EFFECT OF TOPLIGHTING SYSTEMS OF UKM ACADEMIC HALL ON DAYLIGHTING QUALITY AND ENERGY SAVINGS

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DECLARATION

I hereby declare that the work in this dissertation is my own except for quotations and summaries which have been duly acknowledged.

15 June 2014 MOHAMMED SAIF MOHAMMED

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ABSTRACT

Proper design and selection of daylighting systems can significantly help in improving energy efficiency and reducing environmental pollution. Artificial lighting system is considered as one of the major electricity-consuming elements in buildings, regardless of existing climate conditions. Effective integration between daylighting and artificial lighting system occurs when the level of artificial lighting system can be controlled as a function of illuminant levels reaching the working plan. An important factor that can lead to energy saving is the amount of daylight entering the building space, as this can not only reduce the artificial lighting energy use but also reduce artificial lighting internal loads, consequently reducing the cooling loads. The use of toplighting systems in buildings can yield to a uniform light distribution in the entire building space. However, in tropical climates such as that in Malaysia, where there is no heating season, heat transfer through daylighting systems is a critical issue that significantly affects the total energy use of a building. Therefore, the use of toplighting systems in buildings in such locations requires careful testing before any design decisions are made. In addition, limited studies have highlighted toplighting daylighting systems and their integrated effect on energy savings and daylight quality when used in the tropical climate of Malaysia. The main objectives of this study are as follows: to evaluate the energy savings and daylight quality effect of three types of toplighting systems, namely, skylight, sawtooth, and roof monitor in an existing academic hall building at University Kebangsaan Malaysia (UKM) based on a tropical climate; and to determine the effect of different shapes and geometries of toplighting systems on total lighting, cooling, energy and cost savings when used in the UKM case study building. The area inside the case study UKM building was investigated using interior daylight illuminant level measurement to evaluate existing lighting conditions and the possibility of toplighting use. Computer simulation models were created for the case study building (base case) and for all suggested toplighting types for building energy savings and daylight quality evaluation using OpenStudio energy simulation software. OpenStudio 0.7 is a free open-source platform collection of software tools to support whole building energy modeling using EnergyPlus and optionally advanced daylight analysis using Radiance. The building energy consumption analyses were carried out and comprised lighting, cooling, and total energy use and savings for all suggested toplighting options as compared to the base case model. The daylighting analyses were examined and involved illuminant level, uniformity, lighting distribution and daylight factor. The results clearly show the benefit of toplighting daylighting strategies with integrated artificial lighting systems through the lighting control technique. The results also show that in tropical climates with changeable sky conditions such as that in Kuala Lumpur, Malaysia, the roof monitor cases perform better than the skylight and sawtooth cases in terms of energy savings and the daylight quality. The energy analysis for the building indicate that a substantial reduction in lighting and total annual energy consumption could be achieved through the proper design and selection of skylights, sawtooth, and roof monitor cases. Considering the different trends of energy use, all suggested toplighting options cases exhibit better total annual energy savings than the base case.

ABSTRAK

Rekaan dan pemilihan sistem pencahayaan siang yang baik dapat membantu meningkatkan keberkesanan penggunaan tenaga dan mengurangkan pencemaran alam sekitar. Sistem pencahayaan tiruan dianggap sebagai penyumbang terbesar terhadap penggunaan elektrik dalam sesebuah bangunan tanpa mengira keadaan cuaca sekitar. Integrasi antara pencahayaan siang dan pencahayaan tiruan dikatakan berkesan apabila tahap pencahayaan tiruan dapat dikawal sebagai fungsi pencahayaan untuk sampai ke lantai ruang. Faktor utama yang dapat membantu menjimatkan tenaga adalah kuantiti cahaya yang memasuki ruang bangunan, yang bukan hanya mengurangkan penggunaan cahaya tiruan malah mengurangkan beban dalaman pencahayaan tiruan dan secara langsung mengurangkan beban penyejukan. Penggunaan sistem pencahayaan atas di dalam sesebuah bangunan dapat menghasilkan kesekataan pembahagian cahaya ke seluruh kawasan bangunan. Tetapi dengan cuaca tropikal seperti di Malaysia, yang tidak mempunyai musim panas, pengaliran haba melalui pencahayaan siang merupakan isu yang kritikal kerana ia memberi kesan yang signifikan ke atas jumlah penggunaan tenaga bangunan. Ini bererti, penggunaan pencahayaan atas dalam bangunan di kawasan ini memerlukan ujian yang teliti sebelum sesuatu model rekaan dibuat. Selain itu, tidak banyak kajian yang telah dilakukan yang menumpukan kepada sistem pencahayaan siang dan kesannya terhadap penjimatan tenaga dan kualiti cahaya siang apabila digunakan dalam cuaca tropika Malaysia. Objektif utama kajian ini adalah: untuk mengkaji kesan penjimatan tenaga dan kualiti cahaya siang oleh tiga jenis sistem pencahayaan atas yang digunakan di bangunan dewan kuliah di Universiti Kebangsaan Malaysia (UKM), berdasarkan cuaca panas dan lembab. Kedua, untuk mengetahui kesan daripada pelbagai perbezaan bentuk geometri sistem pencahayaan atas terhadap jumlah pencahayaan, penyejukan, jumlah tenaga dan kualiti cahaya siang apabila digunakan di dalam bangunan di UKM. Kawasan dewan di dalam bangunan kuliah di UKM yang dikaji telah dikenalpasti dengan meggunakan pengukuran tahap pencahayaan cahaya siang untuk mengira keadaan pencahayaan sedia ada dan kebolehgunaan pencahayaan atas. Dengan menggunakan OpenStudio 0.7, satu simulasi komputer telah dibuat dengan melibatkan bangunan yang dikaji. OpenStudio merupakan himpunan perisian yang menampung penggunaan EnergyPlus yang digunakan untuk memodelkan tenaga dan radian untuk analisis cahaya siang. Analisis penggunaan tenaga yang diperolehi termasuk pencahayaan, penyejukan dan jumlah tenaga yang digunakan, dan kemudiannya dibandingkan dengan bangunan asal kajian. Analisis pencahayaan siang yang dikaji termasuklah kadar pencahayaan, kesekataan penbahagian cahaya dan faktor cahaya siang. Kajian jelas menunjukkan kelebihan strategi pencahayaan atas yang digabungkan dengan pencahayaan tiruan melalui teknik pengawalan cahaya. Keputusan kajian juga menunjukkan bahawa cuaca tropika yang sering berubah seperti di Kuala Lumpur, aplikasi bentuk bergerigi adalah lebih baik dari cahaya dari atas dan kawalan bumbung dalam konteks penjimatan tenaga serta kualiti cahaya siang. Analisis tenaga ke atas bangunan menunjukkan pengurangan mendadak dalam pencahayaan dan penggunaan jumlah penggunaan tenaga tahunan dapat dicapai melalui rekabentuk pencahayaan atas, bentuk bergerigi dan pengawalan bumbung yang baik. Dengan mengambil kira pelbagai trend penggunaan tenaga, kesemua cadangan pilihan terhadap kaedah pencahayaan membuktikan penjimatan penggunaan tenaga yang lebih baik pada setiap tahun berbanding kaedah asas.

TABLE OF CONTENTS

DECLARATION		III
ACHNOWLEDGMENTS		V
ABSTRACT		VI
ABSTRAK		VII
TABLE OF CONTENTS		VIII
LIST OF TABLES		XIII
LIST OF FIGURES		XX
1	CHAPTER I: INTRODUCTION	1
1.1	BACKGROUND	1
1.2	PROBLEM STATEMENT	7
1.3	RESEARCH OBJECTIVES	11
1.4	SIGNIFICANCE OF THE STUDY	12
1.5	SCOPE AND LIMITATIONS OF THE STUDY	12
1.6	RESEARCH METHODOLOGY	13
1.7	ORGANIZATION OF THE THESIS	14
2	CHAPTER II: LITERATURE REVIEW	17
2.1	CLIMATE OF MALAYSIA	17
2.1.1	Location	17
2.1.2	Temperature and Humidity	18
2.1.3	Rainfall	21
2.1.4	Solar Radiation	24
2.2	LIGHTING	27
2.2.1	Light	27
2.2.2	Lighting Design Requirements	27
2.2.3	Lighting Controls Systems	29
2.3	DAYLIGHTING	33
2.3.1	Defining Daylight and Daylighting Systems	33
2.3.2	Daylight Source and Availability	34
2.3.3	Malaysia Sky Condition	42
2.3.4	Daylighting Design Strategies	52
2.3.4.1	Common Toplighting System Designs	53

UNIVERSITI KEBANGSAAN MALAYSIA

2.3.5 Benefits of Daylighting 55
2.3.6 Daylight Calculations and Analysis 60
2.3.7 Daylighting Potential in Malaysia 62
2.4 DAYLIGHTING AND ENERGY EFFICIENCY 63
2.4.1 Energy Consumption in Buildings 63
2.4.2 Energy Savings Impact of Daylighting 67
2.4.3 Building Thermal Load Impact of Daylighting 70
2.5 ENERGY AND DAYLIGHTING SIMULATION PROGRAMS 72
2.5.1 Building Energy Simulation Programs 74
2.5.2 Daylighting Energy Simulation Programs 82
2.6 PREVIOUS CASE STUDIES IN HOT-HUMID CLIMATES 83
2.7 SUMMARY: THE GAP IN THE LITERATURE REVIEW 91
3 CHAPTER III: RESEARCH METHODOLOGY 94
3.1 INTRODUCTION 94
3.2 STEPS OF THE METHODOLOGY 94
3.2.1 Case Study Building Data Collection 94
3.2.2 Case Study Building Description for Simulation 95
3.3 CASE STUDY BUILDING DESCRIPTIONS 97
3.3.1 General Building Description 97
3.3.2 Case Study Building Description for the Simulation 97
3.3.3 OpenStudio Plug-in Clarification of Case Study Building 108
3.4 SIMULATION PARAMETERS IN ENERGYPLUS 108
3.4.1 Kuala Lumpur Climate 109
3.4.1.1 EnergyPlus Weather Data Format Definition 111
3.4.1.2 EnergyPlus Weather Data Sources 111
3.4.2 Toplighting Shapes, Geometries and Orientations 115
3.4.3 Spacing-to-ceiling height ratio 116
3.4.4 Glazing Types 128
3.5 DAYLIGHTING PERFORMANCE METHODOLOGY 129
3.5.1 Intermediate and Overcast Sky Conditions 130
3.5.2 Instrumentation: EnergyPlus 130
3.5.3 Daylight Measurement Instruments 131
3.5.4 On-site Daylight Measurements 133

UNIVERSITI KEBANGSAAN MALAYSIA

3.5.5 Daylighting Analysis Parameters 143
3.5.6 Location of Lighting Control System 144
3.6 CALIBRATION OF THE ENERGYPLUS7.0 BASE CASE MODEL 145
3.6.1 Initial Simulation Results of the Base Case Model 146
3.6.2 Calibrating to Actual Building Energy Consumption 148
3.6.3 Adjustments for Calibrating the Base Case to Billing History 152
3.6.4 Calibrating to Actual On Site Measured Weather Data 156
3.6.5 Design Limitation of Toplighting System 157
3.7 SUMMARY 158
4 CHAPTER IV: RESULTS AND DISCUSSIONS 160
4.1 DAYLIGHTING ANALYSIS 160
4.1.1 Introduction 160
4.1.2 Comparison of Daylight Measurement of Case study Building and EnergyPlus with OpenStudio Simulation results 160
4.1.2.1 Locations of measurement points for case study building and EneryPlus model 161
4.1.2.2 Analysis of the Overcast Sky Daylight Measurements 163
4.1.2.3 Analysis of Intermediate Sky Daylight Measurements 165
4.1.3 Toplighting Alternatives Analysis: 1-to-1 Spacing-to-Ceiling Height Ratio 170
4.1.3.1 Daylight Factor Analysis 170
4.1.3.2 Illuminance level Analysis 173
4.1.3.3 Daylight Distribution and Uniformity Analysis 186
4.1.4 Toplighting Alternatives Analysis: 1 to 1.5 Spacing-to-Ceiling Height Ratio 210
4.1.4.1 Daylight Factor Analysis 210
4.1.4.2 Illuminance level Analysis 213
4.1.4.3 Daylight Distribution and Uniformity Analysis 227
4.1.5 Summary 252
4.2 ENERGY ANALYSIS 254
4.2.1 Introduction 254
4.2.2 Building Energy Use Evaluation 254
4.2.2.1 EneryPlus Base Case Model With and Without Daylighting 254

UNIVERSITI KEBANGSAAN MALAYSIA

4.2.2.2 Lighting and Cooling Energy Use Analysis 255
4.2.2.3 Total Building Energy Use Analysis 257
4.2.3 Toplighting Alternatives Analysis: 1 to 1 Spacing-to-Height Ratio 258
4.2.4 Lighting Energy Use Analysis 259
4.2.4.1 Comparison of the Lighting Energy Use of Skylight Cases 259
4.2.4.2 Comparison of Lighting Energy Use of Sawtooth Cases 263
4.2.4.3 Comparison of Lighting Energy Use of Roof Monitor Cases 266
4.2.5 Cooling Energy Use Analysis 269
4.2.5.1 Comparison of Cooling Energy Use of Skylight Cases 269
4.2.5.2 Comparison of Cooling Energy Use of Sawtooth Cases 271
4.2.5.3 Comparison of Cooling Energy Use of Roof Monitor Cases 273
4.2.6 Total Building Energy Analysis 275
4.2.6.1 Comparison of Total Energy Use of Skylight Cases 275
4.2.6.2 Comparison of Total Energy Use of Sawtooth Cases 277
4.2.6.3 Comparison of Total Energy Use of Roof monitor Cases 279
4.2.7 Comparison of Energy Savings from Various Toplighting Alternatives 281
4.2.8 Toplighting Alternatives Analysis: 1 to 1.5 Spacing-to-Height Ratio 288
4.2.8.1 Comparison of Lighting Energy Savings 288
4.2.8.2 Comparison of Total Energy Savings 294
4.2.9 Economic Analysis 301
4.2.9.1 Energy Savings Potential from Alternatives Toplighting Designs 301
4.2.9.2 Energy Cost Savings Potential from Toplighting Designs 304
4.2.9.3 National Energy and Cost Savings Potential across Malaysia 308
4.2.10 Summary 313
5 CHAPTER V: CONCLUSIONS AND RECOMMENDATIONS 316
5.1 INTRODUCTION 316
5.2 THE CASE STUDY BUILDING SELECTION 317
5.3 THE CASE STUDY BUILDING DAYLIGHT EVALUATION 318
5.4 THE ENERGYPLUS WITH OPENSTUDIO BASE CASE MODEL 319
5.5 EFFECT OF TOPLIGHTING OPTIONS ON ENERGY SAVINGS 320
5.6 EFFECT OF TOPLIGHTING OPTIONS ON DAYLIGHT QUALITY 322
5.7 ECONOMIC ANALYSIS 323

