group discussion presentation to the participants in the company's conference room is shown in the photos below.



4.7 Summary of Chapter

This chapter has verified the proposed framework evaluation robustness in a sensitivity analysis, comparison analysis, and focus group discussion.

Firstly, sensitivity analysis. Altered criteria weight affected the ranking results based on DHFWA operator of the pavement techniques:

1- flexible pavement in the first rank for the five scenarios (S1-S5) and moved it to the second rank in the remaining scenarios (S6-S9).

2- Rigid pavement raised from the second rank for five scenarios (S1-S5) to the first rank for the four scenarios (S6-S9).

3- Reflective and permeable pavements remained in the fourth and third ranks, respectively.

And affected the ranking results based on DHFWG operator of the pavement techniques:

1- flexible pavement in the first rank for the two scenarios (S1-S2) and moved it to the second rank in the remaining scenarios (S3-S9).

2- Rigid pavement raised from the second rank for two scenarios (S1-S2) to the first rank for the four scenarios (S3-S9).

3- Reflective pavement in the third rank for the four scenarios (S1-S4) and moved it to the fourth rank in the remaining scenarios (S5-S9).

4- Permeable pavement in the fourth rank for the four scenarios (S1-S4) and moved it to the third rank in the remaining scenarios (S5-S9).

Secondly, Comparison analysis. substantial deficiencies arise when comparing DH-FWZIC to DH-AHP as summarized in Table 4-6. DH-FDOSM successfully solved the issues and outperformed other MCDM solutions such as DH-TOPSIS, DH-VIKOR, and DH-TODIM which solved only the imprecise and ambiguous information as shown in Table 4-7. It is concluded that integrating DH-FWZIC with DH-FDOSM is more sensible than the other MCDM methods.

Finally, a focus group discussion is performed by involved assembling a group of six professionals in the construction industry to discuss the proposed framework, which is presented from different perspectives.

To sum up, the findings from the three evaluation techniques show that the content is well-written and well-researched, making it both fascinating and instructive. The framework comprises well-specified variables and situations that will aid in identifying the optimal uses and geographic areas for these pavements.

According to the case study results and framework evaluation, the developed MCDM framework Figure 3.4 is able to use it and provide decision-makers insight when assessing new pavement technologies and their effect on UHI during the design stage. The developed framework Figure 3.4 will be not limited to use in certain areas but It has the flexibility to be used in different areas. The advantage of the developed framework is to select the best alternative relying on weighting of evaluation criteria. And the experts in the specific area will do the evaluation of pavement criteria.

CHAPTER 5

CONCLUSION AND FUTURE WORK

5.1 Introduction

This chapter summarizes the study's contribution, implication, limitations, future work, and finally the overall conclusion. Section 5.2 presents the research conclusion, while the benefits of the research are presented in Section 5.3. The impact of research is demonstrated in Section 5.4. Finally, the research limitations and recommendations are presented in Section 5.5.

5.2 Research Conclusion

The research has successfully achieved the three main objectives of this study. Firstly, the evaluated criteria of pavement effect have been collected and identified based on previous studies using a systematic literature review. A multi-criteria decision-making model has been developed by applying structured expert judgment (SEJ) to identify and select the experts who were tasked to define the importance level of each pavement criterion (Alsalem et al., 2021). Two formulations were developed: a multi-layer dual hesitant fuzzy weighted zero-inconsistency (DH-FWZIC) which can be used for weighting the pavement evaluation criteria, and a dual hesitant fuzzy decision by opinion score method (DH-FDOSM) which can be used for ranking the pavement techniques. Finally, framework evaluation including sensitivity analysis, comparison study, and focus group discussion methods was applied to determine the robustness of the MCDM framework when the criteria weighting was changed. Additionally, a comparison study was performed between the weighting methods (DH-FWZIC and DH-AHP) and the ranking methods (DH-FDOSM, DH-TOPSIS, DH-VIKOR, and DH-TODIM) (Ibrahim et al., 2023). It was concluded that the suggested methods in this study are more preferable than the other methods.

5.3 Contribution to the Body of Knowledge

This study's key contribution entails the creation of a new unified MCDM framework for choosing the best paving plan within the DHFS environment using novel fuzzy MCDM methodologies. The goal of this research is accomplished via three phases. The first step to integrating all three elements environmental, social, and economic of sustainability parameters of pavement techniques in a new development of formulation of the decision matrix by the creation of an evaluation decision matrix by crossing the 30 evaluation criteria with the 4 paving technique alternatives (Ismael et al., 2023). Secondly, the new developing formulation of MCDM methods are developed via two processes: a dual hesitant fuzzy weighted zero inconsistency (DH-FWZIC) procedure weighs the pavement's evaluation criteria, whilst a dual hesitant fuzzy decision by opinion score method (DH-FDOSM) is applied to choose the best pavement approach (Ismael et al., 2023). Third, developing a novel pavement technique selection based on a formulated decision matrix using the two developing formulations DH-FWZIC and DH-FDOSM (Ismael et al., 2023). This research methodology is considered as a theory gap that is proposed to overcome the imprecise and ambiguous issues. In order to use the development framework. Figure 3.4 can help to direct the users and show them the starting point all the way through all steps with applying the equations to transformation or convert the real number to numbers that can be used in the proposal framework.

5.4 The Impact of the Research

The managerial implications of the most desirable pavement can be divided into two categories. Theoretical implications include the creation of a new unified MCDM framework using new fuzzy MCDM methodologies for selecting the best paving plan within the DHFS environment. This framework will assist future researchers and serve as a reference. Practical implications include benefits for human wellness experts, beneficiaries, and governments. By selecting the most sustainable pavement plan, beneficiaries can obtain a sustainable mobility environment while governments can maximize economic performance and reduce energy use. This is particularly important in addressing the challenges posed by the growing UHI phenomenon and global warming. Choosing the right pavement plan can reduce the harmful effects of heat on pedestrians and improve visual perception, leading to a significant positive impact on human wellness.

Finally, this study offers a method for choosing an appropriate paving plan by modifying pigments and coating performance, which can benefit contractors. Overall, the managerial implications of this study can have far-reaching positive impacts on sustainability, human wellness, and economic performance.

5.5 Limitations and Recommendations

This study has several limitations, including treating all experts equally regardless of their level of competence. DH-FWZIC, which uses a single aggregation operator and defuzzification technique, is used to generate the final weighting. DH-FDOSM, which employs a single defuzzification technique, produces the ranking results. The opinion matrices are created using a five-point Likert scale, but using more detailed scales could yield different results.

Future directions for the study include conducting more practical studies to fill the information gap on cool pavement techniques, giving experts different weights based on their level of expertise, using DH-FWZIC to apply additional aggregation operators and defuzzification strategies, creating opinion matrices with more detailed scales, and combining FWZIC and FDOSM with other fuzzy sets, including the picture fuzzy set (Sahu et al., 2021) and complex interval-valued Pythagorean fuzzy set (Ali et al., 2021). The study also recommends investigating the fuzzy failure mode effect analysis to weigh criteria for pavements (Kushwaha et al., 2020). Finally, although the study demonstrated the potential of choosing pavements based on sustainability variables, additional research is needed to combine this sustainability framework with the design criteria for pavement selection.

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APPENDICES

Appendix A

Literature Review Articles Analysis

No /	Title	Authors	place of study	mechanism type	pavement types	Article type	season	time collecting data	classify area
1	THE IMPACT OF ROAD PAVEMENT ON URBAN HEAT ISLAND (UHI) PHENOMENON	Ibrahim 2018	Kota Samarahan. Both east and west the campus of Universiti Malaysia	cooling pavement	(asphalt, concrete, permeable, and industrialized building system (IBS)	Case Study	tropical climate	The surface temperatures of the pavements were collected from 6:00 am to 6:00 pm.	suburban area
2	Modeling the performance of cool pavements and the effect of their aging on outdoor surfaces and air temperatures	tsoka 2018	Thessaloniki northern part of Greece	cooling pavement	highly reflective materials as a mitigation strategy	Case Study	under hot summer conditions	performance of cool paving materials is assessed under hot summer conditions,	an urban district, a high density residential neighborhood
3	Using reflective pavements to mitigate urban heat island in warm climates - Results from a large-scale urban mitigation project	kyriakodis 2017	situated in the western suburbs of Athens, Greece	cooling pavement	cool asphaltic and concrete pavements	Case Study	summer period	An efficient monitoring strategy was conducted in the area during the entirety of the summer period (May–September). between 12:00 and 17:00 LST	the main traffic axis (Thivon Avenue) of the Municipality of Egaleo,
4	Lighting Implications of Urban Mitigation Strategies through Cool Pavements:	Rossi 2018	Torino, Italy	cooling pavement	the cool coating on the existing pavement (asphalt)	Case Study	N/A	N/A	N/A

