

A DECISION SUPPORT SYSTEM FOR THE SELECTION OF GREEN ROOF  
FOR RESIDENTIAL BUILDINGS

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A DECISION SUPPORT SYSTEM FOR THE SELECTION OF GREEN ROOF  
FOR RESIDENTIAL BUILDINGS

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*This thesis lovingly dedicated to  
my wife, Sanaz. Her support,  
encouragement, and constant love have  
sustained me throughout my life.*

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## **ABSTRACT**

Green roofs have been installed as a sustainable approach for many years all around the world. There are myriad benefits for green roof installation in terms of private and public sectors such as energy saving, stormwater management, and carbon reduction. Furthermore, there are three types of green roofs with different levels of benefits and costs; however, there is lack of model, framework, or decision support system (DSS) to facilitate the process of decision making for selecting the optimum type of green roof. The aim of the research is to develop a DSS to determine the optimum type of green roof. The research was conducted on residential buildings due to the highest percentage of green roof installation among other building categories in Malaysia. Enhanced Fuzzy Delphi Method (EFDM) has been developed for this study as the approach for data collection, while Multi-Criteria Decision Making (MCDM) is adopted in order to develop the DSS. Moreover, Cybernetic Fuzzy Analytic Hierarchy Process (CFAHP) was also developed as the method used in MCDM. EFDM and CFAHP were developed due to the shortcomings of previous methods for the novelty in this research. A database was created for the DSS using EFDM, while CFAHP method was used for developing the DSS. Additionally, in terms of DSS evaluation, hypothetical examples were defined and after obtaining the results, multiple criteria approach was conducted to understand its level of effectiveness and efficiency. DSS evaluation has been conducted involving experts in the field of green roof. Finally, it was concluded that the DSS works well and can be utilized in construction industry in the design phase. The experts' feedbacks showed that the developed DSS is effective and efficient, and were satisfied with the performance of the DSS.

## ABSTRAK

Bumbung hijau telah dipasang sebagai pendekatan mampan selama bertahun-tahun di seluruh dunia. Terdapat pelbagai faedah dengan pemasangan bumbung hijau dalam sektor swasta dan awam seperti penjimatan tenaga, pengurusan air hujan, dan pengurangan karbon. Tambahan pula, terdapat tiga jenis bumbung hijau dengan tahap faedah dan kos yang berbeza; bagaimanapun, terdapat kekurangan model, rangka kerja, atau sistem sokongan keputusan (DSS) untuk memudahkan proses membuat keputusan untuk pemilihan jenis bumbung hijau yang optimum. Kajian ini bertujuan untuk membangunkan satu sistem sokongan keputusan untuk menentukan jenis bumbung hijau yang optimum. Skop kajian ini merangkumi bangunan kediaman kerana ia meliputi peratusan tertinggi pemasangan bumbung hijau di kalangan kategori bangunan di Malaysia. Kaedah *Enhanced Fuzzy Delphi Method (EFDM)* telah dibangunkan untuk kajian ini untuk pengumpulan data, manakala *Multi-Criteria Decision Making (MCDM)* diguna pakai dalam usaha untuk membangunkan DSS. Selain itu, *Cybernetic Fuzzy Analytic Hierarchy Process (CFAHP)* telah dibangunkan sebagai kaedah yang digunakan dalam MCDM. EFDM dan CFAHP telah dibangunkan kerana terdapat kelemahan dalam kaedah kajian sebelum ini. Pangkalan data telah dicipta untuk DSS menggunakan EFDM, manakala kaedah CFAHP telah digunakan untuk membangunkan DSS. Selain itu, dari segi penilaian DSS, contoh hipotetikal telah ditetapkan dan selepas mendapat keputusan, pendekatan pelbagai kriteria telah dijalankan untuk memahami tahap keberkesanan dan kecekapan. Penilaian DSS telah dilakukan dengan menggunakan beberapa pakar dalam bidang bumbung hijau. Akhirnya, boleh disimpulkan bahawa DSS berfungsi dengan baik dan boleh digunakan dalam industri pembinaan dalam fasa reka bentuk. Maklum balas daripada pakar menunjukkan bahawa DSS yang dibangunkan berkesan dan cekap, dan berpuas hati dengan prestasi DSS.