UNIVERSITI KEBANGSAAN MALAYSIA

5.8 RECOMMENDATIONS FOR FUTURE RESEARCH 325
REFERENCES 326
LIST OF PUBLICATIONS 337
APPENDIX A: DETAILED RESULTS FOR ENERGY ANALYSIS 338
APPENDIX B: DETAILED RESULTS FOR DAYLIGHTING ANALYSIS 370
APPENDIX C: GLOSSARY 394
APPENDIX D: LIGHT METER FEATURES AND SPECIFICATIONS 397

UNIVERSITI KEBANGSAAN MALAYSIA

LIST OF TABLES

Table No.		Page
1.1	Energy end-use in the ASEAN countries	4
1.2	Lighting end-use in commercial buildings in different countries	5
1.3	UKM case study academic hall monthly electricity energy consumption	9
2.1	Recommended average illuminance values for interior lighting design	28
2.2	Illuminance categories and illuminance values for interior lighting design	28
2.3	Recommended illuminance categories for institutional interiors	29
2.4	Record of mean Cloud Cover record in (Oktas) based on hours of observation from 08:00 a.m. to 20:00 p.m. for the year 1980 to 1993	46
2.5	Relationship between cloud cover and the type of sky	46
2.6	Different Sky types according to Nebulosity Index, Subang Jaya, Malaysia	47
2.7	Energy end-use in the ASEAN countries	64
2.8	Energy end-use in the USA	65
2.9	Comprehensive comparisons of the capabilities of building energy simulation programs	79
2.10	Summary Table for Previous Studies	92
3.1	EnergyPlus input case study building characteristics used for simulation modeling	101
3.2	Main characteristics of case study building air-conditioning system	103
3.3	Daylight Hours of Kuala Lumpur, Malaysia	103
3.4	EnergyPlus input: Case study building occupancy and operation schedules	104

UNIVERSITI KEBANGSAAN MALAYSIA

3.5	EnergyPlus input: Daylight control attributes	107
3.6	Thermal and daylighting main climatic attributes for the Kuala Lumpur city	109
3.7	Monthly Weather File Heating/Cooling Degree Days/Hours for Kuala Lumpur	110
3.8	Location information and the IWEC stations reference numbers	112
3.9	Relationship between type of skies and the cloud cover	113
3.10	Average Cloud Cover for Subang from 2001-2003	113
3.11	Different Sky types according to Nebulosity Index, Subang Jaya, Malaysia	114
3.12	Toplighting dimensions for each toplighting alternative	115
3.13	Optical and thermal attributes of glazing types used in this study for performance comparison	128
3.14	Determination of minimum number of measurement points	135
3.15	UKM case study hall building monthly electricity energy consumption	146
3.16	Initial base case model simulation results versus measured energy consumption	147
3.17	Acceptable Tolerances for Hourly Data Calibration	150
3.18	Acceptable Tolerances for Monthly Data Calibration	151
3.19	Monthly simulated energy consumption versus actual	155
4.1	Daylight factor simulation result from EnergyPlus versus actual case study measurements	165
4.2	Case study computer model interior illuminance levels generated from CSV file in EnergyPlus with OpenStudio	165
4.3	Comparison of daylight illuminance uniformity: 1 to 1 spacing-to- ceiling height ratio, 5% TFR	205
4.4	Comparison of daylight illuminance uniformity: 1 to 1 spacing-to- ceiling height ratio, 10% TFR	205
4.5	Comparison of daylight illuminance uniformity: 1 to 1 spacing-	206

UNIVERSITI KEBANGSAAN MALAYSIA

	to- ceiling height ratio, 15% TFR	
4.6	Comparison of daylight illuminance gradient: 1 to 1 spacing-to-ceiling height ratio, 5% TFR	206
4.7	Comparison of daylight illuminance gradient: 1 to 1 spacing-to-ceiling height ratio, 10% TFR	207
4.8	Comparison of daylight illuminance gradient: 1 to 1 spacing-to-ceiling height ratio, 15% TFR	207
4.9	Comparison of daylight illuminance gradient: 1 to 1.5 spacing-to-ceiling height ratio, 5% TFR	246
4.10	Comparison of daylight illuminance gradient: 1 to 1.5 spacing-to-ceiling height ratio, 10% TFR	246
4.11	Comparison of daylight illuminance gradient: 1 to 1.5 spacing-to-ceiling height ratio, 15% TFR	247
4.12	Daylight illuminance uniformity comparison: 1 to 1.5 spacing-to-ceiling height ratio toplighting alternatives, 5% TFR	247
4.13	Daylight illuminance uniformity comparison: 1 to 1.5 spacing-to-ceiling height ratio toplighting alternatives, 10% TFR	248
4.14	Daylight illuminance uniformity comparison: 1 to 1.5 spacing-to-ceiling height ratio toplighting alternatives, 15% TFR	248
4.15	Comparison of monthly lighting and cooling electricity consumption of base case model without daylighting versus the base case model with daylighting	256
4.16	Comparison of monthly total electricity consumption of base case model without daylighting control versus base case model with daylighting control	258
4.17	Comparison of total energy savings (%) from the various toplighting options with different glazing types and orientations and 5% TFR compared with the base case model	282
4.18	Comparison of total energy savings (%) from the various toplighting options with different glazing types and orientations and 10% TFR compared with the base case model	283
4.19	Comparison of annual total lighting energy savings (%) of different skylights, sawtooth, and roof monitor cases with different glazing types, orientations, and TFR of 5% to 20% versus base case model with 1-to-1.5 spacing-to-height ratio	291

UNIVERSITI KEBANGSAAN MALAYSIA

4.20	Comparison of total energy savings (%) from the various toplighting options with different glazing types in all orientations and 5%TFR versus base case model	295
4.21	Comparison of total energy savings (%) from the various toplighting options with different glazing types in all orientations and 10%TFR versus base case model	296
5.1	Average illuminance level in (lux) for the case study interior space	319
A-1	Total energy savings (%) for different skylight cases with different glazing types across all orientations as compared to the base case model without daylighting	339
A-2	Lighting energy savings (%) for different skylight cases with different glazing types across all orientations as compared to the base case model without daylighting	340
A-3	Cooling energy savings (%) for different skylight cases with different glazing types across all orientations as compared to the base case model without daylighting	341
A-4	Total energy savings (%) for different sawtooth cases with different glazing types across all orientations as compared to the base case model without daylighting	342
A-5	Lighting energy savings (%) for different sawtooth cases with different glazing types across all orientations as compared to the base case model without daylighting	343
A-6	Cooling energy savings (%) for different sawtooth cases with different glazing types across all orientations as compared to the base case model without daylighting	344
A-7	Total energy savings (%) for different roof monitor cases with different glazing types across all orientations as compared to the base case model without daylighting	345
A-8	Lighting energy savings (%) for different roof monitor cases with different glazing types across all orientations as compared to the base case model without daylighting	346
A-9	Cooling energy savings (%) for different roof monitor cases with different glazing types across all orientations as compared to the base case model without daylighting	347
A-10	Total energy savings (%) comparison for the different toplighting options with different glazing types, in all	357

UNIVERSITI KEBANGSAAN MALAYSIA

	orientations and TFR of 15% as compared to the base case model	
A-11	Total energy savings (%) comparison for the different toplighting options with different glazing types, in all orientations and TFR of 20% as compared to the base case model	358
A-12	Total energy savings (%) comparison for the different toplighting options with different glazing types, all orientations, and TFR of 25% as compared to the base case model	359
A-13	Total energy savings (%) comparison for the different toplighting options with different glazing types, in all orientations and TFR of 30% as compared to the base case model	360
A-14	Total energy savings (%) comparison for the different toplighting options with different glazing types, all orientations, and TFR of 40% as compared to the base case model	361
A-15	Total energy savings (%) comparison for the different toplighting options with different glazing types, in all orientations and TFR of 50% as compared to the base case model	362
A-16	Total energy savings (%) comparison for the different toplighting options with different glazing types, all orientations, and TFR of 60% as compared to the base case model	363
A-17	Total lighting energy savings (%) comparison for toplighting alternatives with different glazing types, different orientations and different glazed area TFR. 1 to 1.5 spacing-to-height Ratio	364
A-18	Total cooling energy savings (%) comparison for toplighting alternatives with different glazing types, different orientations and different glazed area TFR. 1 to 1.5 spacing-to-height ratio	365
A-19	Total energy savings (%) comparison for toplighting alternatives with different glazing types, different orientations and different glazed area TFR. 1 to 1.5 spacing-to-height ratio	366
A-20	Total annual building energy and energy cost savings for all the suggested skylight cases. The energy and energy cost savings are addressed into lighting, cooling, and total energy savings	367
A-21	Total annual energy and energy cost savings for all the	368

UNIVERSITI KEBANGSAAN MALAYSIA

	suggested sawtooth cases. The energy and energy cost savings are addressed into lighting, cooling, and total energy savings	
A-22	Total annual energy and energy cost savings for all the suggested roof monitor cases. The energy and energy cost savings are addressed into lighting, cooling, and total energy savings	369
B-1	Daylight illuminance uniformity comparison: 1 to 1 spacing-to-ceiling height ratio toplighting alternatives, 20% TFR	383
B-2	Daylight illuminance uniformity comparison: 1 to 1 spacing-to-ceiling height ratio toplighting alternatives, 25% TFR	383
B-3	Daylight illuminance uniformity comparison: 1 to 1 spacing-to-ceiling height ratio toplighting alternatives, 30% TFR	384
B-4	Daylight illuminance uniformity comparison: 1 to 1 spacing-to-ceiling height ratio toplighting alternatives, 35% TFR	384
B-5	Daylight illuminance uniformity comparison: 1 to 1 spacing-to-ceiling height ratio toplighting alternatives, 40% TFR	385
B-6	Daylight illuminance uniformity comparison: 1 to 1 spacing-to-ceiling height ratio toplighting alternatives, 50% TFR	385
B-7	Daylight illuminance gradient comparison: 1 to 1 spacing-to-ceiling height ratio toplighting alternatives, 20% TFR	386
B-8	Daylight illuminance gradient comparison: 1 to 1 spacing-to-ceiling height ratio toplighting alternatives, 25% TFR	386
B-9	Daylight illuminance gradient comparison: 1 to 1 spacing-to-ceiling height ratio toplighting alternatives, 30% TFR	387
B-10	Daylight illuminance gradient comparison: 1 to 1 spacing-to-ceiling height ratio toplighting alternatives, 35% TFR	387
B-11	Daylight illuminance gradient comparison: 1 to 1 spacing-to ceiling height ratio toplighting alternatives, 40% TFR	388
B-12	Daylight illuminance gradient comparison: 1 to 1 spacing-to-ceiling height ratio toplighting alternatives, 50% TFR	388
B-13	Daylight illuminance gradient comparison: 1 to 1.5 spacing-to-ceiling height ratio toplighting alternatives, 20% TFR	392
B-14	Daylight illuminance gradient comparison: 1 to 1.5 spacing-to-ceiling height ratio toplighting alternatives, 25% TFR	392

UNIVERSITI KEBANGSAAN MALAYSIA

B-15	Daylight illuminance uniformity comparison: 1 to 1.5 spacing-to- ceiling height ratio toplighting alternatives, 20% TFR	393
B-16	Daylight illuminance uniformity comparison: 1 to 1.5 spacing-to- ceiling height ratio toplighting alternatives, 25% TFR	394

UNIVERSITI KEBANGSAAN MALAYSIA

LIST OF FIGURES

Figure No.		Page
1.1	Energy consumption and production in Malaysia	1
1.2	Distribution of electrical energy consumed by different sectors in Malaysia	3
1.3	Energy consumption breakdown in Malaysian school buildings	4
1.4	Characteristics of side lit spaces. (a) Reducing daylight levels with distance, (b) daylight penetration for standard windows	8
1.5	The Problem- A typical side-lit academic hall building in Universiti Kebangsaan Malaysia, Malaysia	8
1.6	Flow chart of the research process and methodology	16
2.1	Malaysia latitude and longitude map	18
2.2	Kuala Lumpur Monthly Average Temperature	19
2.3	Kuala Lumpur Monthly Average Relative Humidity	20
2.4	Mean relative humidity at 24 selected principal meteorological stations, Malaysia	20
2.5	Total rainfall at 24 selected principal meteorological stations, Malaysia	21
2.6	Annual total rainfall at 24 selected principal meteorological stations, Malaysia	22
2.7	Stations that received rainfall over 3,000 mm and number of rainy days, 2010	23
2.8	Kuala Lumpur monthly averages solar radiation (direct normal, diffuse, global horizontal)	25
2.9	Kuala Lumpur monthly average hourly direct normal solar radiation	25
2.10	Kuala Lumpur average hourly diffuse horizontal solar radiation	26
2.11	Kuala Lumpur average hourly global horizontal solar radiation	26
2.12	Daylight availability at Subang, Malaysia	35

UNIVERSITI KEBANGSAAN MALAYSIA

2.13	The relationship between global, direct-beam and diffuse illuminance during clear sky versus solar altitude of the sun	39
2.14	Probability amount of illuminance from global and diffused sky component	39
2.15	Solar Altitude Angle (SAA)	40
2.16	Clear sky vault and condition	41
2.17	Overcast sky vault and condition	42
2.18	Kuala Lumpur's Sun-path diagram	43
2.19	Sun-path diagram of Malaysian Cities	44
2.20	Kuala Lumpur average hourly direct normal solar radiation	48
2.21	Kuala Lumpur average hourly diffuse horizontal solar radiation	48
2.22	Kuala Lumpur average hourly global horizontal solar radiation	49
2.23	Kuala Lumpur monthly averages solar radiation (direct normal, diffuse, global horizontal)	50
2.24	Sections of common toplighting systems designs used in buildings	55
2.25	Annual energy needs (kWh)	71
2.26	EnergyPlus overall simulation program structure	77
3.1	Basic flow chart guide of research methodology	96
3.2	Floor plan of case study UKM academic hall	98
3.3	Perspective and elevations of UKM academic hall: Perspective (a) east elevation (b) and south elevation(c)	99
3.4	Interior and exterior photographs of UKM case study building: (a) when artificial lighting is ON (b) when artificial lighting is Off, (c) photographs for exterior corridor and sidelight system, and photographs for interior sidelight system	100
3.5	Perspective of base case model using EnergyPlus with OpenStudio Plug-in software	108
3.6	Roof plans of selected toplighting alternatives and distribution of 1 to 1 spacing-to-ceiling height ratio varying from 5% to	118