	Energy Savings and Visual Comfort								
5	Cool roofs and cool pavements application in Acharnes, Greece	kolokotsa 2018	Acharnes municipality in Attica, Greece. the application of cool	cooling pavement, cool roof	Cool Pavement	Case Study	The climate is typical Mediterranean with hot summer	on a typical summer day on the 16th of June, 14:00 (cool Pavement state).	urban
6	Outdoor thermal comfort by different heat mitigation strategies- A review	taleghani 2017	in different countries are described	Highly reflective materials (on the roof and on the ground level)	reflective pavement	A review	N/A	N/A	N/A
7	Characterization of different heat mitigation strategies in the landscape to fight against heat islands and improve thermal comfort in hot-humid climate (Part I): Measurement and modeling	Zhao 2017	City University of Hong Kong (CityU) was selected as the field measurement site	HMSs (vegetation, albedo, and water body) in landscape	Cool Pavement	Case Study	It has a monsoon-influenced humid subtropical climate.	The field measurements were carried out from 10:00 to 22:00 local time in August 2015.	since such an institutional campus can be regarded as a small city due to its relatively large coverage.
8	Relating microclimate, human thermal comfort and health during heat waves: An analysis of heat island mitigation strategies through a case study in an urban outdoor environment	Salata 2017	the campus of the Sapienza University of Rome	Cool roofs, cool pavement, more urban vegetation, and a combination of all three configurations	Cool Pavement	Case Study	N/A	N/A	N/A
9	Effect of different pavements on human thermal comfort conditions	IRMAK 2017	The city center of Erzurum is in the Eastern Anatolia region of Turkey.	cooling pavement	Cool Pavement	Case Study	summer days during July.	Surface temperature measurements for these materials were done on sunny days during July, at noon LT for all	City

								pavements.	
10	Using cool pavements to mitigate urban temperatures in a case study of Rome (Italy)	Battista 2017	Rome, Italy	cooling pavement	Cool Pavement	Case Study	N/A	N/A	N/A
11	Laboratory-simulated investigation on thermal behaviors of permeable concrete pavements	wu 2017	Central south university, Changsha, China	cooling pavement	traditional Portland cement concrete (PCC) and Portland cement porous concrete (PCPC)	Case Study	N/A	N/A	N/A
12	Three decades of urban heat islands and mitigation technologies research	Akbari 2016	Simulation, Canada	cool roofs, cool pavements, urban vegetation	Reflective pavement	A review	summertime	N/A	N/A
13	Effect of pavement thermal properties on mitigating urban heat islands: A multi-scale modeling case study in Phoenix	yang2016	The metropolitan Phoenix in Arizona was selected as the testbed	cooling pavement	Cool Pavement	Case Study	N/A	N/A	metropolitan
14	Urban pavements used in Brazil: Characterization of solar reflectance and temperature verification in the field	Carpio 2016	Brazil	cooling pavement	Cool Pavement	Case Study	N/A	N/A	N/A
15	Evaluation of Water Retentive Pavement as Mitigation Strategy for Urban Heat Island Using Computational Fluid Dynamics	Cortes 2016	Suita City is also one of the main cities in Osaka Prefecture.	cooling pavement	Cool Pavement	Case Study	N/A	August 2011 with a 7•day initial spin •up. This period was chosen because there was clear and calm weather	a highly urbanized district with major roads, and residential and industrial buildings.

16	Micrometeorological simulations to predict the impacts of heat mitigation strategies on pedestrian thermal comfort in a Los Angeles neighborhood	taleghani 2016	Eastern Los Angeles County, El Monte, California, located in eastern Los Angeles County	cool roofs, green roofs, cool pavements, street trees	Cool Pavement	Case Study	El Monte has a Mediterranean climate based on the Köppen-Geiger climate classification	an extreme heat day. The simulations were performed on a summer day during a heat wave in July 2014.	N/A
17	LOCAL CLIMATE CHANGE AND URBAN HEAT ISLAND MITIGATION TECHNIQUES - THE STATE OF THE ART	akbari2015	The state of the art	highly reflective materials, cool materials, cool and green roofs, cool pavements,	cool pavements	the state of the art	N/A	N/A	N/A
18	Human Thermal Comfort Modeling the Impact of Different Cool Pavement Strategies	li2016	Sacramento and Los Angeles and Phoenix	cooling pavement	Cool Pavement	Case Study	summer and winter. Summer (July) and winter (January)	N/A	N/A
19	Regulating the damaged thermostat in the cities-Status, impacts and mitigation challenges	Santamouris 2015	Athens, Greece	cooling pavement	Cool Pavement	Case Study	N/A	N/A	N/A
20	Classification of building materials used in the urban envelopes according to their capacity for mitigation of the	alchapar2014	Mendoza, Argentina	Pedestrian pavements, tiles, and vertical claddings	Cool Pavement	Case Study	N/A	N/A	N/A
21	Measuring the effects of urban heat island mitigation techniques in the field: Application to the case of pavement	Hendel2016	Rue du Louvre, Paris, France	cooling pavement	Cool Pavement	Case Study	summers of 2013 and 2014	in average air temperature between 3 am and 6 am on the day after watering both 1.5 m and 4 m above	N/A

	watering in Paris							ground level.	
22	Local urban warming, possible impacts, and a resilience plan to climate change for the historical center of Athens,	Santamouris 2015	Athens, Greece	cooling pavement	Cool Pavement	Case Study	N/A	N/A	N/A
23	UHI effects and strategies to improve outdoor thermal comfort in dense and old neighborhoods	Evola2017	Priolo, which is part of the downtown of the city of Avola,	green roofs, green parks, cool roofs, and cool pavements	reflective materials	Case Study	in warm and temperate	N/A	characterized by a typical urban canyon layout with narrow roads and tall buildings
24	Evaluation of the health-risk reduction potential of countermeasures to urban heat islands	Buchin2016	Data on heat-related mortality from Berlin, Germany, and the US	Cool pavement, urban green, cool roofs, Green roofs and green facades	reflective pavement, evaporative pavement	Case Study	N/A	period from 01.01.2001 to 31.12.2010 in hourly resolution	N/A
25	Do grey infrastructures always elevate urban temperature? No, utilizing grey infrastructures to mitigate urban heat island effects	Qi2019	Australia	cooling pavement	Cool Pavement	Case Study	N/A	N/A	N/A
26	The urban heat island effect, its causes, and mitigation, with reference to the thermal properties of asphalt concrete	Mohajerani 2017	Victoria, Australia	cooling pavement	Cool Pavement	review	N/A	N/A	N/A
27	On the thermal and visual pedestrians' perception about cool natural stones for	Rosso 2016	Kuala Lumpur, Malaysia	cooling pavement	Cool Pavement	Case Study	N/A	N/A	N/A

	urban paving: A field survey in summer conditions								
28	Role of watering practices in large-scale urban planning strategies to face the heat-wave risk in future climate	Daniel 2018	Paris (France)	cooling pavement	Cool Pavement	Case Study	N/A	N/A	the most populated urban areas
29	The impact of increasing urban surface albedo on outdoor summer thermal comfort within a university campus	Taleghani 2018	(a specific part of) the campus of Delft University of Technology in The Netherlands	cool pavement, green	Reflective pavement	Case Study	N/A	N/A	as a delta country
30	Keeping California cool: Recent cool community developments	Gilbert2016	California	cooling pavement	Cool Pavement	Case Study	N/A	N/A	N/A
31	Mitigating the urban heat island in a residential area in Tehran: Investigating the role of vegetation, materials, and orientation of buildings	Farhadi2019	Tehran	urban vegetation, built form, cool materials	reflective pavement	Case Study	N/A	N/A	N/A
32	Assessment of urban overheating mitigation strategies in a square in Rome, Italy	Battista2019	Italy/Roma: Mirti square in the Centocelle district.	Vegetation (grass and trees), cool pavements	Reflective pavement	Case Study	N/A	The monitoring campaign was carried out between the end of July and the beginning of August 2017.	N/A
33	Laboratory investigation on	Xie 2019	Simulation, China	cooling pavement	Reflective pavement	Case Study	N/A	N/A	N/A

	optical and thermal properties of cool pavement nano-coatings for urban heat island mitigation								
34	Innovative pavement surfaces as urban heat islands mitigation strategy: chromatic, thermal and mechanical characterization of clear/colored mixtures	Pasetto 2019	Padua, Italy	cooling pavement	Cool Pavement	Case Study	N/A	N/A	N/A
35	Climate mitigation and adaptation strategies for roofs and pavements: A case study at Sapienza University Campus	Battisti 2018	The Sapienza University campus, a historical site in Rome, Italy	Permeable pavements (pervious)	Cool Pavement	Case Study	during the summer, on a typical hot summer day (15 July)	N/A	N/A
36	A new structure of permeable pavement for mitigating urban heat island	Liu 2018	Tongji University, Shanghai, China	cooling pavement	evaporation-enhancing permeable pavement	Case Study	The weather was sunny or cloudy.	Data analyzed were from 20:00 on 17 April through 20:00 on 24 April 2017.	N/A
37	Experimental investigation on the influence of evaporative cooling of permeable pavements on outdoor thermal environment	Wang 2018	The site is located in the suburbs of Guangzhou (23.06N, 113.15E)	cooling pavement	permeable pavement	Case Study	N/A	Five pavements were constructed in June 2017	N/A
38	The effect of pavement characteristics on pedestrians' thermal comfort in Toronto	Taleghani 2018	Toronto	cooling pavement	Cool Pavement	Case Study	N/A	Simulations were done for a summer heat wave on July 28, 2015	urban open spaces