## TABLE OF CONTENTS

CHAPTER	TITLE	PAGE
	<b>DECLARATION</b>	<b>ii</b>
	<b>DEDICATION</b>	<b>iii</b>
	<b>ACKNOWLEDGEMENT</b>	<b>iv</b>
	<b>ABSTRACT</b>	<b>v</b>
	<b>ABSTRAK</b>	<b>vi</b>
	<b>TABLE OF CONTENTS</b>	<b>vii</b>
	<b>LIST OF TABLES</b>	<b>xii</b>
	<b>LIST OF FIGURES</b>	<b>xiii</b>
	<b>LIST OF ABBREVIATIONS</b>	<b>xv</b>
	<b>LIST OF APPENDICES</b>	<b>xvii</b>
<b>1</b>	<b>INTRODUCTION</b>	<b>1</b>
	1.1 Overview	1
	1.2 Background of Research	3
	1.3 Problem Statement	5
	1.4 Research Questions	6
	1.5 Aim and Objectives	7
	1.6 Scope and Limitations	8
	1.7 Significance of Research	9
	1.8 Thesis Outline	9
<b>2</b>	<b>LITERATURE REVIEW</b>	<b>12</b>
	2.1 Introduction	12
	2.2 History of Green Roof Installation	13
	2.2.1 Europe	13

2.2.2	United States	14
2.2.3	Asia	14
2.3	Types of Green Roof	17
2.3.1	Extensive Green Roof	18
2.3.1.1	Lightweight Green Roof	19
2.3.1.2	Super Lightweight Green Roof	20
2.3.1.3	Extensive Sedum Roof	20
2.3.1.4	Bio Diverse Green Roof	21
2.3.2	Intensive Green Roof	22
2.3.3	Semi-Intensive Green Roof	23
2.4	Significant Characteristics of Major Types of Green Roofs	24
2.5	Construction Detail of a Typical Green Roof	26
2.6	Criteria Influencing the Green Roof Type Selection	27
2.6.1	Non-Financial Criteria Affecting the Green Roof Type Selection	27
2.6.1.1	Use	27
2.6.1.2	Location	36
2.6.1.3	Structural Consideration	39
2.6.1.4	Accessibility of Green Roof	39
2.6.1.5	Maintenance	41
2.6.1.6	Safety	42
2.6.2	Cost Performance Criteria Influencing the Green Roof Type Selection	43
2.6.2.1	Net Present Value	45
2.6.2.2	Payback Period	46
2.7	Decision Making	46
2.7.1	Multi-Criteria Decision Making	48
2.7.1.1	Delphi Method	52
2.7.1.2	Fuzzification of Delphi Method	55
2.7.2	Methods of Weighting Criteria	56
2.7.2.1	AHP Methodology	56
2.7.2.2	Cybernetic Pairwise Comparison	60
2.8	Decision Support System	61
2.8.1	DSS Evaluation	62



	2.8.1.1 Multiple Criteria Approach	63
	2.9 Summary	63
<b>3</b>	<b>RESEARCH METHODOLOGY</b>	<b>65</b>
	3.1 Introduction	65
	3.3 Research Area Identification	67
	3.3.1 Literature Review	67
	3.3.2 Semi-Structured Interview	67
	3.4 Multi-Criteria Decision Making	68
	3.4.1 Alternative Determination	69
	3.4.2 Criteria Selection	69
	3.4.2.1 Enhanced Fuzzy Delphi Method	70
	3.4.2.2 EFDM Expertise Selection	73
	3.4.2.3 EFDM Number of Experts	74
	3.4.2.4 EFDM Rounds	74
	3.4.3 Weighting Criteria, Sub-criteria, and alternatives	77
	3.4.3.1 Cybernetic Fuzzy AHP	78
	3.4.4 Multi-Criteria Decision Analysis	81
	3.4.4.1 Global and Local Weightages	82
	3.5 Prototype DSS Development	82
	3.5.1 Software Utilized in Prototype Development	82
	3.6 Prototype Evaluation	83
	3.6.1 Case Study	84
	3.6.2 Multiple Criteria Evaluation	84
	3.6.2.1 Questionnaire Design	85
	3.7 Summary	85
<b>4</b>	<b>EFDM DATA COLLECTION AND CFAHP ANALYSIS</b>	<b>87</b>
	4.1 Introduction	87
	4.2 Delphi Data Collection	85
	4.2.1 Background of the Respondents	88
	4.2.2 EFDM Round One: Identifying the Alternatives and Criteria	89