UNIVERSITI KEBANGSAAN MALAYSIA

	60% of the roof area	
3.7	Roof plans of selected toplighting alternatives and distribution of 1to 1 spacing-to-ceiling height ratio varying from 5% to 60% of the roof area	119
3.8	Sections of selected toplighting alternatives and distribution of 1 to 1 spacing-to-ceiling height ratio varying from 5% to 60% of the roof area	120
3.9	OpenStudio roof plans and perspectives of selected toplighting design alternatives and distribution of 1 to 1 spacing-to-ceiling height ratio (North/South Orientation)	121
3.10	OpenStudio roof plans and perspectives of selected toplighting design alternatives of 1 to 1 spacing-to-ceiling height ratio (East/West orientation)	122
3.11	Roof plans of selected toplighting alternatives strategies and distribution of 1 to 1.5 spacing-to-ceiling height ratio varying from 5% to 60% of roof area	123
3.12	Roof plans of selected toplighting alternatives and distribution of 1 to 1.5 spacing-to-ceiling height ratio varying from 5% to 60% of roof area	124
3.13	Sections of selected toplighting alternatives and distribution of 1 to 1.5 spacing-to-ceiling height ratio varying from 5% to 60% of roof area	125
3.14	OpenStudio roof plans and perspectives of selected toplighting alternatives and distribution of 1 to 1.5 spacing-to-ceiling height ratio (North/South Orientation)	126
3.15	OpenStudio roof plans and perspectives of selected toplighting alternatives and distribution of 1 to 1.5 spacing-to-ceiling height ratio (East/West orientation)	127
3.16	Visible light transmittance and solar heat gain coefficient for glazing types used in this study	129
3.17	Illuminance meter model LX-1108 used in daylight measurements	132
3.18	LX-1108 Light Meter Sensor	132
3.19	LX-1108 Lutron light Sensor Spectral Response Curve vs CIE Curve (Source: Specifications Sheet for LX-1108 light sensor provided by Lutron)	133

UNIVERSITI KEBANGSAAN MALAYSIA

3.20	Floor plan of the grid layout of the case study building illuminance level measurement points	137
3.21	Measured internal daylight illuminance levels (lux) in case study building space without artificial lighting (March 21, 2011; 12:00 pm to 13.30 pm)	141
3.22	Artificial lighting illuminance levels (lux) measured inside case study building space (March 23, 2011)	142
3.23	EnergyPlus with OpenStudio Plug-in in Google SketchUp representation of the reference points locations inside the case study space	145
3.24	Actual monthly energy consumption of case study building	148
3.25	EnergyPlus procedure for calibrating base case computer model	153
3.26	Comparison of simulated versus actual building energy consumption	155
3.27	Comparison between UKM measured outdoor dry bulb temperatures for case study building and EnergyPlus zone outdoor dry bulb temperatures	157
4.1	Measurement points locations for comparison daylight factor of the actual case study space and EnergyPlus base case model	162
4.2	Measurement points locations for EnergyPlus base case model: daylight factor and illuminance level analysis	162
4.3	Measurement points locations for EnergyPlus base case model: daylight uniformity analysis	163
4.4	Outside views for the UKM case study academic hall surrounded by obstructions, such as corridors columns, trees, and constructions	165
4.5	EnergyPlus average daylight illuminance level map of case study model. 21 March	167
4.6	EnergyPlus average daylight illuminance level map of case study model. 21 Jun	168
4.7	EnergyPlus average daylight illuminance level map of case study model. 21 December	169
4.8	Comparison of daylight factors of 1-to-1 toplighting alternatives and base case with a TFR: a) 5%, b)10%, and c) 15% under	171

UNIVERSITI KEBANGSAAN MALAYSIA

overcast sky conditions

4.9 Illuminance level comparison: 1-to-1 spacing-to-ceiling height ratio, 5% TFR, double low-e clear, 21 of March 174

4.10 Illuminance level comparison: 1-to-1 spacing-to-ceiling height ratio, 5% TFR, double low-e clear, 21 of June 175

4.11 Illuminance level comparison: 1-to-1 spacing-to-ceiling height ratio, 5% TFR, double low-e clear, 21 of December 176

4.12 Illuminance level comparison: 1-to-1spacing-to-ceiling height ratio, 10% TFR, double low-e clear, 21 of March 177

4.13 Illuminance level comparison: 1-to-1 spacing-to-ceiling height ratio, 10% TFR, double low-e clear, 21 of June 178

4.14 Illuminance level comparison: 1-to-1 spacing-to-ceiling height ratio, 10% TFR, double low-e clear, 21 of December 179

4.15 Illuminance level comparison: 1-to-1 spacing-to-ceiling height ratio, 15% TFR, double low-e clear, 21 of March 180

4.16 Illuminance level comparison: 1-to-1 spacing-to-ceiling height ratio, 15% TFR, double low-e clear, 21 of June 181

4.17 Illuminance level comparison: 1-to-1 spacing-to-ceiling height ratio, 15% TFR, double low-e clear, 21 of December 182

4.18 EnergyPlus Skylight Illuminance level maps: 1 to 1 spacing-to-height ratio, 5% TFR, double low-e clear. 21 March 187

4.19 EnergyPlus Skylight Illuminance level maps: 1 to 1 spacing-to-height ratio, 5% TFR, double low-e clear. 21 Jun 188

4.20 EnergyPlus Skylight Illuminance level maps: 1 to 1 spacing-to-height ratio, 5% TFR, double low-e clear. 21 December 189

4.21 EnergyPlus Sawtooth Illuminance level maps: 1 to 1 spacing-to-height ratio, 5% TFR, double low-e clear. 21 March 190

4.22 EnergyPlus Sawtooth Illuminance level maps: 1 to 1 spacing-to-height ratio, 5% TFR, double low-e clear. 21 Jun 191

4.23 EnergyPlus Sawtooth Illuminance level maps: 1 to 1 spacing-to-height ratio, 5% TFR, double low-e clear.21 December 192

4.24 EnergyPlus Roof Monitor Illuminance level maps: 1 to 1 spacing-to-height ratio, 5% TFR, double low-e clear. 21 March 193

UNIVERSITI KEBANGSAAN MALAYSIA

4.25	EnergyPlus Roof Monitor Illuminance level maps: 1 to 1 spacing-to-height ratio, 5% TFR, double low-e clear. 21 Jun	194
4.26	EnergyPlus Roof monitor Illuminance level maps: 1 to 1 spacing-to-height ratio, 5% TFR, double low-e clear. 21 December	195
4.27	EnergyPlus Skylight Illuminance level maps: 1 to 1 spacing-to-height ratio, 10% TFR, double low-e clear. 21 March	196
4.28	EnergyPlus Skylight Illuminance level maps: 1 to 1 spacing-to-height ratio, 10% TFR, double low-e clear. 21 Jun	197
4.29	EnergyPlus Skylight Illuminance level maps: 1 to 1 spacing-to-height ratio, 10% TFR, double low-e clear. 21 December	198
4.30	EnergyPlus Sawtooth Illuminance level maps: 1 to 1 spacing-to-height ratio, 10% TFR, double low-e clear. 21 March	199
4.31	EnergyPlus Sawtooth Illuminance level maps: 1 to 1 spacing-to-height ratio, 10% TFR, double low-e clear. 21 Jun	200
4.32	EnergyPlus Sawtooth Illuminance level maps: 1 to 1 spacing-to-height ratio, 10% TFR, double low-e clear. 21 December	201
4.33	EnergyPlus Roof Monitor Illuminance level maps: 1 to 1 spacing-to-height ratio, 10% TFR, double low-e clear. 21 March	202
4.34	EnergyPlus Roof Monitor Illuminance level maps: 1 to 1 spacing-to-height ratio, 10% TFR, double low-e clear. 21 Jun	203
4.35	EnergyPlus Roof Monitor Illuminance level maps: 1 to 1 spacing-to-height ratio, 10% TFR, double low-e clear. 21 December	204
4.36	Comparison of daylight factor of 1 to 1.5 toplighting alternatives versus base case under overcast sky condition, a) 5%, b)10%, and c) 15% TFR	211
4.37	Illuminance level comparison: 1 to 1.5 spacing-to-ceiling height ratio, 5% TFR, double low-e clear, 21 of March	215
4.38	Illuminance level comparison: 1 to 1.5 spacing-to-ceiling height ratio, 5% TFR, double low-e clear, 21 of June	216
4.39	Illuminance level comparison: 1 to 1.5 spacing-to-ceiling height ratio, 5% TFR, double low-e clear, 21 of December	217
4.40	Illuminance level comparison: 1 to 1.5 spacing-to-ceiling height	218

UNIVERSITI TEKNOLOGI MALAYSIA

ratio, 10% TFR, double low-e clear, 21 of March

4.41 Illuminance level comparison: 1 to 1.5 spacing-to-ceiling height ratio, 10% TFR, double low-e clear, 21 of June 219

4.42 Illuminance level comparison: 1 to 1.5 spacing-to-ceiling height ratio, 10% TFR, double low-e clear, 21 of December 220

4.43 Illuminance level comparison: 1 to 1.5 spacing-to-ceiling height ratio, 15% TFR, double low-e clear, 21 of March 221

4.44 Illuminance level comparison: 1 to 1.5 spacing-to-ceiling height ratio, 15% TFR, double low-e clear, 21 of June 222

4.45 Illuminance level comparison: 1 to 1.5 spacing-to-ceiling height ratio, 15% TFR, double low-e clear, 21 of December 223

4.46 EnergyPlus Skylight Illuminance level maps: 1 to 1.5 spacing-to-height ratio, 5% TFR, double low-e clear. 21 March 228

4.47 EnergyPlus Skylight Illuminance level maps: 1 to 1.5 spacing-to-height ratio, 5% TFR, double low-e clear. 21 Jun 229

4.48 EnergyPlus Skylight Illuminance level maps: 1 to 1.5 spacing-to-height ratio, 5% TFR, double low-e clear. 21 December 230

4.49 EnergyPlus Sawtooth Illuminance level maps: 1 to 1.5 spacing-to-height ratio, 5% TFR, double low-e clear. 21 March 231

4.50 EnergyPlus Sawtooth Illuminance level maps: 1 to 1.5 spacing-to-height ratio, 5% TFR, double low-e clear. 21 Jun 232

4.51 EnergyPlus Sawtooth Illuminance level maps: 1 to 1.5 spacing-to-height ratio, 5% TFR, double low-e clear. 21 December 233

4.52 EnergyPlus Roof Monitor Illuminance level maps: 1 to 1.5 spacing-to-height ratio, 5% TFR, double low-e clear. 21 March 234

4.53 EnergyPlus Roof Monitor Illuminance level maps: 1 to 1.5 spacing-to-height ratio, 5% TFR, double low-e clear. 21 Jun 235

4.54 EnergyPlus Roof Monitor Illuminance level maps: 1 to 1.5 spacing-to-height ratio, 5% TFR, double low-e clear. 21 December 236

4.55 EnergyPlus Skylight Illuminance level maps: 1 to 1.5 spacing-to-height ratio, 10% TFR, double low-e clear. 21 March 237

4.56 EnergyPlus Skylight Illuminance level maps: 1 to 1.5 spacing- 238

UNIVERSITI TEKNOLOGI BRUNEI DARUSSALAM MALAYSIA

	to-height ratio, 10% TFR, double low-e clear. 21 Jun	
4.57	EnergyPlus Skylight Illuminance level maps: 1 to 1.5 spacing-to-height ratio, 10% TFR, double low-e clear. 21 December	239
4.58	EnergyPlus Sawtooth Illuminance level maps: 1 to 1.5 spacing-to-height ratio, 10% TFR, double low-e clear. 21 March	240
4.59	EnergyPlus Sawtooth Illuminance level maps: 1 to 1.5 spacing-to-height ratio, 10% TFR, double low-e clear. 21 Jun	241
4.60	EnergyPlus Sawtooth Illuminance level maps: 1 to 1.5 spacing-to-height ratio, 10% TFR, double low-e clear. 21 December	242
4.61	EnergyPlus Roof Monitor Illuminance level maps: 1 to 1.5 spacing-to-height ratio, 10% TFR, double low-e clear. 21 March	243
4.62	EnergyPlus Roof Monitor Illuminance level maps: 1 to 1.5 spacing-to-height ratio, 10% TFR, double low-e clear. 21 Jun	244
4.63	EnergyPlus Roof Monitor Illuminance level maps: 1 to 1.5 spacing-to-height ratio, 10% TFR, double low-e clear. 21 December	245
4.64	Comparison of monthly lighting energy consumption of base case model without and with daylighting	255
4.65	Comparison of monthly cooling energy consumption of base case model without and with daylighting	256
4.66	Comparison of monthly total building energy consumption of base case model with and without daylighting control technique	258
4.67	Comparison of annual lighting energy consumption of skylight cases with different glazing types for [a) North, b) South, c) East, and d) West orientations] and base case computer model without daylighting	262
4.68	Comparison of annual lighting energy consumption of sawtooth cases with different glazing types for [a) North, b) South, c) East, and d) West orientations] and base case computer model without daylighting	265
4.69	Comparison of annual lighting energy consumption of roof monitor cases with different glazing types for [a) North, b) South, c) East, and d) West orientations] and base case computer model without daylighting	268
4.70	Comparison of annual cooling energy consumption of different	270

UNIVERSITI KEBANGSAAN MALAYSIA

	skylight cases with different glazing types and orientations and versus base case model without daylighting	
4.71	Comparison of annual cooling energy consumption of sawtooth cases with different glazing types and orientations and the base case computer model without daylighting	272
4.72	Comparison of annual cooling energy consumption of roof monitor cases with different glazing types and orientations and base case computer model without daylighting	274
4.73	Comparison of total energy consumption of skylight cases with various glazing types and four orientations versus base case model without daylighting	276
4.74	Comparison of total energy consumption of sawtooth cases with various glazing types and orientations versus base case model with no daylighting control	278
4.75	Comparison of total energy consumption of roof monitor cases with different glazing types and orientations versus base case model without daylighting	280
4.76	Lighting, cooling, and total energy savings for skylight, sawtooth, and roof monitor cases with better performance glazing (double clear and double low-e) and 5% TFR across all orientations compared with base case model	286
4.77	Lighting, cooling, and total energy savings for skylight, sawtooth, and roof monitor cases with better performance glazing (double clear and double low-e) and 10% TFR across all orientations as compared with base case model	287
4.78	Comparison of annual total lighting energy savings (%) of toplighting cases with different glazing types, different glazed area (TFR), and northward orientation versus base case model with 1-to-1.5 spacing-to-height ratio	292
4.79	Impact of toplighting orientation on the total annual lighting energy savings of 5%TFR case	293
4.80	Lighting, cooling, and total energy savings from skylight, sawtooth, and roof monitor cases with better performance glazing (double clear and double low-e) and 5%TFR across all orientations versus base case model	298
4.81	Lighting, cooling, and total energy savings from skylight, sawtooth, and roof monitor cases with better performance glazing (double clear and double low-e) and 10%TFR across all	299

UNIVERSITI KEBANGSAAN MALAYSIA

	orientations versus base case model	
4.82	Lighting, cooling, and total energy savings for the suggested skylight cases with better performance yielded by the glazing double low-e clear type and northward orientation	303
4.83	Lighting, cooling, and total energy savings for the suggested sawtooth cases with better performance yielded by the glazing double low-e clear type and southward orientation	303
4.84	Lighting, cooling, and total energy savings for the suggested roof monitor cases with better performance yielded by the glazing double low-e clear type and southward orientation	304
4.85	Total annual energy and energy cost savings by end use (lighting, cooling, and total) for suggested skylight cases	305
4.86	Total annual energy and energy cost savings by end use (lighting, cooling, and total) for suggested sawtooth cases	306
4.87	Total annual energy and energy cost savings by end use (lighting, cooling, and total) for suggested roof monitor cases	307
4.88	Effect of different climate conditions of four Malaysian cities on total energy and energy cost saving for the suggested sawtooth cases with better performance yielded by the glazing double low-e clear type. Orientation considered is South	309
4.89	Total annual energy savings from lighting, cooling, and total for base case model simulated in Kuching	310
4.90	Total annual energy cost savings from lighting, cooling, and total for base case model simulated in Kuching	311
4.91	Total annual energy savings from lighting, cooling, and total for base case model simulated in George Town	312
4.92	Total annual energy cost savings from lighting, cooling, and total for base case model simulated in George Town	312
A-1	Total energy savings (%) for different skylight cases with different glazing types across all orientations as compared to the base case model without daylighting. 1 to 1 Spacing-to-Height Ratio	348
A-2	Lighting energy savings (%) for different skylight cases with different glazing types across all orientations as compared to the base case model without daylighting. 1 to 1 Spacing-to-Height Ratio	349