39	Microscale heat Island characterization of rigid pavements	sen2017	United State	cooling pavement	Cool Pavement	Case Study	N/A	N/A	N/A
40	Development and validation of a mechanistic-empirical design method for permeable interlocking concrete pavement	li2016	United State	cool pavement strategies	Fully permeable (or porous or pervious) pavements	Case Study	N/A	N/A	N/A
41	A review of the development of cool pavements to mitigate urban heat island effect	Qin2015	China	cool pavement strategies	Cool Pavement	review	N/A	N/A	N/A
42	Urban heat island in Padua, Italy: Simulation analysis and mitigation strategies	noro2015	Padua, a city in the North-East of Italy.	cool pavement & green ground	albedo surface	Case Study	a typical summer day.	During 2012–2014 period. 24 h, from 6 am to 6 pm	in different zones of the city area: urban, suburban, and rural
43	Urban Heat Island: Mechanisms, Implications, and Possible Remedies	phelan2015	United State	cooling pavement	Cool Pavement	Case Study	N/A	N/A	N/A
44	Review on urban heat island mitigation strategy through vegetation and pavements characterization	Tukiran2015	Malaysia	cool pavement, vegetation	reflective pavement	conference, review	N/A	N/A	N/A
45	The Urban Heat Island Effect in the City of Toronto	wang2015	Toronto	cool pavement, cool roof, vegetation	Cool Pavement	conference	N/A	N/A	N/A

Appendix B

Criteria Frequency

First Criteria: UHI																																			
Sub criteria	Size and population of the city (urbanization)	Global climate change	Pavement type / Design	Anthropogenic heat flux,		Evapotranspiration	Material	Building, road, hardscape	Seasons (winter, summe)	Daytime, nighttime	Climate Condition		Urban morphology, Urban constituents, urban factors								Optical properties	Heat Flux													
S. Sub criteria				Human activity, greenhouse gases	Electric energy						precipitation	prevailing wind speed & direction	Water area	SVF	Green ratio / trees shade	Pav. Percentage / street geometry & orientation	Building density & height width ratio (Canyon-like) / shade, tree canopy	Design planning, Urban geometry	Development of cities & urban expansion	General		Solar radiation	Surface reflectance	Thermal inertia	Absorb (solar and infrared radiation) & store / heat capacity	Radiative heat transfer coefficient	Albedo	Thermal diffusivity	Thermal conductivity	Emissivity	Volumetric heat capacity	conductivity	diffusivity	General	Melting temp.
Reference																																			
Adachi 2012	//																																		
Hajat 2009	//																																		
Oke 1973	//																																		
Steeneveld 2011	//																																		
Taha 1997				//			//																												
Hamilton 2009					//																														
Rodríguez-Rojas 2018						//																													
Scalenghe 2009						//																													
Arnfield 2003						//																													
Gui 2007																									//									//	
Anting 2017	//			//											//																				
Ibrahim 2018				//		//																//			//									//	
Zhong 2018			//																																
Battista2019				//									//		//							//			//										

Salata2017	//	//							//																										
Zaumanis 2018			//																																
Li2013																																			
HU2017																																			
Zaumanis 2018							//																												
Gui2007							//																												
Anting 2017							//																											//	
Carpio 2016						//									//						//	//	//	//	//					//				//	
Daniel 2018						//																													
Wu2017			//			//																													
Taleghani 2016			//			//									//		//				//			//	//									//	
Taleghani 2017	//	//					//															//	//		//										
Taleghani 2018			//				//			//			//		//						//			//	//										
Salata2017				//	//		//														//				//	//									
Rossi2018	//	//		//	//	//										//					//														
Tukiran 2015	//	//		//		//	//					//			//	//	//	//																	
Cortes 2016						//																													
Anupriya 2016								//																											
Sen2017			//	//			//	//		//					//									//	//										
Tsoka2018			//																																
Noro2015			//			//								//	//		//																		
Phelan 2015	//		//				//	//	//			//			//																				
Battista 2017	//																//	//	//																
Akbari 2015								//																											
Evola2017		//						//									//	//																	
Tong2017	//							//	//	//	//	//	//	//	//					//															
Qi2019			//					//													//														
Mohajerani 2017			//					//																											
Irmak 2017	//		//					//																											
Santamouis 2015			//	//		//							//		//											//									
Tong 2017									//	//		//	//	//	//	//	//																		
Jusuf and Wong 2009											//	//	//	//	//		//					//													
Michelozzi 2005									//																										
Cao 2017												//			//	//	//					//									//				
Danioel 2018															//		//																		
Zhao 2017						//							//		//												//								
Yang 2016																	//																		
Choi 2018														//																					
Anupriya 2016															//		//																		
Mohajerani 2017											//	//	//		//		//	//								//									
Irmak 2017															//																				
Xie 2017																					//	//												//	

Second Criteria: Quality

Sub criteria	Paving materials	durability	Pav. type	Aging (design life)	performance risk	Climate condition, environment	Traffic volume & loading	Moisture sensitivity	Design
Gui2007	//								
Ibrahim2018		//							
Zhong2018			//						
Qin2015				//	//				
Sabih2018				//		//	//		
Klinsky2018	//			//		//	//	//	//
Zaumanis2018	//		//						

Third Criteria: Strength

Sub criteria	Pav. type	Aggregate physical characteristics			Replacement material		Compaction	Mix design	Mechanical prop. Of structure							Additives	Pore structure properties: non-transport & transport	
S. Sub criteria		Size	Shape	Distribution	Type	thickness			Design thickness	Compressive strength	Flexural strength	Fatigue life	Abrasion	Freeze-thaw resistance	Ductility		Volumetric Porosity, Pore size, Distribution	Effective porosity, Pore connectivity, tortuosity
Hu2017	//																	
Chandrappa 2016		//	//	//	//	//	//	//	//	//	//	//	//	//	//	//		

Forth Criteria: Cost

S. Sub criteria	UHI		Material production or provides (Current market)	Replacement material	Additives	Initial cost		
S. Sub criteria	Energy consumption	Water consumption				Design	(Construction , installation, application) period/methods	Materials employed
Taleghani2017	//							
akbari2004	//							
akbari2005	//							
Taleghani2016	//							
Gui2007	//	//						
Taleghani2018								
Chandrappa2016	//		//					
EPA	//							
Chandrappa2016						//	//	//
Qin2015	//		//				//	
Zaumanis2018			//					
Klinsky2018								
Daniel2018	//	//						
Qi2019								
Liu2018								

Appendix C

Criteria Definitions

		Criteria	Definitions
GEC	**A1**	Environment	Consider as one of the triple items to achieve pavement sustainability. It is highly associated with neighborhood ambiance, climate change, and various emissions factors (Plati, 2019).
	A1-1	Urban Heat Island (UHI)	The UHI is a global issue that threatens the operation and habitability of our cities and urban environments. This phenomenon is characterized by the development of air temperature in the city areas compared with rural areas (Mohajerani et al., 2017).
	A1-2	Local Environment	Indicates to the surrounding environment is affected by emissions from the ground surface (Tsoka et al., 2018).
	A1-3	Pavement Limitation	Some pavement performance changes with external factors. It might be better or worse depending on the mechanical properties of the pavement type (Daniel et al., 2018).
	A1-3-1	Climate	Considered one of the factors that impact pavement performance. The climate is different in the world depending on latitude and longitude parameters (Li, He, et al., 2016).
	A1-3-2	Water	In some types of pavement, water is important to show the best performance, it helps to drop pavement surface temperature by evaporating held water existing in the pavement layers (Daniel et al., 2018).
	A1-3-3	Windy	Wind speed is one of the most important natural variables of the UHI effect. Higher wind speeds can decrease urban temperatures, improve air circulation, improve cooling systems, and dissipate pollutants (Mohajerani et al., 2017).
	B1	Economy	Consider as one of the triple items to achieve pavement sustainability. More related to structural characteristics and expenses (Plati, 2019).
	B1-1	Aged	Aged pavement's influence on pavement performance value either increases or decreases depending on material type (Tsoka et al., 2018).
	B1-2	Physical Properties	physical characteristics such as color, surface texture, and material for the top layer of the pavement surface are a contributor to the formation of heat islands (Junsong Wang et al., 2018).
	B1-2-1	Reflective	Is specific for the material that can be able to reflect solar radiation. A high value will help to keep the structure surface cool. Albedo is an expression to measure how much sunlight reflects from the pavement surface (Kyriakodis & Santamouris, 2018).
	B1-2-2	Absorb	It is working reverse the reflectance, pavement surface tends to absorb and store solar radiation and then develop the UHI phenomenon (Irmak et al., 2017).
	B1-2-3	Permeability	Water absorption is significantly influenced by the physical properties such as pore characteristics of permeable paving materials (Yong Liu et al., 2018).
	B1-3	Maintenance	Maintenance and rehabilitation are routine processes required to treat a pavement to keep pavement performance in a good condition (Ibrahim et al., 2018).