4.2.2.1	Alternative Formulation	90
4.4.2.2	Criteria and Sub-Criteria Identification	90
4.2.3	Round One Results and Discussions	91
4.2.4	EFDM Round Two: Importance of the Criteria	93
4.2.5	Round Two Results and Discussions	93
4.2.6	Criteria influential in DM	96
4.3	Weighting the Alternatives	98
4.4	Summary	104
<b>5</b>	<b>PROTOTYPE DEVELOPMENT</b>	<b>105</b>
5.1	Introduction	105
5.2	Prototype DSS Architecture	107
5.2.1	Opening Window of the Prototype DSS	108
5.2.2	Ranking Module	109
5.2.3	Database and Calculation Modules	112
5.2.4	Result Module	112
5.3	User Requirements	114
5.4	Development of Functional Prototype	114
5.4.1	Analysis Module	116
5.4.1.1	Cybernetic Pairwise Comparison Matrix	116
5.4.1.2	Fuzzification of Cybernetic Pairwise Comparison Matrix	117
5.4.1.3	Defuzzification of Cybernetic Pairwise Comparison Matrix	118
5.4.1.4	Global Weighting	119
5.4.2	Alternative Rank-Order	119
5.5	Summary	120
<b>6</b>	<b>EVALUATION OF THE PROTOTYPE SYSTEM</b>	<b>121</b>
6.1	Introduction	121
6.2	Hypothetical Case Implementation	123
6.3	Case Implementation Results	123
6.4	Evaluation Results and Discussion	125

6.5	Users' Feedback	131
6.5.1	Benefit of the Prototype DSS	131
6.5.2	Suggestions for improvement	132
6.6	Summary	133
<b>7</b>	<b>CONCLUSIONS AND RECOMMENDATIONS</b>	<b>134</b>
7.1	Conclusions of the Research	134
7.2	Recommendations for future Researches	136
	<b>REFERENCES</b>	<b>138</b>
	Appendices A-H	159-240

## LIST OF TABLES

<b>TABLE NO.</b>	<b>TITLE</b>	<b>PAGE</b>
2.1	Major characteristics of green roofs	25
2.2	Fundamental scale of the AHP	59
3.1	FAHP scale used to evaluate the importance of criteria	79
3.2	Hypothetical cases	84
4.1	Background of the experts	89
4.2	Added and deleted sub-criteria within the first round of EFDM	91
4.3	Criteria membership function	94
4.4	Sub-criteria membership function	94
4.5	Experts' answers for ranking the alternatives	100
4.6	Alternatives' weightages with respect to each sub-criterion	102
5.1	Choices and their priority values	111
6.1	Results obtained from cases implementation from those involved in DSS development	124
6.2	Results obtained from cases implementation from out of team involved in DSS development	125
6.3	Evaluation results	127
6.4	Suggestion for improvement and benefit of prototype system	133

## LIST OF FIGURES

FIGURE NO.	TITLE	PAGE
1.1	Research scope	8
2.1	Green roof installation trend	15
2.2	Different types of green roofs in Malaysia	16
2.3	Green roof categories	17
2.4	Extensive green roof	19
2.5	Lightweight extensive green roof	19
2.6	Extensive sedum roof	20
2.7	Bio-diverse green roof	21
2.8	Intensive green roof in Kuala Lumpur	22
2.9	Semi-intensive green roof in Kuala Lumpur	24
2.10	Types of vegetation in green roofs	24
2.11	Typical green roof construction detail	26
2.12	Rainfall run-off based on the depth of substrate	29
2.13	UHI effect	32
2.14	Decision making process	48
2.15	Single and hybrid approaches used in MCDM	50
2.16	Definition of the abbreviation used in MCDM methods	51
2.17	Delphi procedure	52
2.18	Flexible Point System for the Qualification of Expert Panelists	54
2.19	Triangular Fuzzy number	55
2.20	AHP structure	58
2.21	AHP process	58
3.1	Research methodology flowchart	66
3.2	Steps of MCDM	69
3.3	EFDM framework	72