UNIVERSITI MALAYSIA SABAH

A-3	Cooling energy savings (%) for different skylight cases with different glazing types across all orientations as compared to the base case model without daylighting. 1 to 1 Spacing-to-Height Ratio	350
A-4	Total energy savings (%) for different sawtooth cases with different glazing types across all orientations as compared to the base case model without daylighting. 1 to 1 Spacing-to-Height Ratio	351
A-5	Lighting energy savings (%) for different sawtooth cases with different glazing types across all orientations as compared to the base case model without daylighting. 1 to 1 Spacing-to-Height Ratio	352
A-6	Cooling energy savings (%) for different sawtooth cases with different glazing types across all orientations as compared to the base case model without daylighting. 1 to 1 Spacing-to-Height Ratio	353
A-7	Total energy savings (%) for different roof monitor cases with different glazing types across all orientations as compared to the base case model without daylighting. 1 to 1 Spacing-to-Height Ratio	354
A-8	Lighting energy savings (%) for different roof monitor cases with different glazing types across all orientations as compared to the base case model without daylighting. 1 to 1 Spacing-to-Height Ratio	355
A-9	Cooling energy savings (%) for different roof monitor cases with different glazing types across all orientations as compared to the base case model without daylighting. 1 to 1 Spacing-to-Height Ratio	356
B-1	Illuminance Level comparison: 1 to 1 spacing-to-ceiling height ratio, 20% TFR, double Low-e clear, 21 of March	371
B-2	Illuminance Level comparison: 1 to 1 spacing-to-ceiling height ratio, 20% TFR, double Low-e clear, 21 of June	372
B-3	Illuminance Level comparison: 1 to 1 spacing-to-ceiling height ratio, 20% TFR, double Low-e clear, 21 of December	373
B-4	Illuminance Level comparison: 1 to 1 spacing-to-ceiling height ratio, 25% TFR, double Low-e clear, 21 of March	374
B-5	Illuminance Level comparison: 1 to 1 spacing-to-ceiling height ratio, **25**% TFR, double Low-e clear, 21 of June	375

UNIVERSITI MALAYSIA SARAWAK

B-6	Illuminance Level comparison: 1 to 1 spacing-to-ceiling height ratio, 25% TFR, double Low-e clear, 21 of December	376
B-7	Illuminance map comparison: 1to1 spacing-to-height ratio toplighting alternatives, 15% TFR, dabule Low-e clear	377
B-8	Illuminance map comparison: 1to1 spacing-to-height ratio toplighting alternatives, 20% TFR, dabule Low-e clear	378
B-9	Illuminance map comparison: 1to1 spacing-to-height ratio toplighting alternatives, 25% TFR, dabule Low-e clear	379
B-10	Illuminance map comparison: 1to1 spacing-to-height ratio toplighting alternatives, 30% TFR, dabule Low-e clear	380
B-11	Illuminance map comparison: 1to1 spacing-to-height ratio toplighting alternatives, 40% TFR, double Low-e clear	381
B-12	Illuminance map comparison: 1to1 spacing-to-height ratio toplighting alternatives, 50% TFR, double Low-e clear	382
B-13	Illuminance map comparison: 1to1.5 spacing-to-height ratio toplighting alternatives, 15% TFR, double low-e clear	389
B-14	Illuminance map comparison: 1 to 1.5 spacing-to-height ratio toplighting alternatives, 20% TFR, dabule Low-e clear	390
B-15	Illuminance map comparison: 1 to 1.5 spacing-to-height ratio toplighting alternatives, 25% TFR, dabule Low-e clear	391

UNIVERSITI KEBANGSAAN MALAYSIA

CHAPTER I

INTRODUCTION

1.1 BACKGROUND

According to the United States Energy Information Administration (EIA), most energy produced today in Malaysia comes from fossil fuels, namely, coal, natural gas, crude oil, and natural gas plant liquids (EIA 2008). In 2006, fossil fuels accounted for 93 percent of the total energy production in Malaysia, with other sources including renewable ones, accounting for the remaining production (Husaini & Lean 2012). Figure 1.1 shows an overview of the energy consumption and production trend from 1980 to 2006 (Husaini & Lean 2012). Total energy consumption refers to the total amount of primary energy consumed from all sources in the year specified.

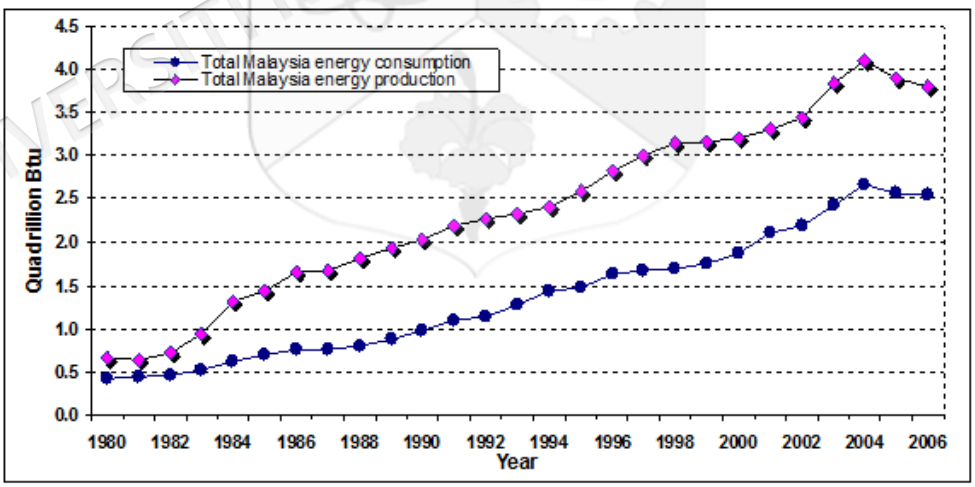

Figure 1.1 Energy consumption and production in Malaysia

Source: Husaini & Lean 2012

As shown in Figure 1.1 the total Malaysia energy consumption had increased steadily over the past 26 years. It is estimated to reach about 4 Quadrillion of British

Thermal Units (QBTU) in 2006 which is more than 400% increase from 1980. This is considered relatively high among developing countries. Aside from that, the number of final Malaysia energy production has also increased drastically due to rapid urbanization and industrialization.

The Malaysian population has grown from 13.879 million in 1980 to 28.964 million in 2011, denoting an increase of 108.7%, according to a latest survey in 2011. The gross domestic product (GDP) of the country grew at an average rate of approximately 9.8% in the last 10 years. Therefore, Malaysia has become a fast developing country and its energy consumption is expected to continue to increase and grow with the same trend as GDP. As in many industrializing countries, economic and development increase continues to influence the demand and consumption of energy in the country (Ong et al. 2011). The total primary energy supply had increased steadily over the past 18 years. It is estimated to reach about 64 million tons of oil equivalent (Mtoe) in 2008 which is more than 200% increase from 1990. This is considered relatively high among developing countries. Thus, the final energy consumption has also increased drastically due to rapid urbanization and industrialization (Ong et al. 2011). Hence, energy saving measures such as daylighting in buildings is becoming an effective and sustainable strategy for enhancing energy-efficiency and visual comfort as the fossil fuels are non-renewable energy.

The efficient use of electricity has economic and environmental benefits. Artificial lighting is one of the major electricity consuming items in many different buildings. In Malaysia, high economic growth has led to a dramatic increase in energy consumption in recent years, particularly electrical energy use in commercial and residential buildings, with the residential and commercial sector consuming almost half of the total electricity generated (Chandran et al. 2010). According to (EC 2007), the commercial sector is the second largest user, accounting for about 32% of the total energy consumption in Malaysia. Figure 1.2 presents the distribution of total electrical energy use by sectors in Malaysia during the year 2007.

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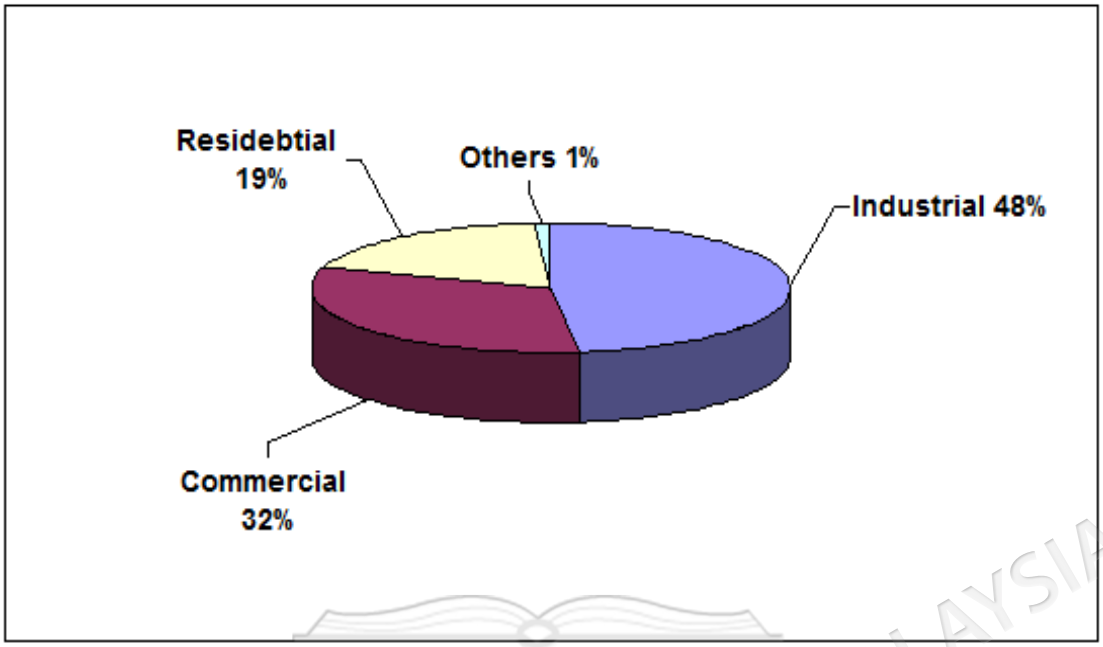

Figure 1.2 Distribution of electrical energy consumed by different sectors in Malaysia (EC, 2007)

Figure 1.3 shows the energy consumption patterns for five secondary schools in Kuala Lumpur in 2009. The study conducted by the Secondary School Energy Efficiency Action Project (SSEEAP). SSEEAP is a 12 months project managed by Center for Environment, Technology and Development, Malaysia (CETDEM). CETDEM is the only Malaysian NGO that has done such studies, through the DDC, ABC and WCPJ Projects (SSEEAP 209). The overall aim for the project was to encourage secondary school students and teachers to reduce their energy consumption in order to reduce the Greenhouse Gas emissions by taking measures to conserve energy and be more energy efficient in schools. It was found that air condition system consumed the highest amount of energy (35%), followed by artificial lighting (30%), ceiling fans (25%), computers (8%), photocopy machines (1%), and printers (1%).

UNIVERSITI KEBANGSAAN MALAYSIA

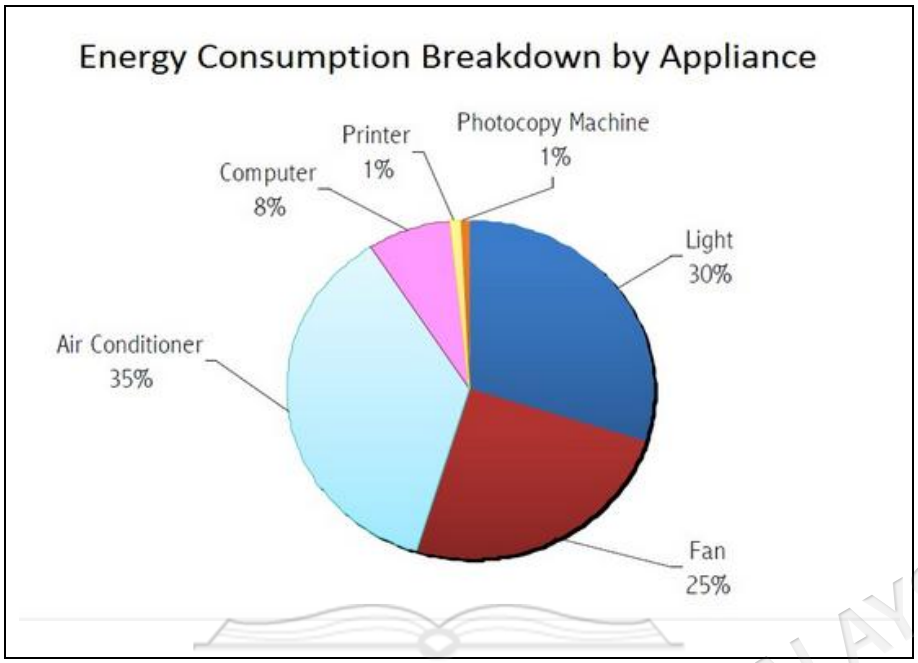

Figure 1.3 Energy consumption breakdown in Malaysian school buildings

Source : SSEEAP 2009

Malaysia, Indonesia, Philippines, Singapore, and Thailand are the countries that joined the Association of South East Asian Nations (ASEAN). Table 2.1 presents energy end-use for buildings located in those countries (Ghisi, 2002). The main purpose of such an analysis is to present data showing how energy is used in buildings, identifying those end-uses that are responsible for the highest consumption. In average, cooling end-use is about 60.0% of the energy consumption in offices, hotels, hospitals, and supermarkets. Lighting end-use ranges from 14.7% to 23.1% of the energy consumption in offices, hotels, and schools. In the store analyzed in Malaysia, it reaches 46.5%. It can be noted that lighting and cooling together account for most of the energy used in buildings in those countries.

Table 1.1 Energy end-use in the ASEAN countries

Building Type	Country	Quantity	End-Use (%)		
			Cooling	Lighting	Others
Offices	Indonesia	1	80.1	11.8	8.1
	Malaysia	5	68.8	23.1	8.1
	Philippines	24	61.2	22.5	15.6

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UNIVERSITI KEBANGSAAN MALAYSIA

Continued

	Singapore	4	49.8	24.2	26.0
	Average	34	61.6	22.5	15.5
Hotels	Indonesia	4	57.6	18.5	23.9
	Malaysia	3	61.1	22.8	16.1
	Philippines	8	63.9	16.2	18.2
	Singapore	2	55.4	38.6	6.0
	Average	17	60.9	20.6	17.7
Hospitals	Malaysia	1	77.9	14.7	7.4
	Philippines	8	56.1	6.6	34.5
	Average	9	58.5	7.5	31.5
Stores	Malaysia	1	40.1	46.5	13.4
Schools	Singapore	1	71.0	22.0	7.0
Supermarkets	Philippines	4	58.9	6.6	34.5
Hospitals	Malaysia	1	77.9	14.7	7.4

Source: Ghisi 2002

In the commercial sector 25% of the total electricity used is consumed by lighting systems. Such use ranges significantly from country to country and is due not only to climatic conditions but also to cultural habits. Table 1.2 presents the average lighting end-use in commercial buildings for certain countries, where developed countries present a higher lighting end-use (Ghisi&Tinker 2005).