	B1-3-1	Cost	It is an additional cost needed to rehabilitate and maintain the pavement surface. Easy maintenance work means less money (Ibrahim et al., 2018).
	B1-3-2	Frequency	This one indicates how many times maintenance is needed in the year. more maintenance means additional work (Ibrahim et al., 2018).
	B1-4	Implementation	To build the road the contractor should have the knowledge and experience to do it. Some of the strategies are common and have short construction lengths while others have performance risks and take longer (Qin, 2015).
	B1-5	Energy Usage	Indicate the energy used to produce the product, road lighting, and energy consumption for cooling (Ibrahim et al., 2018) (Rossi et al., 2018) (Taleghani, 2017).
	C1	Social	Consider as one of the triple items to achieve pavement sustainability. It is associated with human and social systems (Plati, 2019).
	C1-1	Strength	This factor indicates the ability of pavement to carry on the traffic load. It depends on the design itself. Pavement is classified according to how much able to carry the load depending on the purpose of usage (Plati, 2019).
	C1-2	Human Comfort	Indicate human comfort and health that represent at the ground level. Affected by heat released from the pavement and reduce human comfort (Li, He, et al., 2016).
	C1-3	Driving Safety	Driving safety factors include driving visibility, tire resistance, and speed of traffic all these factors depend on pavement material type and mechanism (Qin, 2015).
	A2	Region's Environment	Consider as one of the triple items to achieve pavement sustainability. It is highly associated with neighborhood ambiance, climate change, and various emissions factors which are different from regaining to another accordingly (Plati, 2019).
	A2-1	Urban Surface	Ground pavement surface has been proven to be one major contributing factor to the urban heat island or UHI phenomenon (Cortes et al., 2016).
	A2-2	Air temperature	It is limited to pedestrian level (i.e. close to 1.5 m height from the ground) and affected directly by emissions from the pavement top layer (Tsoka et al., 2018).
SEC	A2-3	Urban design	urban morphology design features involving, orientation and Height/Width ratio will strongly influence the wind speed and direction and short-wave and long-wave radiation (Tsoka et al., 2018).
	A2-4	Day & Night Difference	Variable time in the same location shows different pavement performance during the sunrise with solar radiation compared with nighttime (Junsong Wang et al., 2018) (Phelan et al., 2015).
	A2-5	Season	Indicate to various climate regions the pavement technique helps improve the environment in a specific season while being uncomfortable in others (Li, He, et al., 2016).
	A2-6	Shading	Indicate enhancing the shading on the pavement with trees or in other ways. this combination is a very effective strategy to reduce the pavement surface temperature and physiological equivalent temperature (PET) (Battisti et al., 2018).
	B2	Initial Cost	The initial cost is important to select a project type. Some of the new techniques are costly but can be compensated by the benefits. This factor is greatly different due to location, currency, and local economic factors (Qin, 2015).

Personal Information

The only usage of the data you supply will be for research reasons, and it will all be maintained as confidential. If you decide to take part in the survey, some of your personal information may be gathered. We won't share your private information with outside parties.

1. What would you say about yourself in terms of your current job?

2. Your Organization's name?

3. Work Experience?

< 1 year	
1 – 2	
3 – 5	
6 – 10	
10 - 15	
> 15	

Fuzzy Weighted Zero-Inconsistency (FWZIC)
First Questionnaire

General Evaluated Criteria

1. The evaluation general criteria are divided into three main categories: Environment, Economy, and Social. Each of these has sub-criteria and indicators used to evaluate their effectiveness on pavement performance. Please rate the importance of criteria starting with extremely important to not important for evaluating pavement performance.

Criteria	definition	Not Important	Slightly Important	Moderately Important	Important	Extremely Important
Environment	Consider as one of the triple items to achieve pavement sustainability. It is highly associated with neighborhood ambiance, climate change, and various emissions factors					
Economy	Consider as one of the triple items to achieve pavement sustainability. More related to structural characteristics and expenses					
Social	Consider as one of the triple items to achieve pavement sustainability. It is associated with human and social systems					

2. The evaluation criteria – Environment depends on three sub-criteria: Urban Heat Island (UHI), Local Environment, and Pavement Limitation. Please rate the importance of sub-criteria starting with extremely important to not important for evaluating pavement performance.

Criteria	definition	Not Important	Slightly Important	Moderately Important	Important	Extremely Important
Urban Heat Island (UHI)	The UHI is a global issue that threatens the operation and habitability of our cities and urban environments. This phenomenon is characterized by the development of air temperature in the city areas compared with rural areas					
Local Environment	Indicates to the surrounding environment is affected by emissions from the ground surface					
Pavement Limitation	Some pavement performance changes with external factors. It might be better or worse depending on the mechanical properties of the pavement type					

3. The evaluation sub-criteria – Pavement Limitation depends on three S. sub-criteria: Climate, Water, and Wind. Please rate the importance of sub-criteria starting with extremely important to not important for evaluating pavement performance.

Criteria	definition	Not Important	Slightly Important	Moderately Important	Important	Extremely Important
Climate	Considered one of the factors that impact pavement performance. The climate is different in the world depending on latitude and longitude parameters.					
Water	In some types of pavement, water is important to show the best performance, it helps to drop pavement surface temperature by evaporating held water existing in the pavement layers.					
Wind	Wind speed is one of the most important natural variables of the UHI effect. Higher wind speeds can decrease urban temperatures, improve air circulation, improve cooling systems, and dissipate pollutants.					

4. The evaluation criteria – Economy depends on five sub-criteria: Aged, Physical Properties, Maintenance, Implementation, and Energy Usage. Please rate the importance of sub-criteria starting with extremely important to not important for evaluating pavement performance.

Criteria	definition	Not Important	Slightly Important	Moderately Important	Important	Extremely Important
Aged	Pavement's age influence on pavement performance value either increases or decreases depending on material type.					
Physical Properties	Physical characteristics such as color, surface texture, and material for the top layer of the pavement surface are a contributor to the formation of heat islands.					
Maintenance	Maintenance and rehabilitation are routine processes required to treat a pavement to keep pavement performance in a good condition.					
Implementation	To build the road the contractor should have the knowledge and experience to do it. Some of the strategies are common and have short construction periods while others have risky performance and take longer.					
Energy Usage	Indicate the energy used to produce the product, road lighting, and energy consumption for cooling.					

5. The evaluation sub-criteria – Physical Properties depends on three S. sub-criteria: Reflective, Absorb, and Permeability. Please rate the importance of sub-criteria starting with extremely important to not important for evaluating pavement performance.

Criteria	definition	Not Important	Slightly Important	Moderately Important	Important	Extremely Important
Reflective	Is specific for the material that can be able to reflect solar radiation. A high value will help to keep the structure surface cool. Albedo is an expression to measure how much sunlight reflects from the pavement surface.					
Absorb	It is working reverse the reflectance, pavement surface tends to absorb and store solar radiation and then develop the UHI phenomenon.					
Permeability	Water absorption is significantly influenced by the physical properties such as pore characteristics of permeable paving materials.					

6. The evaluation sub-criteria – Maintenance depends on two s.sub-criteria: Cost, and Frequency. Please rate the importance of sub-criteria starting with extremely important to not important for evaluating pavement performance.

Criteria	definition	Not Important	Slightly Important	Moderately Important	Important	Extremely Important
Cost	It is an additional cost needed to rehabilitate and maintain the pavement surface. Easy maintenance work means less money.					
Frequency	This one indicates how many times maintenance is needed in the year. more maintenance means additional work.					

7. The evaluation criteria –Social depends on three sub-criteria: Strength, Human Comfort, and Driving Safety. Please rate the importance of sub-criteria starting with extremely important to not important for evaluating pavement performance.