3.4	Flexible point system for the qualification of expert panelists	73
3.5	Steps of CFAHP	80
4.1	Percentage of the experts contributed to this study	88
4.2	Influential criteria in DM	97
4.3	Number of added and deleted sub-criteria	98
4.4	AHP model for green roof type selection	99
4.5	A sample of alternatives' weightages calculation	101
5.1	Prototype DSS development process	106
5.2	Prototype DSS architecture	107
5.3	Screenshot from the opening window of prototype system	108
5.4	Criteria ranking window of prototype system	109
5.5	Sub-criteria ranking window of prototype system	110
5.6	A sample of help for "structural consideration"	111
5.7	Screenshot from the result window of prototype system	113
5.8	Flowchart of prototype system	115
5.9	Local and global weights of criteria and "Application" sub-criteria	119
6.1	The process of using conventional method and prototype DSS for green roof type selection	122
6.2	The effectiveness of prototype DSS	129
6.3	The efficiency of prototype DSS	130
6.4	The satisfaction of Prototype DSS	130
6.5	The use of prototype DSS	131

## LIST OF ABBREVIATIONS

AHP	-	Analytic Hierarchy Process
ANP	-	Analytic Network Process
BREEAM	-	Building Research Establishment's Environmental Assessment Method
CABE	-	Commission Of Architecture And The Built Environment
CFAHP	-	Cybernetic Fuzzy Analytic Hierarchy Process
CI	-	Consistence Index
CR	-	Consistence RATIO
CTLA	-	Council Of Trees And Landscape Appraisers
DEA	-	Data Envelopment Analysis
DM	-	Decision Making
DSS	-	Decision Support System
EFDM	-	Enhanced Fuzzy Delphi Method
EGR	-	Extensive Green Roof
ELECTTRE	-	Elimination Et Choix Traduisant La Realite
FDM	-	Fuzzy Delphi Method
FSs	-	Fuzzy Sets
FwD	-	Fuzzy With Delphi
GA	-	Genetic Algorithm
GBI	-	Green Building Index
GST	-	Grey System Theory
HK-BEAM	-	Hong Kong Building Environmental Assessment Method
HOQ	-	House Of Quality
IGR	-	Intensive Green Roof
LEED	-	Leadership In Energy & Environmental Design

MCDA	-	Multi-Criteria Decision Analysis
MCDM	-	Multi-Criteria Decision Making
MCS	-	Monte Carlo Simulation
MIVES	-	Modelo Integrado De Valor Para Evaluaciones Sostenibles
NPV	-	Net Present Value
PROMET	-	Preference Ranking Organization Method For Enrichment Of Evaluations
Semi-IGR	-	Semi-Intensive Green Roof
TFN	-	Triangular Fuzzy Number
TOPSIS	-	Technique For Order Of Preference By Similarity To Ideal Solution
UHI	-	Urban Heat Island
VIKOR	-	Vise kriterijumska Optimizacija I Kompromisno Resenje



**LIST OF APPENDICES**

<b>APPENDIX</b>	<b>TITLE</b>	<b>PAGE</b>
A	Categories of green roofs based on the literature	
B	EFDM panel formation's questionnaire	167
C	Panelist's scores	170
D	feedbacks regarding the potential criteria and sub-criteria affect DM	
E	EFDM questionnaire of second round	172
F	Experts' responses of second round of EFDM	178
G	Questionnaire of alternative weighting	179
H	Alternative weightage calculation process	180
I	Calculation process of CFAHP	220
J	Prototype system evaluation	223

## CHAPTER 1

### INTRODUCTION

#### 1.1 Overview

Green Revolution is the main theme of the era in 21st century (Rahman *et al.*, 2013; Wu, 2014). Many scholars around the world, are investigating and promoting the importance of green revolution using green technology in order to reduce the impact of environmental issues. Global warming, urban heat island (UHI), high-energy demands, air pollution, and lack of green spaces are the most crucial environmental issues in urban areas (Costanzo *et al.*, 2015; Berardi *et al.*, 2014), while construction practices are recognized as one of the main contributors for environmental issues (Karteris *et al.*, 2016). Moreover, sustainable approaches are especially known to be as the contributors for energy saving and reduction of carbon emissions. As a result, these approaches have been introduced to reduce the adverse impacts on environment that created by the construction industry (Akadiri *et al.*, 2013; Alyami *et al.*, 2013; Lundholm and Peck, 2008).