Table 1.2 Lighting end-use in commercial buildings in different countries

Country	Lighting end-use %
China	15
Korea	20
USA	39
Brazil	24
Mexico	30
UK	30-60
Netherlands	55

Source: Ghisi&Tinker 2005

UNIVERSITI KEBANGSAAN MALAYSIA

The tropical sky has a lot of potential for daylighting applications due to the high daylight availability. Study conducted by Zain-Ahmad et al. (2002), identified the Malaysian sky type as intermediate sky with average cloud cover value of 6-7 oktas. Moreover, the Malaysian global, beam and diffuse illuminance values is within 10-80 Klx during office hours from 8:00am until 17:00pm. The total percentage of external illumination that falls above 10 Klx during office hours is 93% (Ahmed 2000; Zain-Ahmed et al. 2002).

Zain-Ahmad et al. (2002) discussed the effects of interior illumination of the room due to their openings. Seven sizes of window opening from 10% to 40% of the total floor area were used in a room of 3m (length) by 4m (width). The results were then made to improve energy efficient measures for the buildings. Artificial sky was used to test the model fitted with windows of different sizes of opening. The results showed that window to floor ratio (WFR) value of 0.40 will provide adequate daylight into a space and will definitely reduce energy consumption of electric lighting. It was found that at least 10% of energy could be saved by integrating daylighting in Malaysian buildings while maintaining acceptable indoor thermal comfort criteria for young Malaysians. Furthermore, less heat is dissipated from artificial lighting system.

Ahmad (1996) and Ahmad and Rasdi (2000) had identified 8 commercial buildings around Kuala Lumpur that were built with top-light and sidelight atria. The buildings were analyzed using DF method to evaluate the daylight level for both design type. Two modeling approaches, namely, computer modeling using Radianc and physical model evaluation under artificial sky were chosen as the research methodology. The finding showed that side-lit atria have considerable potential to be used in tropical climates because the design adapted well in both overcast and clear sky conditions. Side-lit spaces were also observed to be providing pleasant interior illumination with minimum glare compared to top-light spaces. With excessive daylighting of up to 28% of DF during clear sky condition, top-light spaces unfortunately suffer from overheating and over lit. This particular type of atria (i.e. top-light) implementation in tropical building was therefore concluded to be unfit unless mechanical environment controls were installed (Ahmad and Rasdi 2000).

UNIVERSITI KEBANGSAAN MALAYSIA

In a study on the exterior illuminance of Kota Kinabalu in Malaysia, the researchers employed two prediction models: Perez and Du Mortier–Perraudeau–Page–Littlefair models. The study used the models to predict the vertical hourly illuminance of the city and further compared the results of the two employed models. The authors then reported that with an average illuminance of 500 lx, the vertical illuminance availability is up to 75% of the working year with room depth of 5 m. In addition, when the room depth is changed to 8 m, the average internal illuminance of up to 55% is attained (Djamila et al. 2011).

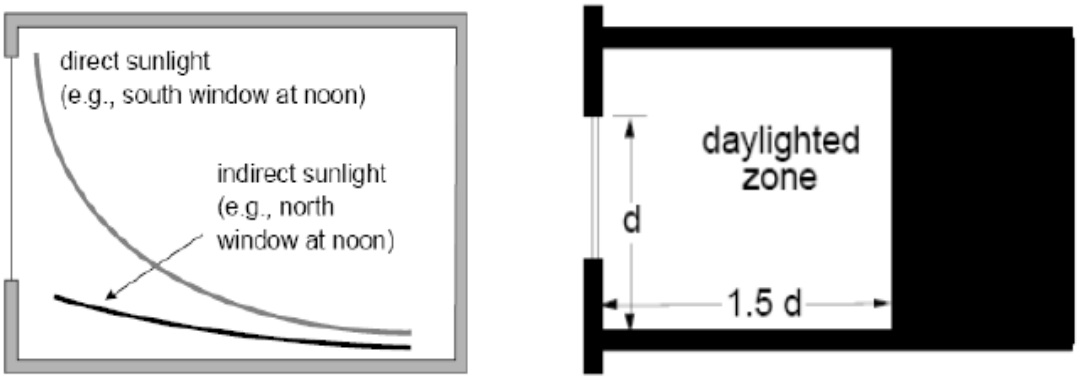
The energy consumption for lighting in Malaysia is about 25-35% of the total energy supplied to buildings (Zain-Ahmad, 2000). The use of artificial lighting not only consumes energy but dissipates waste heat into the building space which contributes heating or cooling (as in the case of Malaysia) load (Zain-Ahmed et al. 2002b). Daylighting design can not only save energy but also lead to a light, airy architecture of great beauty (Hastings, 1989). In fact daylighting has become a major topic in energy conscious design in recent years.

1.2 PROBLEM STATEMENT

This study was performed with an existing of deep plan academic hall space at Universiti Kebangsaan Malaysia, Kuala Lumpur. Shading devices such as corridors were constructed on the east and west façades of the case study building to prevent direct sunlight to the interior zone of a 54 meter by 35 meter academic hall building. The windows systems were installed on the east and west walls of the case study building, resulting in building core with limited access to daylight.

The most common form of daylighting occurs through windows. The amount of daylight levels in this case reduces with distance as shown in Figure 1.4a. And the rule of thumb for side-lighting is shown in Figure 1.4b.

UNIVERSITI KEBANGSAAN MALAYSIA



(a) (b)

Fig. 1.4. Characteristics of side lit spaces. (a) Reducing daylight levels with distance, (b) daylight penetration for standard windows.

Source: J O'connor et al. 1997

But this leaves most of the core areas with insufficient daylight. For academic hall with 35 meter deep, 5.5 meter deep daylight zones from both sides are typical for hall space. The light levels near the windows reduced significantly with in the east and west facades. Although overhangs or corridors somewhat useful on the east and west windows. Toplighting systems were derived to yields a uniformly distributed of light throughout a space and could solve the problem of insufficient daylight in deep plan space. But they are mostly use in one-story buildings or on the top floor of taller buildings only. Figure 1.5 summarized the typical side-lit academic hall building in UKM, Malaysia.

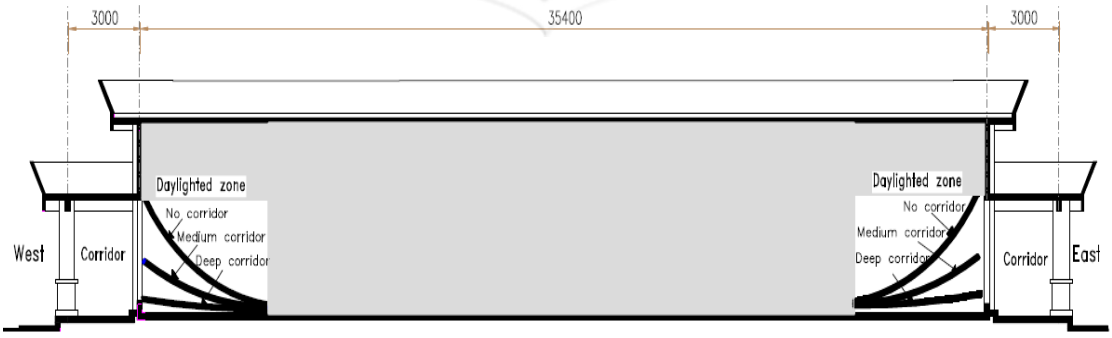


Figure 1.5: The Problem- A typical side-lit academic hall building in Universiti Kebangsaan Malaysia, Malaysia

In this situation, a considerable amount of the energy supplied to a building is consumed by artificial lighting and air-conditioning systems. Thus, certain measures should be taken to optimize the performance of these systems so that a building can conserve energy. An important strategy that can lead to saving energy is the quantity of daylight that penetrates a space as this can minimizes not only the load of artificial lighting systems but also the load of air-conditioning systems at the same time.

For the existing UKM case study hall building, monthly electricity energy consumption (based on monthly utility bills) for the year 2010 were obtained from the Jabatan Pengurusan Pembangunan (JPP or Department of Development Management), whereas the daily average dry-bulb temperature has been obtained from Makmal Iklim, Faculty of Social Sciences and Humanities at the UKM campus. This information will be used as reference data during the proposed study. The actual monthly electricity energy use for the UKM hall case study building is presented in Table 1.3, where it can be seen that the energy consumption ranges from approximately 30000-35000kWh in the months of Februry, April, May, August, September, November and December, and from approximately 35000-40000kWh in the months of January, March, Jun, July and October. The average energy performance for UKM academic hall building to be 222 kWh/m2/yr. This information will be used as reference data during the proposed study.

Table 1.3 UKM case study academic hall monthly electricity energy consumption

Month/year	Actual Energy Consumption (kWh)
January 2010	36731
February 2010	33006
March 2010	40958
April 2010	34175
May 2010	34307
Jun 2010	37423
July 2010	35148
August 2010	34252

Continued

UNIVERSITI KEBANGSAAN MALAYSIA

Continued

September 2010	31435
October 2010	35959
November 2010	32754
December 2010	31968
Annual energy use	418116

From the table also, it is estimated that the electricity bill for the UKM academic building is 222 kWh/m^2.yr X 1890 m^2 (floor area) X 28.8 sent/kWh in peak period from 7am-7pm. This result in 12083904 sent which is equal to RM 120,839.04 per annum. This is equivalent to USD 37,411.47 at the current exchange rate of 1 USD = 3.23 RM. The real electricity bill for the UKM case study building for the year 2010 was RM 120,839.04 (USD 37,411.47). Specifying an ideal toplighting system for the UKM academic hall in which there is a balance between daylight provision and solar thermal load would lead to a scenario whereby the energy consumption of the building is optimized.

The idea of toplighting strategy was studied in relation to the lighting requirements in the interior space of the UKM case study academic hall. This research focused on the availability and feasibility of daylight usage as compared with artificial light in the interior space of the case study academic building. The factors considered under this aspect of the research included studying the toplighting type, glazing type, and size of toplighting alternative, and energy and daylighting conditions in the case study space. The suggested toplighting strategy will maintain a balance between daylighting and energy performance.

Moreover, excessive daylight through toplighting systems because of large glazing areas or the use of inefficient glazing material allows substantial amounts of daylight into a space and therefore considerably reduces the need for using artificial lighting systems. However, large daylight systems areas could also provide poor daylight quality and could permit an excessive amount of heat gains or losses into the space, which increases the use of air-conditioning systems and the cooling load, and consequently raises energy consumption. Small daylight systems areas generally

UNIVERSITI KEBANGSAAN MALAYSIA

limited gains or losses of heat, but artificial lighting may have to be required during office hours in the building in order to provide the required levels of illuminance on the work plan surface. Thus, the optimum scenario is to specify the daylighting systems, namely, skylight, sawtooth, and roof monitor in which an ideal balance exists between daylight provision and the energy consumed by the artificial lighting and air-conditioning systems.

The effect of toplighting systems on the energy consumption of a building is not commonly considered during the design stage. One reason is that toplighting systems cannot be easily controlled by building users. Investigating the effect of toplighting shapes and geometries can improve understanding of how much energy can be saved and how toplighting systems can be designed and integrated with artificial lighting to optimize building energy savings. The effect of toplighting systems on daylight quality has been studied to a certain extent; however, only a few studies have addressed toplighting systems designs in tropical climates.

This study examines three types of toplighting systems performance which includes the effect on building energy usage and daylight quality. The EnergyPlus building energy simulation program is used with parametric studies to enhance understanding of how to design and optimize toplighting systems for energy conservation in academic or similar building applications, as well as how their design strategies affect daylight quality.

1.3 RESEARCH OBJECTIVES

This study primarily aims to evaluate the effect of toplighting daylighting systems and their design strategies on building energy consumption and daylight quality. The goal is to optimize energy savings in lighting and cooling, as well as total building energy savings by using toplighting design strategies together with integrated artificial lighting by lighting control systems and to provide acceptable daylight quality for academic building applications in Malaysia. The main research objective will be achieved through the following detailed goals:

UNIVERSITI KEBANGSAAN MALAYSIA

1. To test and evaluate the effect of each shape and geometry of toplighting systems on annual lighting, cooling and total building energy savings in academic buildings based on the tropical climate of Malaysia by using OpenStudio with EnergyPlus energy simulation program;
2. To test and evaluate the effect of the shape and geometry of each toplighting system on illuminance level, daylight factor, and daylight uniformity and distribution in academic buildings through OpenStudio with EnergyPlus energy simulation program;
3. To estimate the annual energy cost savings potential from different toplighting options design when integrated with lighting control systems while providing acceptable levels of luminance on the work plan surface; and
4. To provide design guidelines for architects and designers for using toplighting systems for similar facilities in similar climates.

1.4 SIGNIFICANCE OF THE STUDY

This study expects to be significant in the following ways:

1. It provides useful information on the application of toplighting daylighting strategies in academic hall buildings in a tropical climate, which will be generic to similar educational buildings located in similar climates.
2. It contributes to existing research on the application of building energy and daylighting analysis using EnergyPlus with OpenStudio building energy simulation program.

1.5 SCOPE AND LIMITATIONS OF THE STUDY

This study does not attempt to analyze toplighting system performance in aspects other than energy and daylighting performance such as the psychological aspect.

This study addresses toplighting shapes, geometries, glazing types, and toplighting orientations to optimize building energy savings and daylight quality.

UNIVERSITI KEBANGSAAN MALAYSIA

These are the main factors that influence the selection of the optimum toplighting design.

This study limited to academic buildings that located in tropical climates and low latitude locations where mostly no heating period occurs throughout the year. The analysis location is Kuala Lumpur city, Malaysia.

1.6 RESEARCH METHODOLOGY

This section explains in summary the methodology used in this research. The purpose of this research was to evaluate the importance of toplighting daylighting application in academic halls in climates similar to that of UKM, Kuala Lumpur. For this purpose, the methodology included of the following steps: 1) Field measurement of the case study UKM hall building, Kuala Lumpur, as a base case model, 2) Developing a computer simulation model of the UKM hall building using EnergyPlus energy simulation program.

The monthly energy consumption data were obtained from the Department of Development Management at the UKM campus. The core area inside the case study UKM hall building was investigated using walkthrough, illuminance level, and daylight factor measurements to understand existing daylighting conditions and the potential for toplighting daylighting use and to compare the results of the actual space values and the simulated results of the toplighting alternatives applications. Computer simulation model was created for the case study building (base case). The initial simulation did not consider daylighting control system (WITHOUT DAYLIGHTING). The case study model (base case) was then modified to include daylighting and was simulated again to determine the effect of the daylighting input (WITH DAYLIGHTING) in EnergyPlus with OpenStudio.