Criteria	definition	Not Important	Slightly Important	Moderately Important	Important	Extremely Important
Strength	This factor indicates the ability of pavement to carry on the traffic load. It depends on the design itself. Pavement is classified according to how much able to carry the load depending on the purpose of usage.					
Human Comfort	Indicate human comfort and health that represent at the ground level. Affected by heat released from the pavement and reduce human comfort.					
Driving Safety	Driving safety factors includes driving visibility, tire resistance, and speed of traffic all these factors depend on pavement material type and mechanism.					

Specific Evaluated Criteria

1. The evaluation general criteria are divided into two main categories: Environment, and Cost. The environment criteria have sub-criteria and indicators used to evaluate their effectiveness on pavement performance. Please rate the importance of criteria starting with extremely important to not important for evaluating pavement performance.

Criteria	definition	Not Important	Slightly Important	Moderately Important	Important	Extremely Important
Environment	Consider as one of the triple items to achieve pavement sustainability. It is highly associated with neighborhood ambiance, climate change, and various emissions factors which are different from regaining to another accordingly.					
Cost	The initial cost is important to select a project type. Some of the new techniques are costly but can be compensated by the benefits. This factor is greatly different due to location, currency, and local economic factors.					

2. The evaluation criteria – Environment depends on sex sub-criteria: Urban Surface, Air Temperature, Urban Design, Day and Night Difference, Season, and Shading. Please rate the importance of sub-criteria starting with extremely important to not important for evaluating pavement performance.

Criteria	definition	Not Important	Slightly Important	Moderately Important	Important	Extremely Important
Urban Surface	Ground pavement surface has been proven to be one major contributing factor to the urban heat island or UHI phenomenon.					
Air Temperature	It is limited to pedestrian level (i.e. close to 1.5 m height from the ground) and affected directly by emissions from the pavement top layer					
Urban Design	urban morphology design features involving, orientation and Height/Width ratio will strongly influence the wind speed and direction and short-wave and long-wave radiation.					
Day and Night Difference	Variable time in the same location shows different pavement performance during the sunrise with solar radiation compared with nighttime					
Season	Indicate to various climate regions the pavement technique helps improve the environment in a specific season while being uncomfortable in others					
Shading	Indicate enhancing the shading on the pavement with trees or in other ways. this combination is a very effective strategy to reduce the pavement surface temperature and physiological equivalent temperature (PET)					

Fuzzy Decision by Opinion Score Method (FDOSM)
Second Questionnaire

To select and benchmark pavement strategies according to criteria affecting, four types of pavement strategies: flexible pavement, rigid pavement, reflective pavement, and permeable pavement are used in this questionnaire. Please rate the best strategy for pavement starting with ideal (no difference) to huge difference.

Layer 1 / General Evaluation Criteria

Criteria	Alternatives	Ideal	Slight Difference	Difference	Big Difference	Huge Difference
Environment	Flexible Pavement (Asphalt)					
	Rigid Pavement (Concrete)					
	Reflective Pavement					
	Permeable Pavement					

Criteria	Alternatives	Ideal	Slight Difference	Difference	Big Difference	Huge Difference
Economy	Flexible Pavement (Asphalt)					
	Rigid Pavement (Concrete)					
	Reflective Pavement					
	Permeable Pavement					

Criteria	Alternatives	Ideal	Slight Difference	Difference	Big Difference	Huge Difference
Environment	Flexible Pavement (Asphalt)					
	Rigid Pavement (Concrete)					
	Reflective Pavement					
	Permeable Pavement					

Layer 2 / Environment

Sub. Criteria	Alternatives	Ideal	Slight Difference	Difference	Big Difference	Huge Difference
Urban Heat Island (UHI)	Flexible Pavement (Asphalt)					
	Rigid Pavement (Concrete)					
	Reflective Pavement					
	Permeable Pavement					

Sub. Criteria	Alternatives	Ideal	Slight Difference	Difference	Big Difference	Huge Difference
Local Environment	Flexible Pavement (Asphalt)					
	Rigid Pavement (Concrete)					
	Reflective Pavement					
	Permeable Pavement					

Sub. Criteria	Alternatives	Ideal	Slight Difference	Difference	Big Difference	Huge Difference
Pavement Limitation	Flexible Pavement (Asphalt)					
	Rigid Pavement (Concrete)					
	Reflective Pavement					
	Permeable Pavement					

Layer 2 / Economy						
Sub. Criteria	Alternatives	Ideal	Slight Difference	Difference	Big Difference	Huge Difference
Aged	Flexible Pavement (Asphalt)					
	Rigid Pavement (Concrete)					
	Reflective Pavement					
	Permeable Pavement					
Sub. Criteria	Alternatives	Ideal	Slight Difference	Difference	Big Difference	Huge Difference
Physical Properties	Flexible Pavement (Asphalt)					
	Rigid Pavement (Concrete)					
	Reflective Pavement					
	Permeable Pavement					
Sub. Criteria	Alternatives	Ideal	Slight Difference	Difference	Big Difference	Huge Difference
Maintenance	Flexible Pavement (Asphalt)					
	Rigid Pavement (Concrete)					
	Reflective Pavement					
	Permeable Pavement					
Sub. Criteria	Alternatives	Ideal	Slight Difference	Difference	Big Difference	Huge Difference
Implementation	Flexible Pavement (Asphalt)					
	Rigid Pavement (Concrete)					
	Reflective Pavement					
	Permeable Pavement					
Sub. Criteria	Alternatives	Ideal	Slight Difference	Difference	Big Difference	Huge Difference
Energy Usage	Flexible Pavement (Asphalt)					
	Rigid Pavement (Concrete)					
	Reflective Pavement					
	Permeable Pavement					

Layer 2 / Social						
Sub. Criteria	Alternatives	Ideal	Slight Difference	Difference	Big Difference	Huge Difference
Strength	Flexible Pavement (Asphalt)					
	Rigid Pavement (Concrete)					
	Reflective Pavement					
	Permeable Pavement					
Sub. Criteria	Alternatives	Ideal	Slight Difference	Difference	Big Difference	Huge Difference
Human Comfort	Flexible Pavement (Asphalt)					
	Rigid Pavement (Concrete)					
	Reflective Pavement					
	Permeable Pavement					
Sub. Criteria	Alternatives	Ideal	Slight Difference	Difference	Big Difference	Huge Difference
Driving Safety	Flexible Pavement (Asphalt)					
	Rigid Pavement (Concrete)					
	Reflective Pavement					
	Permeable Pavement					

Layer 3 / Pavement Limitation						
S Sub. Criteria	Alternatives	Ideal	Slight Difference	Difference	Big Difference	Huge Difference
Climate	Flexible Pavement (Asphalt)					
	Rigid Pavement (Concrete)					
	Reflective Pavement					
	Permeable Pavement					
S Sub. Criteria	Alternatives	Ideal	Slight Difference	Difference	Big Difference	Huge Difference
Water	Flexible Pavement (Asphalt)					
	Rigid Pavement (Concrete)					
	Reflective Pavement					
	Permeable Pavement					
S Sub. Criteria	Alternatives	Ideal	Slight Difference	Difference	Big Difference	Huge Difference
Wind	Flexible Pavement (Asphalt)					
	Rigid Pavement (Concrete)					
	Reflective Pavement					
	Permeable Pavement					
Layer 3 / Physical Properties						

S Sub. Criteria	Alternatives	Ideal	Slight Difference	Difference	Big Difference	Huge Difference
Reflective	Flexible Pavement (Asphalt)					
	Rigid Pavement (Concrete)					
	Reflective Pavement					
	Permeable Pavement					

S Sub. Criteria	Alternatives	Ideal	Slight Difference	Difference	Big Difference	Huge Difference
Absorb	Flexible Pavement (Asphalt)					
	Rigid Pavement (Concrete)					
	Reflective Pavement					
	Permeable Pavement					

S Sub. Criteria	Alternatives	Ideal	Slight Difference	Difference	Big Difference	Huge Difference
Permeability	Flexible Pavement (Asphalt)					
	Rigid Pavement (Concrete)					
	Reflective Pavement					
	Permeable Pavement					

Layer 3 / Maintenance

S Sub. Criteria	Alternatives	Ideal	Slight Difference	Difference	Big Difference	Huge Difference
Cost	Flexible Pavement (Asphalt)					
	Rigid Pavement (Concrete)					
	Reflective Pavement					
	Permeable Pavement					

S Sub. Criteria	Alternatives	Ideal	Slight Difference	Difference	Big Difference	Huge Difference
Frequency	Flexible Pavement (Asphalt)					
	Rigid Pavement (Concrete)					
	Reflective Pavement					
	Permeable Pavement					