Currently, considering the term “sustainability” in all aspects of construction industry is a crucial issue around the world, and governments have found the necessity of using sustainable approaches for the next generations. Green roof as a sustainable alternative of the conventional roof, is defined as the use of vegetation covering the roof of a building (Refahi and Talkhabi, 2015). Installing green roof among private and public sectors is increasing due to the fact of having multiple benefits (Claus and Rousseau, 2012). Many buildings in developed countries have used green roof as one of the solutions to increase green area along with its benefits. Moreover, green roofs are becoming a trend, especially in modern high-rise building’s design in Kuala

Lumpur (Zahir *et al.*, 2014). From the beginning of installing green roof as an environmentally-friendly approach, different types with different construction details were used throughout the world (Kosareo and Ries, 2007). For instance, in Germany, around 14% of all flat roofs have adapted green roof (Zahir *et al.*, 2014), while extensive green roof (a light type) was installed more than the other types. However, in Malaysia, intensive green roof (a heavy type like roof garden) is currently the most popular type of green roof (Rahman *et al.*, 2013; Claus and Rousseau, 2012). There are significant differences in the benefits, costs, maintenance periods, and the plant types that can be planted in each type of green roof; however, all types of green roofs are recognized as a sustainable and environmentally-friendly type of roofs in comparison with conventional roofs.

Green roofs can partially compensate for the loss of green areas by replacing impervious surfaces, and developing urban bio diversity (Wu, 2014). As stated by Getter and Rowe (2006), in most urban areas, the roof surfaces are accounted for roughly 21 to 26 percent of the total areas; thus, the use of green roofs can increase the urban green area. "The Greening of Greater KL," initiated by Ministry of Federal Territories and Urban Wellbeing, aims at converting a total area of 150,000 m<sup>2</sup> of the conventional roofs to green roofs by 2020 (Zahir *et al.*, 2014). Literature indicates that green roof has lots of environmental, social, and economic benefits (Getter and Rowe, 2008; Rahman *et al.*, 2013; Vijayaraghavan, 2016). In addition, the use of green roof results in the construction of an energy-efficient building since this approach reduces the amount of energy consumed for air conditioning (Liu, 2014). The environmental condition of the area can be positively affected by green roofs in terms of issues such as mitigation of storm water (Wong and Jim, 2015; Mentens *et al.*, 2006; Stovin *et al.*, 2012), sequestration of carbon (Ismail *et al.*, 2012), reduction of flash flood (Wong and Jim, 2015), and the replenishment of greenery in the urban area (Wu, 2014; Brenneisen, 2006).

This research aims to identify the criteria affecting green roof type selection, and to develop a Decision Support System (DSS) to obtain the optimum type of green roof. Wrong decision regarding the selection of green roof's type, results in waste of money and energy, and the DSS could help the designers and decision makers for

green roof type selection. At the end of the research, the DSS would play the role of an assistant for the designers to select the optimum type of green roof for any building.

## 1.2 Background of Research

Lack of greeneries causes many adverse environmental impacts such as UHI, global warming, and air pollution and so on (Zahir *et al.*, 2014; Rahman *et al.*, 2013). A study showed that Kuala Lumpur's green areas have been reduced to 59.4% (around 14,386 hectare from its original 24,222 hectare of city area) (Yusof and Johari, 2012). Moreover, global warming and UHI effect impose a dual warming impact on cities (Silva *et al.*, 2016; Jim, 2015a). The global warming phenomenon has triggered the movement towards sustainability in Malaysian construction industry (Zahir *et al.*, 2014). On the other hand, construction industry destroys the green spaces and vegetation for the purpose of building construction (Bianchini and Hewage, 2012). Furthermore, most of the environmental issues have been originated from constructing non-environmentally friendly buildings. Consequently, as we cannot stop the construction of buildings, we do have to search for alternative solutions to improve the performance of the buildings, and a new balance is needed to be applied between economic and environmental concerns.