After this comparison, the computer simulation model for the base case was modified to include all suggested toplighting alternatives for building energy and daylighting performance evaluation using the EnergyPlus with OpenStudio and the Kuala Lumpur IWEC weather file. Illuminance level and daylight factor from the

UNIVERSITI KEBANGSAAN MALAYSIA

actual space measurements and computer simulation outputs were compared for trends in interior daylight illuminance levels. Annual energy consumption and savings analyses were performed using EnergyPlus with OpenStudio and involved lighting, cooling, and total energy savings comparisons of all suggested toplighting alternatives with the base case computer model. Daylight quality analyses were then performed and involved daylight factors, illuminance level and daylight distribution and uniformity comparisons of all proposed toplighting alternatives with the base case computer model. Figure 1.6 illustrates the research process and methodology.

1.7 ORGANIZATION OF THE THESIS

This thesis has documented into six chapters and four appendix sections.

Chapter I present a brief introduction and background information on the problem under investigation, research objectives, scope and limitations, significance of the study, and research methodology.

Chapter II reviews and documents toplighting daylighting properties and previous studies on the energy and daylighting performance of toplighting strategies, existing studies on electric lighting control systems, energy simulation studies of toplighting systems, studies on daylight quality and the potential of toplighting application in hot-humid climate, as well as gaps in the literature.

Chapter III explains in detail the methodology used for this research project, including the different stages of the case study buildings information, design of toplighting options, use of EnergyPlus building energy simulation program for energy and daylighting evaluations, and EnergyPlus base case computer model calibration. The calibration stages involve graphical and statistical methods for monthly model calibration.

Chapter IV explains the simulation results of the energy performance evaluation of the toplighting options, and concludes with an evaluation of the energy and energy cost savings that can be achieved through the suggested toplighting cases.

UNIVERSITI KEBANGSAAN MALAYSIA

The three toplighting alternatives suggested and evaluated are the skylight, sawtooth, and roof monitor techniques for entering daylight into the interior space to promote energy conservation. Chapter IV also discusses the simulation results and daylight quality impact evaluation of each case of toplighting option. The chapter evaluates the daylight performance of series toplighting alternatives of 1 to 1 spacing-to-height ratio, and the toplighting options series of 1 to 1.5 spacing-to-height ratio, and concludes with an evaluation of the energy savings and energy cost savings that can be achieved through the suggested toplighting cases.

Chapter V concludes the study in terms of energy savings and daylight quality. Certain recommendations are provided for designers when toplighting strategies are used for buildings in tropical climates. Recommendations for future work that can be conducted in this area of study are suggested.

Lastly, all references used in this study are documented at the end of the chapters. Appendix sections A, B, C and D provide additional graphical and tabular data on the simulation alternatives results of Chapter III and IV.

UNIVERSITI KEBANGSAAN MALAYSIA

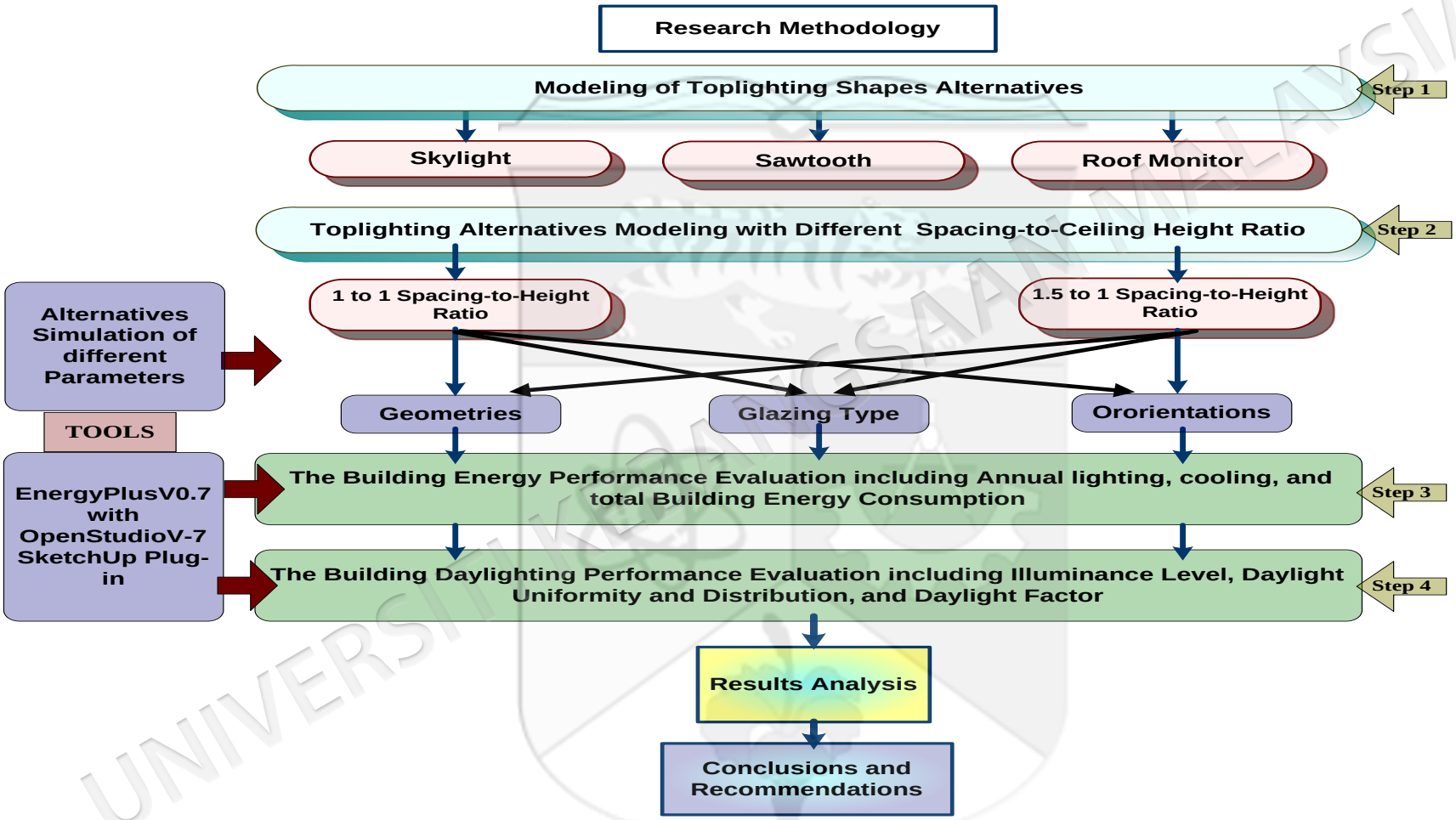


Figure 1.6 Flow chart of the research process and methodology

CHAPTER II

LITERATURE REVIEW

2.1 CLIMATE OF MALAYSIA

The Malaysian climate is a tropical one characterized by uniform temperatures for most parts of the year, high levels of humidity as well as a heavy of rainfall. The country also experiences light wind movements most of the time. Given its geographic location in the equatorial doldrums region, Malaysia hardly experiences a complete day of clear sky regardless of the season of the year. Yet, apart from the northeast monsoon season, hardly does a few consecutive days pass by with completely no sunshine. The word "monsoon" is derived from the Arabic word "mausim" which means season. Ancient traders plying in the Indian Ocean and adjoining Arabian Sea used it to describe a system of alternating winds which blow persistently from the northeast during the northern winter and from the opposite direction, the southwest, during the northern summer (MOSTI 2008). There are two monsoon seasons in Malaysia: the southwest (late May to September) and the northwest (November to March).

2.1.1 Location

Malaysia is situated slightly north of the equator in Southeast Asia. Malaysia lies entirely in the equatorial zone, between latitude 1º to 7ºNorth and between longitude 100º to 120ºEast (Ibrahim & Zain-Ahmed 2007), Malaysia is situated slightly north of the equator in Southeast Asia. Malaysia lies entirely in the equatorial zone, between latitude 1º to 7ºNorth and between longitude 100º to 120ºEast (Ibrahim & Zain-Ahmed 2007), with Kuala Lumpur as its capital city which is located between longitude 101°55' East and latitude 3°12'N. Figure 2.1 shows Malaysia latitude and longitude map. Malaysia also exhibits various land forms across the different regions of the country. Despite the fact that Malaysia is a tropical country, due to its latitude

UNIVERSITI KEBANGSAAN MALAYSIA

and longitude, the country's climate is typically influenced by the monsoon. Thus, the country experiences hot summers and high levels of humidity (www.mapofworld.com).

Figure 2.1 Malaysia latitude and longitude map
Source: www.mapofworld.com

2.1.2 Temperature and Humidity

According to the Malaysian Meteorological Department (MMD) of Ministry of Science, Technology and Innovation, Malaysia experiences uniform temperatures the year round, with annual variations below 2°C except the eastern coast of Peninsular Malaysia, where due to the infringement of the cold conditions from Siberia during the monsoon, experiences annual variations below 3°C. On the daily basis, temperature ranges from 5°C to 10°C along the coastline and from 8°C to 12°C in the interior. As shown in Figure 2.2 below, Jun and July are the months that had the highest average monthly temperature for Kuala Lumpur city. As indicated, the country is not prone to the extreme daily heat of the continental tropics. Also, despite the fact that the hot days are frequently experienced, in Malaysia, the night is generally cooling across the country (MMD 2010).

Malaysia also experiences high relative humidity. The country's humidity readings range from 70 to 90% depending on the location as well as the period of the year. However, for any specific location, minimum mean monthly humidity ranges from 3% (Bintulu) to 15% (Alor Star), compared to Peninsular Malaysia where the mean minimum relative humidity ranges from 80% in February up to 88% in November. This maximum humidity is most typical of AlorStar which experiences from 72% to 87% humidity levels. Apart from Kelantan and Terengganu in the east which experience their minimum humidity in March, minimum humidity is experienced in Peninsula Malaysia in the months of January and February while maximum humidity is experienced in November (MMD 2010). Figure 2.3 below, shown Kuala Lumpur monthly average relative humidity.

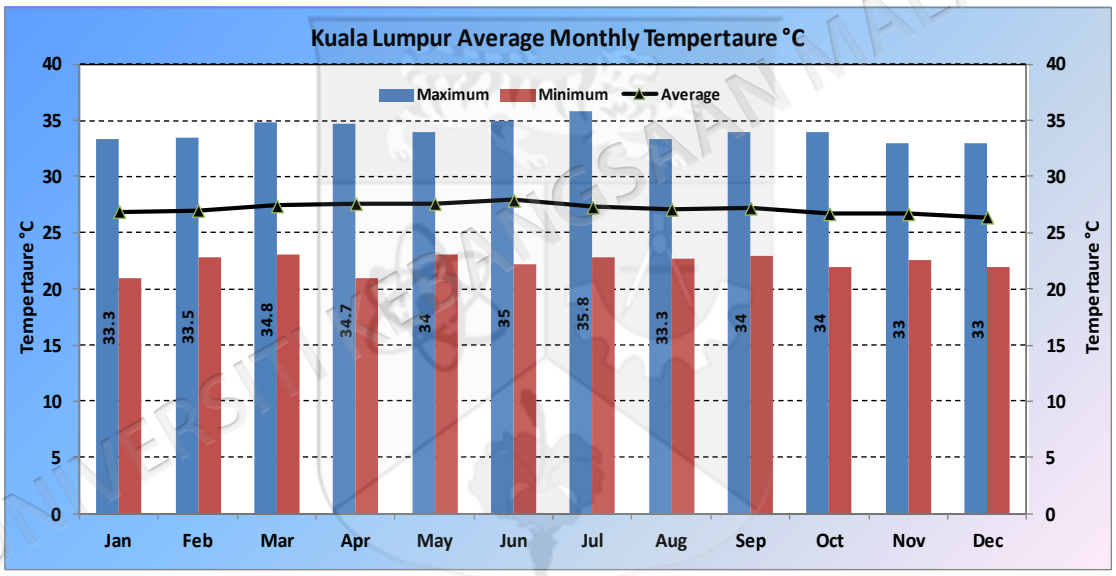


Figure 2.2 Kuala Lumpur Monthly Average Temperature
Source: ASHRAE Handbook 2009

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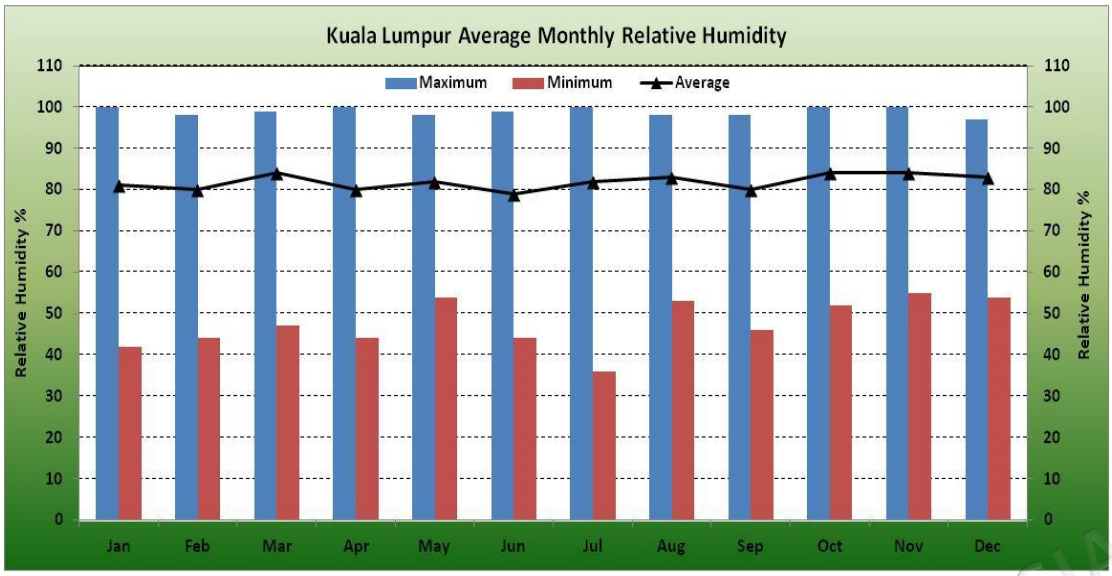


Figure 2.3 Kuala Lumpur Monthly Average Relative Humidity
Source: ASHRAE Handbook 2009

In 2010, the mean relative humidity for Peninsular Malaysia was between 78.8 per cent (Langkawi International Airport) and 89.4 per cent (Cameron Highlands), while in Sabah and Sarawak was between 80.5 per cent (Tawau Airport) and 85.6 per cent (Kuching International Airport) (MMD 2010). Figure 2.4 below, shown mean relative humidity at 24 selected principal meteorological stations, Malaysia, 2009 and 2010.