Layer 1 / Specific Evaluation Criteria

Criteria	Alternatives	Ideal	Slight Difference	Difference	Big Difference	Huge Difference
Environment	Flexible Pavement (Asphalt)					
	Rigid Pavement (Concrete)					
	Reflective Pavement					

	Permeable Pavement					
Criteria	Alternatives	Ideal	Slight Difference	Difference	Big Difference	Huge Difference
Cost	Flexible Pavement (Asphalt)					
	Rigid Pavement (Concrete)					
	Reflective Pavement					
	Permeable Pavement					

Layer 2 / Environment						
Sub. Criteria	Alternatives	Ideal	Slight Difference	Difference	Big Difference	Huge Difference
Urban Surface	Flexible Pavement (Asphalt)					
	Rigid Pavement (Concrete)					
	Reflective Pavement					
	Permeable Pavement					
Sub. Criteria	Alternatives	Ideal	Slight Difference	Difference	Big Difference	Huge Difference
Air Temperature	Flexible Pavement (Asphalt)					
	Rigid Pavement (Concrete)					
	Reflective Pavement					
	Permeable Pavement					
Sub. Criteria	Alternatives	Ideal	Slight Difference	Difference	Big Difference	Huge Difference
Urban Design	Flexible Pavement (Asphalt)					
	Rigid Pavement (Concrete)					
	Reflective Pavement					
	Permeable Pavement					
Sub. Criteria	Alternatives	Ideal	Slight Difference	Difference	Big Difference	Huge Difference
Day and Night Difference	Flexible Pavement (Asphalt)					
	Rigid Pavement (Concrete)					
	Reflective Pavement					
	Permeable Pavement					
Sub. Criteria	Alternatives	Ideal	Slight Difference	Difference	Big Difference	Huge Difference
Season	Flexible Pavement (Asphalt)					
	Rigid Pavement (Concrete)					
	Reflective Pavement					

	Permeable Pavement					
Sub. Criteria	Alternatives	Ideal	Slight Difference	Difference	Big Difference	Huge Difference
Shading	Flexible Pavement (Asphalt)					
	Rigid Pavement (Concrete)					
	Reflective Pavement					
	Permeable Pavement					

Appendix E

FWZIC and FDOSM Results

Section 1: FWZIC results

FWZIC 1
General Criteria

Layer 1	**Experts**	**A1**					**B1**								**C1**		
	E1	5					4								4		
	E2	5					4								3		
	E3	5					4								3		
	E4	4					5								4		
Layer 2		A1-1	A1-2	A1-3			B1-1	B1-2			B1-3		B1-4	B1-5	C1-1	C1-2	C1-3
	E1	5	5	3			4	5			4		5	3	4	4	5
	E2	5	5	4			4	4			5		5	4	5	4	5
	E3	5	5	3			4	5			5		5	5	5	4	5
	E4	4	4	4			4	4			5		4	4	5	3	4
Layer 3				A1-3-1	A1-3-2	A1-3-3		B1-2-1	B1-2-2	B1-2-3	B1-3-1	B1-3-2					
	E1			2	3	2		5	5	4	4	3					
	E2			4	4	2		5	4	5	3	5					
	E3			5	5	2		5	4	5	4	4					
	E4			4	4	3		4	5	4	3	4					

FWZIC2
General Criteria

Layer	Experts	A1					B1								C1		
Layer 1	**E1**	5					5								5		
	E2	4					5								4		
	E3	5					4								4		
	E4	5					5								3		
Layer 2		A1-1	A1-2	A1-3			B1-1	B1-2			B1-3		B1-4	B1-5	C1-1	C1-2	C1-3
	E1	5	5	4			3	4			4		4	4	5	5	5
	E2	5	4	3			3	5			4		4	3	4	4	4
	E3	4	4	3			4	4			5		5	4	5	3	5
	E4	5	5	4			4	5			4		5	5	5	4	5
Layer 3				A1-3-1	A1-3-2	A1-3-3		B1-2-1	B1-2-2	B1-2-3	B1-3-1	B1-3-2					
	E1			3	4	3		5	4	5	5	4					
	E2			5	3	2		4	4	4	4	4					
	E3			4	4	3		5	5	4	3	3					
	E4			4	5	2		5	4	5	4	5					

Specific Criteria
FWZIC / 1

	Experts	A2						B2
Layer 1	E1	5						4
	E2	5						3
	E3	5						4
	E4	5						4
Layer 2		A2-1	A2-2	A2-3	A2-4	A2-5	A2-6	
	E1	5	5	3	4	4	4	
	E2	4	5	3	4	5	4	
	E3	5	5	3	4	5	3	
	E4	5	4	3	4	5	4	

Specific Criteria
FWZIC / 2

	Experts	A2						B2
Layer 1	E1	5						3
	E2	4						4
	E3	5						5
	E4	5						4
Layer 2		A2-1	A2-2	A2-3	A2-4	A2-5	A2-6	
	E1	4	5	4	3	5	4	
	E2	5	4	4	4	5	5	
	E3	4	5	3	4	4	3	
	E4	5	5	4	3	5	4	

Section 2:FDOSM Results

FDOSM / 1
General Criteria

Expert 1	A1					B1								C1		
Flexible Pavement (Asphalt)	5					4								5		
Rigid Pavement (Concrete)	4					5								5		
Reflective Pavement	2					2								2		
Permeable Pavement	1					1								1		
	A1-1	A1-2	A1-3			B1-1	B1-2			B1-3		B1-4	B1-5	C1-1	C1-2	C1-3
Flexible Pavement (Asphalt)	5	5	1			1	5			2		2	5	1	5	4
Rigid Pavement (Concrete)	4	3	1			4	4			2		2	2	1	4	2
Reflective Pavement	1	1	1			3	1			1		1	3	1	2	3
Permeable Pavement	1	1	3			5	2			4		5	1	4	1	1
			A1-3-1	A1-3-2	A1-3-3		B1-2-1	B1-2-2	B1-2-3	B1-3-1	B1-3-2					
Flexible Pavement (Asphalt)			1	2	1		4	1	2	1	2					
Rigid Pavement (Concrete)			1	1	1		2	4	4	3	1					
Reflective Pavement			3	1	1		1	5	5	1	3					
Permeable Pavement			4	4	4		5	1	1	4	4					

Expert 2	A1					B1								C1		
Flexible Pavement (Asphalt)	5					4								4		
Rigid Pavement (Concrete)	4					4								4		
Reflective Pavement	1					2								2		
Permeable Pavement	1					1								1		
	A1-1	A1-2	A1-3			B1-1	B1-2			B1-3		B1-4	B1-5	C1-1	C1-2	C1-3
Flexible Pavement (Asphalt)	4	5	1			3	4			3		1	5	1	5	4
Rigid Pavement (Concrete)	5	4	2			1	5			2		3	4	1	4	5
Reflective Pavement	2	1	1			2	1			1		2	3	1	4	3
Permeable Pavement	1	1	3			1	2			3		5	1	3	1	1
			A1-3-1	A1-3-2	A1-3-3		B1-2-1	B1-2-2	B1-2-3	B1-3-1	B1-3-2					
Flexible Pavement (Asphalt)			1	3	1		5	1	3	1	3					
Rigid Pavement (Concrete)			2	1	2		2	3	3	2	1					
Reflective Pavement			3	1	2		1	5	5	1	3					
Permeable Pavement			4	4	3		5	2	1	4	4					

Expert 3	A1					B1								C1		
Flexible Pavement (Asphalt)	4					5								4		
Rigid Pavement (Concrete)	4					4								4		
Reflective Pavement	1					2								3		
Permeable Pavement	1					1								1		
	A1-1	A1-2	A1-3			B1-1	B1-2			B1-3		B1-4	B1-5	C1-1	C1-2	C1-3
Flexible Pavement (Asphalt)	5	5	1			3	5			3		3	5	1	5	4
Rigid Pavement (Concrete)	4	3	2			3	5			1		3	3	2	5	4
Reflective Pavement	2	1	1			2	2			2		1	3	1	3	2
Permeable Pavement	1	1	3			1	1			4		5	1	3	1	1
			A1-3-1	A1-3-2	A1-3-3		B1-2-1	B1-2-2	B1-2-3	B1-3-1	B1-3-2					
Flexible Pavement (Asphalt)			1	2	1		4	1	3	1	2					
Rigid Pavement (Concrete)			1	1	1		2	3	4	2	1					
Reflective Pavement			4	1	2		1	4	5	2	4					
Permeable Pavement			5	3	4		4	1	1	4	5					