Green roof installation as a sustainable alternative for conventional roof construction initiates from 1960 in Germany. After that, an increasing trend can be seen in green roof installation in European and other countries such as U.S., Singapore, and Japan (Zhang *et al.*, 2015). Based on the location of the buildings and the project requirements, green roofs have been installed with different construction details and different types of plants. These different types of green roofs can be categorized into three major category namely extensive green roof, semi-intensive green roof, and intensive green roof (Catalano *et al.*, 2016).

In intensive green roofs, a thick layer of growing medium or substrate is applied, wherein a variety of plants can be grown, especially in cases that irrigation is available. It is noteworthy that, additional structural support is needed due to the heavy

weight of substrate; thus, this type of green roof can be applied to the buildings considering additional structural support (Schrader and Böning, 2006; Nagase and Dunnett, 2010). Whereas, in case of extensive green roof, a thinner layer of substrate is applied, which is a relatively lightweight and thus in some cases little or even no additional structural support is needed. Therefore, this type of roofs is applicable to a wider range of buildings. This advantage, together with a lower need for irrigation and lower maintenance requirement, have led to a wider application of extensive green roofs. On the other hand, the extensive green roofs provide a harsh environment for plant growth with wide temperature fluctuations, limited water availability, and high exposure to solar radiation and wind, which causes a highly stressed environment for growing plants (Bianchini and Hewage, 2012). Extensive green roofs are used to increase the surface area covered by vegetation in big cities, whereby reduce the UHI effect, promote carbon dioxide sequestration, and increase bio diversity and urban-wildlife habitats (William *et al.*, 2016; Ondono *et al.*, 2016). Moreover, semi-intensive green roof is a simple intensive green roof. Semi-intensive green roof is introduced to cover the green roofs which cannot be categorized neither in extensive nor intensive green roofs. These green roofs have a thicker soil layer in comparison with extensive green roofs, while, the plant diversity in these roofs is limited compared to intensive green roofs. Furthermore, additional structural support is required for installing semi-intensive green roofs, and regular maintenance is also necessary.

It is worth mentioning that there are some differences in the cost of green roofs considering net present value and payback period. Mahdiyar *et al.* (2016) focused on all the private factors affecting probabilistic cost-benefit analysis of installing two types of green roofs in Kuala Lumpur including initial cost, property value, energy saving, O&M costs, lifespan, and the acoustic effect. NPV and payback period of green roof installation were analyzed through Monte Carlo simulation. After obtaining the results, it is concluded that installing an extensive green roof is a low-risk investment and owners benefit from installing extensive green roof with a low probability of loss. Furthermore, installing an extensive green roof is a long-term investment with a short term return in Kuala Lumpur. For intensive green roof, the payback period is longer than extensive green roof in Kuala Lumpur; however, it also can be considered as a short-term investment.

Using greeneries onto the buildings as a sustainable way (not as a source of a renewable-energy system) reduces energy consumption and addresses some environmental issues caused by construction industry. Although there are many proven private and environmental benefits of integrating greeneries to the buildings (Gargari *et al.*, 2016), there is still lack of knowledge on the significant criteria that should be considered throughout the process of decision making for green roof selection (Zhang *et al.*, 2012). Although there are lots of studies conducted in the field of green roof, and the characteristics of all types of green roofs are discussed in previous studies (Vijayaraghavan, 2016), it is rare to find a study focused on the criteria related to the selection of appropriate type of green roof. Financial and non-financial criteria are involved throughout the process of decision making for obtaining the optimum type of green roof. Moreover, due to the high number of effective criteria, it's not easy to find the optimum type of green roof for any building. The aim of green roof installation, location of the green roof, structural considerations, maintenance of the green roof and some other criteria are non-financial criteria affecting the decision making. Considering all these criteria is a complicated process for decision making. Additionally, there are some significant financial criteria that play a critical role during this process. Consequently, all these criteria have to be taken into account in order to obtain the optimum result during the process of decision making for green roof type selection.