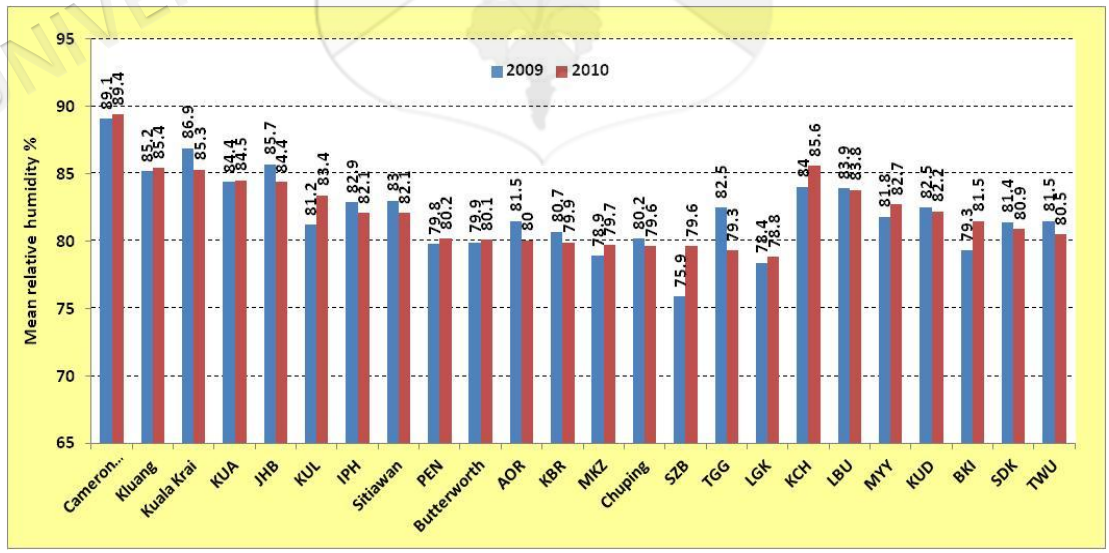


Figure 2.4 Mean relative humidity at 24 selected principal meteorological stations, Malaysia, 2009 and 2010
Source: Malaysian Meteorological Department (MMD 2010)

2.1.3 Rainfall

Malaysia's climate is categorized as equatorial, has a uniform temperature, copious rainfall and humid throughout the year (MMD 2010). This climate is influenced by the Northeast monsoon blows from November to March and the Southwest monsoon from May to September. The east coast Peninsular Malaysia and the coastal areas of Sabah and Sarawak are very much influenced by the Northeast monsoon season. However, the west coast of Peninsular Malaysia is not affected because it is protected by the soaring mountain ranges. Figure 2.5 shows the total rainfall at 24 selected principal meteorological stations in Malaysia from 2006 to 2011. Total annual rainfall decreased from 68,017.1 mm in 2009 to 59,517.8 mm in 2010. On the other hand, during the first six months of 2011, total rainfall increased to 34,796.5 mm as compared to 24,737.7 mm for the same period in 2010.

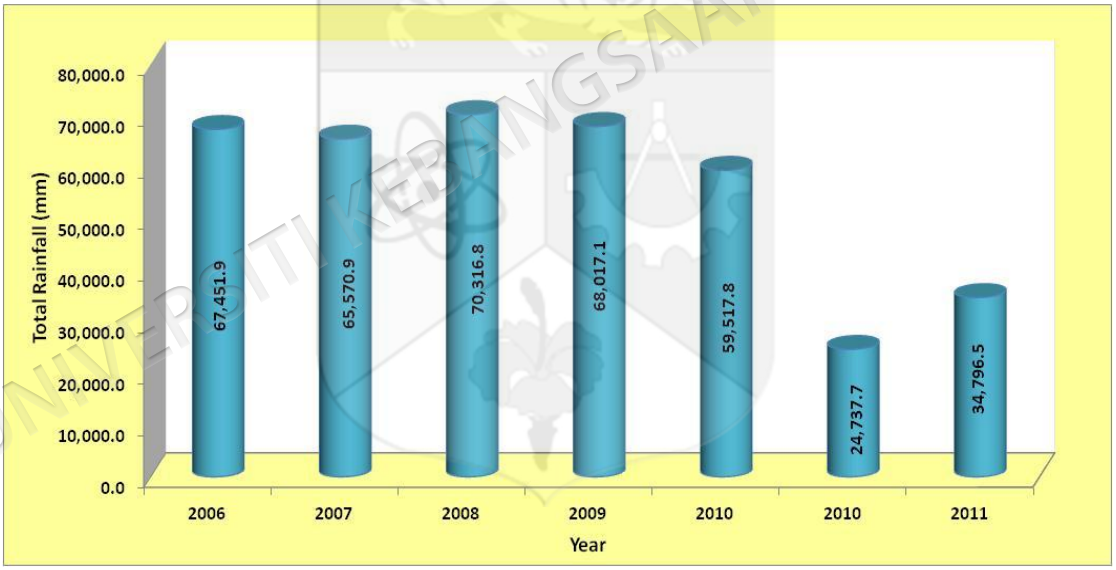


Figure 2.5 Total rainfall at 24 selected principal meteorological stations, Malaysia, 2006–2011
Source: Malaysian Meteorological Department (MMD 2010)

Figure 2.6 shows annual total rainfall at 24 selected principal meteorological stations, Malaysia, 2009 and 2010. Six stations received less than 2,000 mm of rainfall as compared to four stations in 2010. These stations were Batu Berendam Airport (1,992.8 mm), Kluang (1,852.7 mm), Kudat Airport (1,830.6 mm), Tawau Airport (1,674.6 mm), Sitiawan (1,517.6 mm) and Sultan Mahmud Airport (1,265.8 mm).

UNIVERSITI KEBANGSAAN MALAYSIA

Eight stations recorded increases while 16 experienced a decrease compared to 2009. Five stations i.e. Sultan Azlan Shah Airport, Kota Kinabalu International Airport, Kuching International Airport, Sultan Abdul Aziz Shah Airport and Labuan International Airport experienced rainfall that exceeded 3,000 mm (MMD 2010).

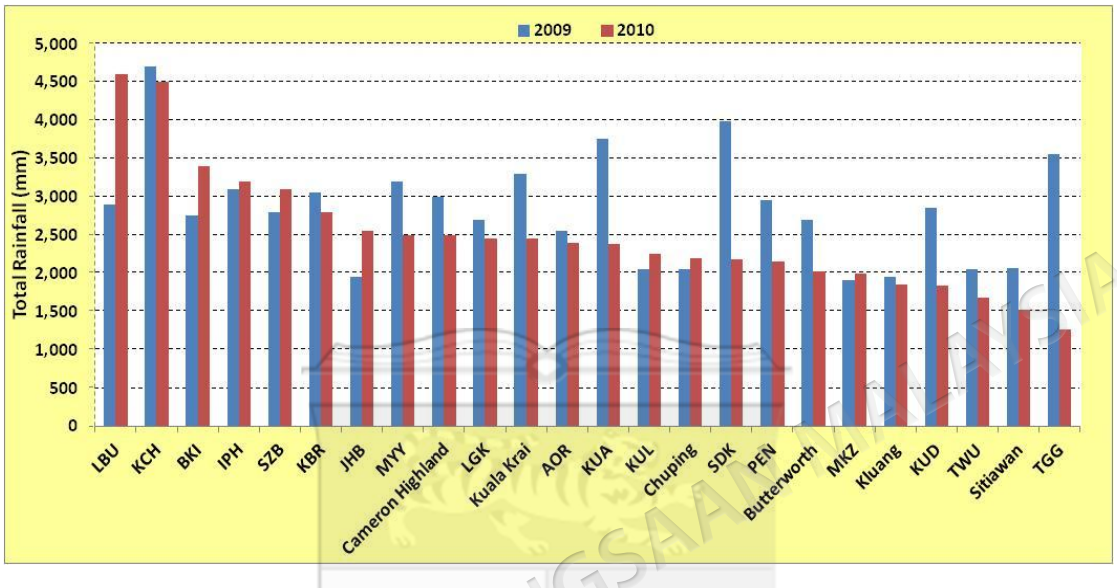
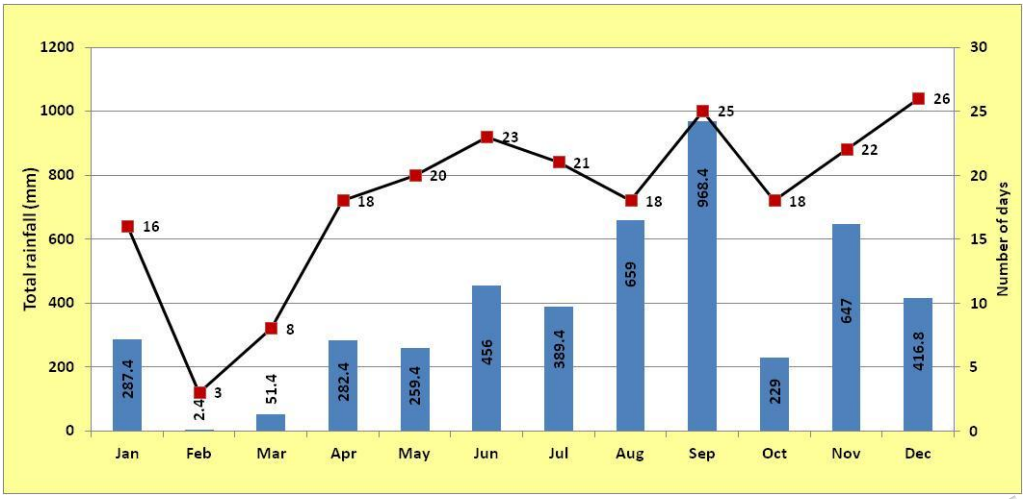


Figure 2.6 Annual total rainfall at 24 selected principal meteorological stations, Malaysia, 2009 and 2010
Source: Malaysian Meteorological Department (MMD 2010)

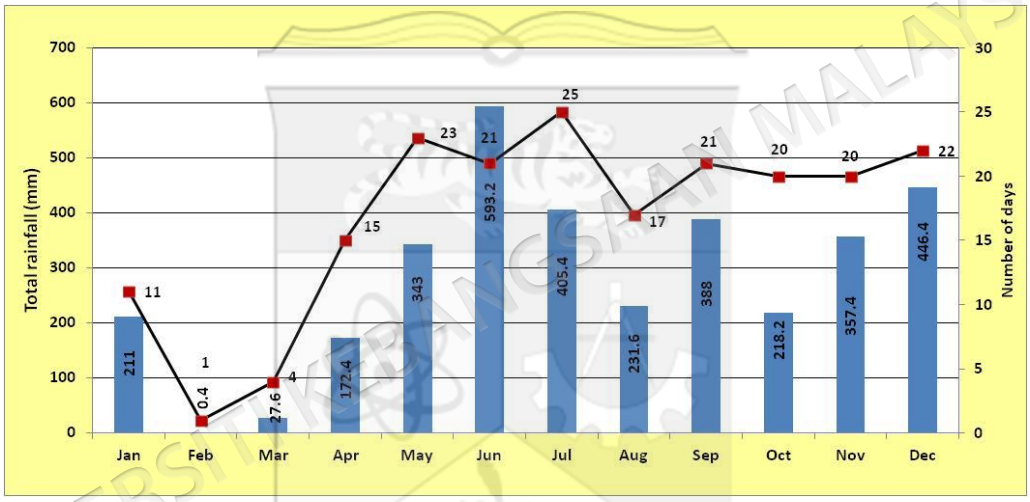
LBU-*Labuan International Airport*
KCH –*Kuching International Airport*
BKI –*Kota Kinabalu International Airport*
IPH –*Sultan Azlan Shah Airport*
SZB –*Sultan Abdul Aziz Shah Airport*, Subang
KBR –*Sultan Ismail Petra Airport*
JHB –*Sultan Ismail International Airport*
MYY –*Miri Airport*
LGK –*Langkawi International Airport*
AOR –*Sultan Abdul Halim Airport*
KUA –*Sultan Haji Ahmad Shah Airport*
KUL –*Kuala Lumpur International Airport*
SDK –*Sandakan Airport*
PEN –*Penang International Airport*
MKZ –*Batu Berendam Airport*
KUD –*Kudat Airport*
TWU –*Tawau Airport*
TGG –*Sultan Mahmud Airport*

In tropical climate, during most of the months of the year, rainfall occurs on a daily basis on average. February is the only dry month in the whole year (Rumana and MH Ahmad 2009). Figure 2.7 (a - c) shows the total monthly rainfall and number of rainy days for three stations that recorded heavy rainfall exceeded 3,000 mm.

(a) Labuan International Airport



(b) Kota Kinabalu International Airport, Sabah



(c) Sultan Abdul Aziz Shah Airport, Subang, Selangor

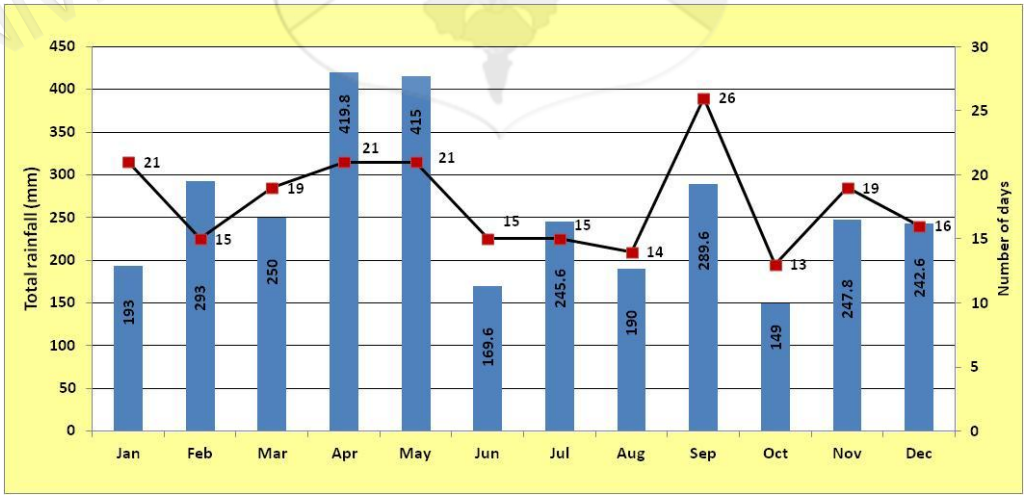


Figure 2.7 Stations that received rainfall over 3,000 mm and number of rainy days, 2010

Source: Malaysian Meteorological Department (MMD 2010)

UNIVERSITI KEBANGSAAN MALAYSIA

2.1.4 Solar Radiation

Solar radiation is defined as irradiation that has quantity of energy (Wh/m^2) and it is integrated over a specific period of time and would be received by building in three modes consist of direct, diffuse and reflected irradiation. Another measure value of sun radiation is global horizontal radiation. It is the sum of direct horizontal and diffuse horizontal values (Muneer 2012).

Given its close proximity to the equator, Malaysia enjoys abundant sunshine and thus solar radiation. Nevertheless, hardly does a complete day pass by without any intermittent cloudiness even during periods of complete drought. Thus, cloudiness blocks parts of the country from the direct contact with the sun and thus solar radiation. The country receives an estimated 6 hours of sunshine on a daily basis, despite the fact that there are variations in the sunshine levels across the different seasons. For example, Alor Setar and Kota Bharu attain up to 7 hours of daily sunshine on average compared to Kuching which only attains 5 hours per day. In extreme cases, the daily average sunshine of Kuching falls to as low as 3.7 hours, which usually occurs in January; while Alor Setar on the other extreme attains the maximum average of 8.7 hours daily during the same month (MMD 2008). Figure 2.8 to Figure 2.11 show the Kuala Lumpur monthly averages solar radiation (direct normal, diffuse, global horizontal).