Expert 4	A1					B1								C1		
Flexible Pavement (Asphalt)	5					3								4		
Rigid Pavement (Concrete)	3					5								5		
Reflective Pavement	1					1								2		
Permeable Pavement	1					1								1		
	A1-1	A1-2	A1-3			B1-1	B1-2			B1-3		B1-4	B1-5	C1-1	C1-2	C1-3
Flexible Pavement (Asphalt)	4	4	1			3	4			4		1	5	1	4	5
Rigid Pavement (Concrete)	4	4	2			1	4			3		2	2	2	4	5
Reflective Pavement	2	2	1			2	1			1		2	4	2	5	4
Permeable Pavement	1	1	3			2	2			3		4	1	3	1	1
			A1-3-1	A1-3-2	A1-3-3		B1-2-1	B1-2-2	B1-2-3	B1-3-1	B1-3-2					
Flexible Pavement (Asphalt)			1	2	1		3	1	4	1	3					
Rigid Pavement (Concrete)			1	2	1		2	4	5	3	1					
Reflective Pavement			4	1	2		1	5	5	1	4					
Permeable Pavement			3	5	3		4	2	1	5	5					

FDOSM / 2
General Criteria

Expert 1	A1					B1								C1		
Flexible Pavement (Asphalt)	4					3								5		
Rigid Pavement (Concrete)	4					5								4		
Reflective Pavement	1					3								1		
Permeable Pavement	1					1								1		
	A1-1	A1-2	A1-3			B1-1	B1-2			B1-3		B1-4	B1-5	C1-1	C1-2	C1-3
Flexible Pavement (Asphalt)	5	4	1			1	5			3		3	5	1	4	4
Rigid Pavement (Concrete)	4	4	2			3	5			2		3	3	1	5	4
Reflective Pavement	2	2	1			5	2			1		1	3	1	3	2
Permeable Pavement	1	1	3			4	1			3		5	1	3	1	1
			A1-3-1	A1-3-2	A1-3-3		B1-2-1	B1-2-2	B1-2-3	B1-3-1	B1-3-2					
Flexible Pavement (Asphalt)			1	2	2		3	1	2	1	2					
Rigid Pavement (Concrete)			2	2	1		2	3	3	3	1					
Reflective Pavement			4	1	1		1	5	5	2	3					
Permeable Pavement			4	5	4		5	2	1	5	3					

Expert 2	A1					B1								C1		
Flexible Pavement (Asphalt)	4					3								5		
Rigid Pavement (Concrete)	4					5								4		
Reflective Pavement	1					1								1		
Permeable Pavement	2					1								1		
	A1-1	A1-2	A1-3			B1-1	B1-2			B1-3		B1-4	B1-5	C1-1	C1-2	C1-3
Flexible Pavement (Asphalt)	5	4	1			3	4			4		2	5	1	5	5
Rigid Pavement (Concrete)	4	5	1			3	4			3		2	3	1	4	4
Reflective Pavement	1	1	1			2	2			1		1	4	1	5	2
Permeable Pavement	1	1	2			1	1			3		5	1	4	1	1
			A1-3-1	A1-3-2	A1-3-3		B1-2-1	B1-2-2	B1-2-3	B1-3-1	B1-3-2					
Flexible Pavement (Asphalt)			1	2	2		5	1	2	1	2					
Rigid Pavement (Concrete)			1	2	1		3	4	3	3	1					
Reflective Pavement			4	1	2		1	5	5	2	4					
Permeable Pavement			4	5	4		5	2	1	4	4					

Expert 3	A1					B1								C1		
Flexible Pavement (Asphalt)	4					4								5		
Rigid Pavement (Concrete)	3					4								5		
Reflective Pavement	2					2								2		
Permeable Pavement	1					1								1		
	A1-1	A1-2	A1-3			B1-1	B1-2			B1-3		B1-4	B1-5	C1-1	C1-2	C1-3
Flexible Pavement (Asphalt)	4	5	1			3	4			2		2	5	1	5	4
Rigid Pavement (Concrete)	5	4	1			2	5			2		2	2	2	4	3
Reflective Pavement	1	2	2			2	1			1		1	3	2	2	3
Permeable Pavement	1	1	3			1	2			4		4	1	4	1	1
			A1-3-1	A1-3-2	A1-3-3		B1-2-1	B1-2-2	B1-2-3	B1-3-1	B1-3-2					
Flexible Pavement (Asphalt)			1	2	2		4	1	4	1	2					
Rigid Pavement (Concrete)			2	2	1		3	4	4	3	1					
Reflective Pavement			3	1	2		1	5	5	2	3					
Permeable Pavement			5	4	3		5	2	1	5	5					

Expert 4	A1					B1								C1		
Flexible Pavement (Asphalt)	4					4								4		
Rigid Pavement (Concrete)	4					4								5		
Reflective Pavement	1					2								1		
Permeable Pavement	2					1								1		
	A1-1	A1-2	A1-3			B1-1	B1-2			B1-3		B1-4	B1-5	C1-1	C1-2	C1-3
Flexible Pavement (Asphalt)	5	4	1			3	5			3		1	5	1	5	4
Rigid Pavement (Concrete)	4	5	2			1	4			1		3	3	2	4	5
Reflective Pavement	1	1	1			2	1			2		2	3	1	4	3
Permeable Pavement	2	1	2			1	2			4		4	1	3	1	1
			A1-3-1	A1-3-2	A1-3-3		B1-2-1	B1-2-2	B1-2-3	B1-3-1	B1-3-2					
Flexible Pavement (Asphalt)			1	2	2		3	1	4	1	2					
Rigid Pavement (Concrete)			2	1	1		2	3	4	3	1					
Reflective Pavement			4	1	2		1	5	5	2	3					
Permeable Pavement			4	4	4		5	1	1	5	4					

Specific Criteria
FDOSM / 1

	Expert 1	A2						B2
Layer 1	Flexible Pavement (Asphalt)	5						3
	Rigid Pavement (Concrete)	4						5
	Reflective Pavement	2						2
	Permeable Pavement	1						1
		A2-1	A2-2	A2-3	A2-4	A2-5	A2-6	
Layer 2	Flexible Pavement (Asphalt)	5	5	3	4	1	2	
	Rigid Pavement (Concrete)	3	4	3	4	1	2	
	Reflective Pavement	1	1	3	2	4	1	
	Permeable Pavement	2	2	1	1	5	1	
	Expert 2	A2						B2
Layer 1	Flexible Pavement (Asphalt)	5						3
	Rigid Pavement (Concrete)	5						4
	Reflective Pavement	2						1
	Permeable Pavement	1						2
		A2-1	A2-2	A2-3	A2-4	A2-5	A2-6	
Layer 2	Flexible Pavement (Asphalt)	5	5	3	4	1	3	
	Rigid Pavement (Concrete)	4	4	2	3	4	2	
	Reflective Pavement	1	1	4	1	5	1	
	Permeable Pavement	3	2	1	2	5	2	

	Expert 3	A2						B2
Layer 1	Flexible Pavement (Asphalt)	4						3
	Rigid Pavement (Concrete)	4						4
	Reflective Pavement	1						1
	Permeable Pavement	1						3
		A2-1	A2-2	A2-3	A2-4	A2-5	A2-6	
Layer 2	Flexible Pavement (Asphalt)	5	5	3	4	2	4	
	Rigid Pavement (Concrete)	3	4	2	3	1	2	
	Reflective Pavement	1	3	3	2	5	1	
	Permeable Pavement	3	1	1	1	5	1	
	Expert 4	A2						B2
Layer 1	Flexible Pavement (Asphalt)	5						5
	Rigid Pavement (Concrete)	5						4
	Reflective Pavement	1						2
	Permeable Pavement	1						1
		A2-1	A2-2	A2-3	A2-4	A2-5	A2-6	
Layer 2	Flexible Pavement (Asphalt)	4	4	4	4	1	3	
	Rigid Pavement (Concrete)	4	4	2	4	4	2	
	Reflective Pavement	1	2	4	1	4	2	
	Permeable Pavement	2	1	1	2	4	1	

Specific Criteria
FDOSM / 2

Expert 1	A2						B2
Flexible Pavement (Asphalt)	5						4
Rigid Pavement (Concrete)	3						5
Reflective Pavement	1						1
Permeable Pavement	1						1
	A2-1	A2-2	A2-3	A2-4	A2-5	A2-6	
Flexible Pavement (Asphalt)	5	4	3	4	2	3	
Rigid Pavement (Concrete)	3	4	2	3	1	2	
Reflective Pavement	1	2	4	1	5	2	
Permeable Pavement	3	1	1	2	5	1	

Expert 2	A2						B2
Flexible Pavement (Asphalt)	5						4
Rigid Pavement (Concrete)	4						4
Reflective Pavement	3						1
Permeable Pavement	1						1
	A2-1	A2-2	A2-3	A2-4	A2-5	A2-6	
Flexible Pavement (Asphalt)	4	5	3	4	1	4	
Rigid Pavement (Concrete)	3	3	2	4	4	2	
Reflective Pavement	1	2	3	2	5	1	
Permeable Pavement	2	1	1	1	4	1	