### **1.3 Problem Statement**

There is an increasing trend of implementing green roof instead of conventional one. This growing trend is not just for aesthetic perspective rather for the positive environmental impacts (Gabrych *et al.*, 2016; Rahman *et al.*, 2013). Each type of green roof has its own advantages and disadvantages. Therefore, the purpose of having a green roof should be determined and understood before selecting the optimum type of green roof to meet the goal of any construction project. According to the recent paper written by Abdul Rahman *et al* (2013), installing each type of green roof in Malaysia has been based on the professional's intention. As reported, some professionals in Malaysia, select intensive green roof because they consider only the

benefit of aesthetic, and guess that intensive green roof is more beneficial in comparison with other green roof types. Moreover, some of the other professionals select extensive green roof due to the lower required maintenance. However, different types of green roofs provide different costs and benefits (Jaffal *et al.*, 2012). The cost of intensive green roof installation is higher than the other types; however, it may not necessarily result in significant benefit for the client. As a result, there must be no allowance for guesswork by the designer's team because it can only lead to wrong specification or costly mistakes. Consequently, all effective criteria in decision making for green roof type selection have to be identified and considered during the process of decision making.

On the other hand, a semi-structured interview with the green roof contractors (with more than 21 years of experience) showed that, at the design stage of green roof installation, only two questions are often asked, firstly, how much the budget of the client is, and secondly, what type of green roof the client wants to be installed. This implies that, although many studies have investigated the costs and benefits for each type of green roof, still a serious challenge exists at the design stage of green roof installation. According to Johnson and Gibson (2014), the discipline of design is the process of decision making; however, there is still lack of a system, framework or guideline for decision-making in terms of selecting the optimum type of green roof. As a result, there is a need to have a tool to assist the designers to find the most appropriate type of green roof for any building.

#### **1.4 Research Questions**

The main research question in this research that is needed to be addressed is:

“How to select the optimum type of green roof for any building?”

The main research question was extended into five more specific sub-questions, which included:

1. What types of green roofs exist for construction?
2. Is the cost of installing green roof the only criterion that needed to be considered during the selection of type of green roofs?
3. What are the influential criteria in selecting the most appropriate type of green roof for any building?
4. Is it possible to make a right decision without any decision making tool for green roof type selection?
5. How can one make sure that the developed system for decision making on green roof type selection is effective, usable, and efficient?

### **1.5 Aim and Objectives**

The research has highlighted the research gap on lack of any model or framework for green roof type selection. Therefore, the aim of this research is to propose a decision support system in order to determine the optimum type of the green roof for a building. In order to achieve this aim following objectives have been determined:

1. To identify the major types of green roof and their characteristics;
2. To identify the significant criteria affecting decision making for the selection of green roof;
3. To develop a prototype decision support system to determine the optimum type of green roof;
4. To evaluate the effectiveness and efficiency of the prototype decision support system.



## 1.6 Scope and Limitations

Green roof installation carries a large number of private and environmental benefits that could be appropriate for any climate, especially in tropical climate with rainy weather (Jim, 2015a; Nagase and Dunnett, 2010). This research focuses on decision making for green roof type selection in green roof installation projects. The research was limited to Malaysia with high potential of green roof installation. There are many studies conducted on the green roof installation for residential buildings, due to the suitability of this building category for green roof installation, e.g. (Refahi and Talkhabi, 2015; Gabrych *et al.*, 2016; Nyuk Hien *et al.*, 2007; Jim, 2015b). Moreover, according to a recent study, residential buildings are one of the major building's category for green roof installation in Malaysia (Rahman *et al.*, 2013). As a result, this research focused on "residential buildings" category, and three hypothetical cases were selected in order to evaluate the developed prototype system. In addition, criteria related to this research were gathered from all available references; however, the experts for refining these criteria were selected from construction industry and academicians in Malaysia. This research focused on all the criteria and sub-criteria influencing the selection of optimum type of green roof in green roof installation projects. Figure 1.1 indicates the summary of the scope of this research.

Building category	<ul style="list-style-type: none"> <li>• Residential buildings</li> </ul>
Data collection for DM	<ul style="list-style-type: none"> <li>• Collected from all available references</li> <li>• Refined with Malaysia experts</li> </ul>
Case study	<ul style="list-style-type: none"> <li>• Three hypothetical cases including condominium, apartment, and bangalow</li> </ul>
Type of project	<ul style="list-style-type: none"> <li>• New buildings (not for retrofiting)</li> </ul>
Project life-cycle	<ul style="list-style-type: none"> <li>• Engineering and design stage</li> </ul>

**Figure 1.1:** Research scope

## 1.7 Significance of Research

This research highlights three important aspects that would be achieved in this research, i.e. identifying the criteria affecting green roof type selection, giving a new insight to the green roof's type selection, and developing a decision support system for the selection of optimum type of green roof to prevent the waste of cost, energy and material.

Green roof type selection is the most critical decision that should be made at the design stage of a green roof installation project. Currently, there is lack of adequate knowledge among developers, contractors, and architects about the suitability of each type of green roof for different buildings' categories (Rahman *et al.*, 2013). Generally, the decision can be made by the project designer or green roof contractor; however, in some cases the client's idea is the priority for the decision making. Clients or even the designers are not aware of lots of benefits and some costs that green roofs offer, and in many cases, they just take care of the beauty and cost. The research gives a new insight to the designers by introducing all positive and negative aspects of green roof installation. A decision support system helps the designers and decision-makers to select the optimum type of green roof based on the project requirements. There are many criteria affecting decision making for green roof type selection such as application of green roof, project features and etc., and without a tool it is impossible to consider all these criteria and get an optimum result.

## 1.8 Thesis Outline

This thesis consists of seven chapters. The chapters were arranged according to the sequence of the objectives and rationale behind the research. **Chapter 1** formulates the proposal of the research. **Chapter 2** reviews all the related fields of studies have been conducted regarding green roof installation. All the criteria affecting decision making for green roof type selection were presented throughout this section as well. Moreover, different types of green roofs that can be installed, and their characteristics were described in detail. At the end of this chapter, the methods that

have been used for developing a DSS in construction industry have been critically reviewed.

**Chapter 3** presents all the methodologies that have been used for this research. It begins with the preliminary studies, including reviewing the literature, semi-structured interviews and content analysis, followed by the main methodology of this research, multi-criteria decision making (MCDM). There are many criteria affecting DM for green roof selection; as a result MCDM was employed. Alternative formulation is the first step of MCDM, and the second step is criteria selection. Moreover, Enhanced Fuzzy Delphi Method (EFDM) was developed for this research as a method for criteria selection, while current methodologies for data collection were not appropriate for this research. In addition, in order to deal with the weaknesses of analytic hierarchy process (AHP), Cybernetic fuzzy AHP (CFAHP) was developed and discussed in the third step of MCDM for weighting the criteria and alternatives. At the end of this chapter, multi criteria evaluation approach was discussed in order to evaluate the prototype DSS.

**Chapter 4** presents the results and analyses of the research. It starts with alternative formulation followed by showing the results of criteria and sub-criteria identification. Then, the alternatives got weighted by the experts with respect to each sub-criterion that were identified during the process of EFDM. The results of this chapter were used as the material and the database for developing the prototype DSS.

**Chapter 5** presents the process of prototype development. It starts by the architecture of the software prototype, followed by the user requirements, and at the end, functional prototype was developed and discussed. Additionally, all the formulas that have been used for prototype system development were discussed.

**Chapter 6** evaluates the developed DSS through three cases from residential buildings. The priorities of the criteria were indicated based on the project requirements and the opinions of the users of the prototype DSS. Then the final results were presented including the optimum type of green roof for the cases as well as the most effective criterion and sub-criterion in the process of decision making. At the end

of this chapter, the evaluation of the prototype DSS was presented and discussed regarding the efficiency, effectiveness, satisfaction, and use of the prototype system.

Finally, based on the objectives of the research, the conclusions derived from the research were presented in **Chapter 7**. Moreover, the recommendations for future works were highlighted throughout this chapter.

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