Expert 3	A2						B2
Flexible Pavement (Asphalt)	5						4
Rigid Pavement (Concrete)	4						4
Reflective Pavement	2						1
Permeable Pavement	1						2
	A2-1	A2-2	A2-3	A2-4	A2-5	A2-6	
Flexible Pavement (Asphalt)	5	5	4	4	1	3	
Rigid Pavement (Concrete)	4	3	3	4	2	2	
Reflective Pavement	1	1	3	1	4	1	
Permeable Pavement	3	1	1	2	5	2	

Expert 4	A2						B2
Flexible Pavement (Asphalt)	5						5
Rigid Pavement (Concrete)	4						3
Reflective Pavement	1						2
Permeable Pavement	2						1
	A2-1	A2-2	A2-3	A2-4	A2-5	A2-6	
Flexible Pavement (Asphalt)	5	4	4	4	1	4	
Rigid Pavement (Concrete)	3	5	3	3	3	3	
Reflective Pavement	1	1	2	2	4	2	
Permeable Pavement	1	2	1	1	5	1	

Appendix F

Feedback Evaluation Forms

PROPOSED FRAMEWORK EVALUATION

(SUSTAINABLE PAVEMENT STRATEGY SELECTION BASED ON MCDM METHODS)

Name: WASSEM GHANEM

Company: Chevron Phillips

Position: Construction Manager / SME

Please rate your agreement with the following statements on a scale of 1 to 5, where 1 being 'very good' and 5 being 'not very good'.

Very Good 1	Good 2	Neither agree nor disagree 3	Not good 4	Not very good 5

1. To what extent do you believe the developed framework effectively addresses the selection of pavement strategy based on environmental, economic, and social factors?	1
2. To what extent do you believe the developed framework is suitable for application in practice?	1
3. To what extent do you believe the developed framework provides a clear and comprehensive guide for addressing the selection of pavement strategy based on environmental, economic, and social factors?	1
4. To what extent do you believe the developed framework can be easily implemented within existing organizational structures and processes?	2
5. To what extent do you believe the developed framework has the potential to improve outcomes in practice?	1

Your opinion is matter to us

- In one sentence describe the overall content of the proposed framework

It was a clear statement on the issue along with highlighting the comparison and identifying the better path and benefits associated with it

Thank you for your participation!

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Proposed Framework Evaluation

(Sustainable pavement strategy selection based on MCDM methods)

Name: Tye holloway

Company: W I Byler

Position: Construction Manager

Please rate your agreement with the following statements on a scale of 1 to 5, where 1 being 'very good' and 5 being 'not very good'.

Very Good	Good	Neither agree nor disagree	Not good	Not very good
1	2	3	4	5

1. To what extent do you believe the developed framework effectively addresses the selection of pavement strategy based on environmental, economic, and social factors?	1
2. To what extent do you believe the developed framework is suitable for application in practice?	2
3. To what extent do you believe the developed framework provides a clear and comprehensive guide for addressing the selection of pavement strategy based on environmental, economic, and social factors?	1
4. To what extent do you believe the developed framework can be easily implemented within existing organizational structures and processes?	1
5. To what extent do you believe the developed framework has the potential to improve outcomes in practice?	1

Your opinion is matter to us

- In one sentence describe the overall content of the proposed framework

It was very interesting research as well The content and The Framework well organized and useful information.

Thank you for your participation!

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Proposed Framework Evaluation

(Sustainable pavement strategy selection based on MCDM methods)

Name: Jeffrey Lopez

Company: W.T. Byler

Position: Project Manager / Project engineer.

Please rate your agreement with the following statements on a scale of 1 to 5, where 1 being 'very good' and 5 being 'not very good'.

Very Good	Good	Neither agree nor disagree	Not good	Not very good
1	2	3	4	5

1. To what extent do you believe the developed framework effectively addresses the selection of pavement strategy based on environmental, economic, and social factors?	2
2. To what extent do you believe the developed framework is suitable for application in practice?	3
3. To what extent do you believe the developed framework provides a clear and comprehensive guide for addressing the selection of pavement strategy based on environmental, economic, and social factors?	1
4. To what extent do you believe the developed framework can be easily implemented within existing organizational structures and processes?	2
5. To what extent do you believe the developed framework has the potential to improve outcomes in practice?	2

Your opinion is matter to us

- In one sentence describe the overall content of the proposed framework

It is very informative & resourceful to the changes that need to take place as times are changing.

Thank you for your participation!

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PROPOSED FRAMEWORK EVALUATION

(SUSTAINABLE PAVEMENT STRATEGY SELECTION BASED ON MCDM METHODS)

Name: Seth Bannick

Company: W.T. Byler

Position: COST ENGINEER

Please rate your agreement with the following statements on a scale of 1 to 5, where 1 being 'very good' and 5 being 'not very good'.

Very Good	Good	Neither agree nor disagree	Not good	Not very good
1	2	3	4	5

1. To what extent do you believe the developed framework effectively addresses the selection of pavement strategy based on environmental, economic, and social factors?	1
2. To what extent do you believe the developed framework is suitable for application in practice?	2
3. To what extent do you believe the developed framework provides a clear and comprehensive guide for addressing the selection of pavement strategy based on environmental, economic, and social factors?	1
4. To what extent do you believe the developed framework can be easily implemented within existing organizational structures and processes?	3
5. To what extent do you believe the developed framework has the potential to improve outcomes in practice?	1

Your opinion is matter to us

- In one sentence describe the overall content of the proposed framework

Good in use of area with high population & warmer climate.

Thank you for your participation!

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PROPOSED FRAMEWORK EVALUATION

(SUSTAINABLE PAVEMENT STRATEGY SELECTION BASED ON MCDM METHODS)

Name: Russell Sitton

Company: WT Byler

Position: Scheduler

Please rate your agreement with the following statements on a scale of 1 to 5, where 1 being 'very good' and 5 being 'not very good'.

Very Good	Good	Neither agree nor disagree	Not good	Not very good
1	2	3	4	5

1. To what extent do you believe the developed framework effectively addresses the selection of pavement strategy based on environmental, economic, and social factors?	1
2. To what extent do you believe the developed framework is suitable for application in practice?	1
3. To what extent do you believe the developed framework provides a clear and comprehensive guide for addressing the selection of pavement strategy based on environmental, economic, and social factors?	1
4. To what extent do you believe the developed framework can be easily implemented within existing organizational structures and processes?	2
5. To what extent do you believe the developed framework has the potential to improve outcomes in practice?	2

Your opinion is matter to us

- In one sentence describe the overall content of the proposed framework

The content was very informative and interesting as well as very well researched and composed.

Thank you for your participation!

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Proposed Framework Evaluation

(Sustainable pavement strategy selection based on MCDM methods)

Name: Fernando Lopez

Company: WT Byler

Position: Assistant Project Engineer

Please rate your agreement with the following statements on a scale of 1 to 5, where 1 being 'very good' and 5 being 'not very good'.

Very Good	Good	Neither agree nor disagree	Not good	Not very good
1	2	3	4	5

1. To what extent do you believe the developed framework effectively addresses the selection of pavement strategy based on environmental, economic, and social factors?	1
2. To what extent do you believe the developed framework is suitable for application in practice?	2
3. To what extent do you believe the developed framework provides a clear and comprehensive guide for addressing the selection of pavement strategy based on environmental, economic, and social factors?	1
4. To what extent do you believe the developed framework can be easily implemented within existing organizational structures and processes?	3
5. To what extent do you believe the developed framework has the potential to improve outcomes in practice?	2

Your opinion is matter to us

- In one sentence describe the overall content of the proposed framework

Framework includes well described factors and scenarios for which applications and regions these pavements will best be utilized/applied to.

Thank you for your participation!

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LIST OF PUBLICATIONS

SFI Al-Humairi et al., "Sustainable pavement: A review on the usage of pavement as a mitigation strategy for UHI," 2021 IOP Conf. Ser.: Mater. Sci. Eng. 1075 012010, dio: 10.1088/1757-899X/1075/1/012010.

S. F. Ismael et al., "Toward Sustainable Transportation: A Pavement Strategy Selection Based on the Extension of Dual-Hesitant Fuzzy Multicriteria Decision-Making Methods," in IEEE Transactions on Fuzzy Systems, vol. 31, no. 2, pp. 380-393, Feb. 2023, doi: 10.1109/TFUZZ.2022.3168050.

S. F. Ismael et al., "Mitigation Urban Heat Island Effects: A Review of Innovative Pavement Technologies and Integrated Solutions," in Structural Durability & Health Monitoring, doi:10.32604/sdhm.2024.050088.