UNIVERSITI KEBANGSAAN MALAYSIA

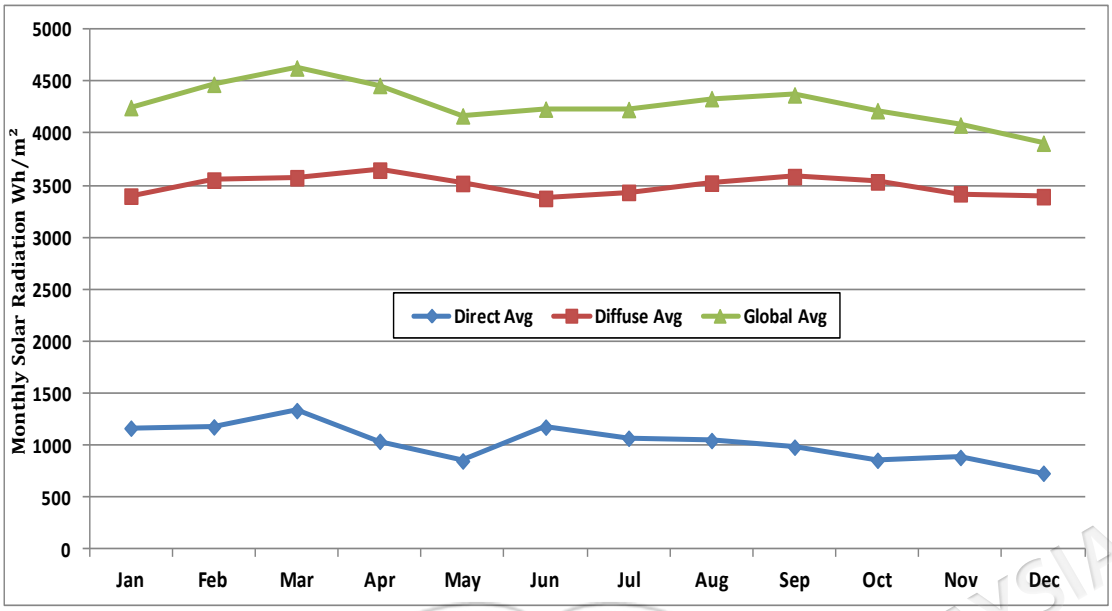


Figure 2.8 Kuala Lumpur monthly averages solar radiation (direct normal, diffuse, global horizontal)

Source: ASHRAE Handbook 2009

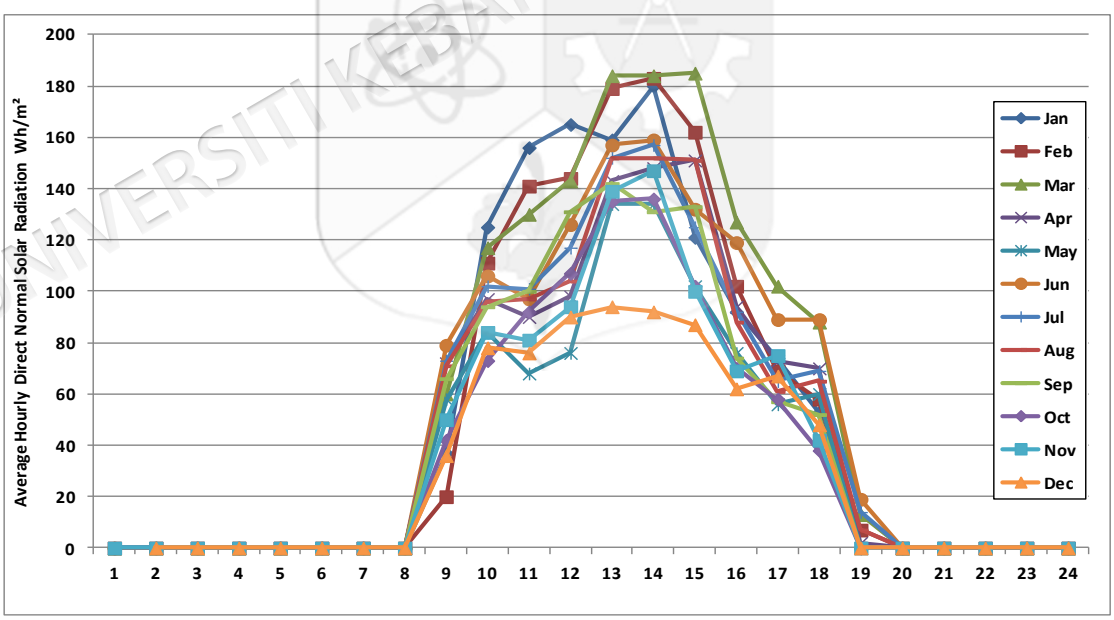


Figure 2.9 Kuala Lumpur monthly average hourly direct normal solar radiation

Source: ASHRAE Handbook 2009

UNIVERSITI KEBANGSAAN MALAYSIA

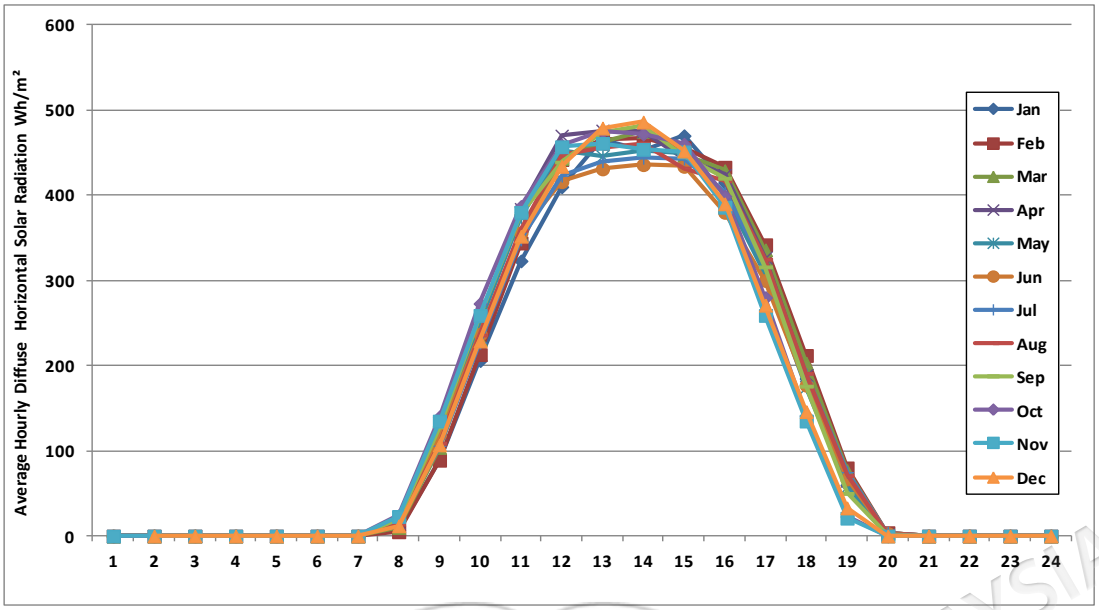


Figure 2.10 Kuala Lumpur average hourly diffuse horizontal solar radiation

Source: ASHRAE Handbook 2009

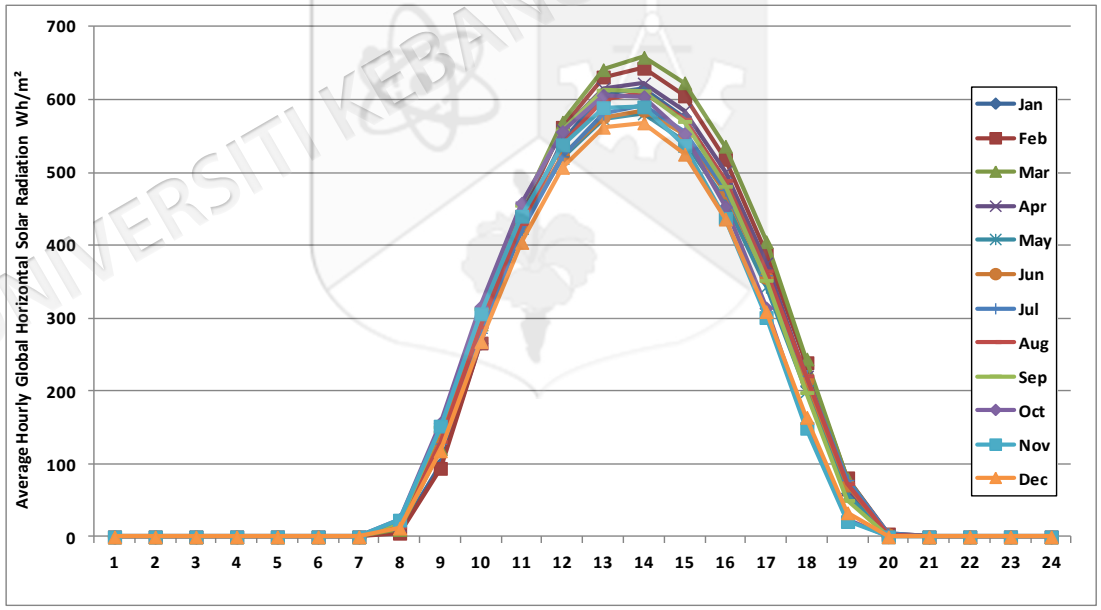


Figure 2.11 Kuala Lumpur average hourly global horizontal solar radiation

Source: ASHRAE Handbook 2009

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2.2 LIGHTING

2.2.1 Light

According to the Illuminating Engineering Society of North America (IESNA) Lighting Handbook (IESNA 2000), light can be defined as 'the radiant energy that is capable of exciting the human retina and creating a visual sensation', with Lighting Design being defined as 'the creative process to produce lighting methods and solutions for safe, productive, and enjoyable use of the built environment, utilizing available illuminating engineering technology." Natural light in the form of sunlight is a powerful source with an average illuminance of 1600 mega candelas per square meter, as viewed from the sea level (IESNA 2000).

2.2.2 Lighting Design Requirements

The Malaysian Standard (MS) and IESNA have described general and specific lighting guidelines to facilitate lighting design in the building interiors. A design procedure recommended by the IESNA incorporates four steps: defining visual tasks in the proposed design, selection of illuminance category, determining the amount of lighting required, and establishing a target illuminance value for design (Standard 2007; IESNA 2000). The following three tables are part of the MS and IESNA recommended illuminance categories and illuminance values for interior lighting design and target light levels. Table 2.1 defined the recommended average illuminance levels for general building area. Table 2.2 defines the illuminance categories and respective values, whereas Table 2.3 relates the activity type with specific illuminance category as defined in the earlier table.

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Table 2.1 Recommended average illuminance values for interior lighting design

Task	Illuminance value		Area/ activity
	Lux	Foot-candles	
Lighting for infrequently used area	20	2	Minimum service illuminance
	100	10	Interior walkway, car-park, bedroom, corridor, stairs, Entrance and exit, stores, lobbies and waiting room.
	150	15	Escalator
Lighting for working interiors	200	20	Infrequent reading and writing
	300-400	30-40	General offices, shops and stores, reading and writing and drawing office
	300-500	30-50	Classroom, library
	200-750	20-75	Shop/Supermarket/Store
	300	30	Museum and gallery
Localized lighting for exacting task	500	50	Proof reading
	1000	100	Exacting drawing
	2000	200	Detailed and precise work

Source: Malaysian Standard (MS 2007)

Table 2.2 Illuminance categories and illuminance values for interior lighting design

Type of activity	Illuminance Category	Ranges of Illuminances	
		Lux	Foot-candles
Visual tasks of high contrast or large size	D	200-300-500	20-30-50
Visual tasks of medium contrast or small size	E	500-750-1000	50-75-100
Visual tasks of low contrast or large size	F	1000-1500-2000	100-150-200

Source: IESNA 2000

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Table 2.3 Recommended illuminance categories for institutional interiors

Educational Facilities	Illuminance Category	Average value	
		Lux	Foot-candles
Classrooms/Proof reading	D	500	50
General/ Drafting/ Science Labs	E	750	75
Lecture rooms / Audience / Demonstration	F	1500	150
Music rooms / Shops / Study halls / Typing	F	1500	150

Source: IESNA 2000

The type of activity in classroom similar to spaces generally involves visual tasks of high contrast or large size (category D), and Malaysian Standard (MS 2007) suggests the use of this category for educational facilities like schools. The average illuminance value selected for the daylighting analysis in the proposed research will be between 300 to 500 Lux. The toplighting alternatives suggested will focus on achieving this range of illuminance in the analysis academic hall space. This is the light level required which makes it easy and comfortable to carry out school and library activities and excessive of illuminance level across the area where activities take place can be distracting and reduce visual comfort.

Both the Illuminating Engineering Society of North America (IESNA) and the Chartered Institution of Building Services Engineers (CIBSE) lighting standards provide recommended daylight factor values for lighting performance of each daylighting system. The IESNA recommended daylight factor values between 2 to 3 % for reading areas, while in CIBSE the minimum recommended daylight factor should not fall below 5% (IESNA 2000 : CIBSE 1994) .

2.2.3 Lighting Controls Systems

Lighting control can be defined as all techniques by which the lighting system will be operated and covers both manual and automatic controls. When the lighting design

started the control strategies should be decided because the control scheme must be appropriate to the light source (IESNA 2000). The main advantages of the using lighting control are:

1. Energy management:
    - Reduced energy usage.
    - Reduced air conditioned costs.
    - Longer lamp and ballast life.
2. Aesthetics: provide the ability to change space functions and can create emotional appeal.

A. Lighting Control Techniques

According to (IESNA 2000) two types of daylighting controls are generally utilized to reduce electrical lighting use in buildings. These are:

1. Continuous dimming controls: the illuminance level in each space can be varied smoothly and continuously to dynamically match visual requirements. The dimming control is a suitable model for daylighting applications. However, the dynamic range of daylight is much larger than it is for electric lighting. Thus, cautions have to be applied in choosing the suitable dimming control and sensitivity setting.

2. Switching controls: lighting loads are switched on and off. This switching can be done in various ways, the simplest of which is by using manual wall switches. Remote switching is also possible using relays or switchable circuit breakers or by occupancy sensors. A different way to achieve switched light levels is through light level switchable ballast. Instead of switching between lamps, the light level switchable ballast can reduce the light from all lamps in the luminaire.

UNIVERSITI KEBANGSAAN MALAYSIA

B. Lighting Controls and Energy Savings

Many research studies have analyzed the effect of lighting control on energy consumption in buildings. Some of the key studies in this area are highlighted in the following paragraphs.

Li and Lam (2001) reported field measurements of daylighting in an air-conditioned office building in Hong Kong. The study reported that, just below 20% and about 30% of the time, an indoor illuminance of 500 lx can be achieved from daylight for the north and south–facing offices, respectively, when the on-off control is implemented. It is recorded that with daylighting controls, substantial lighting energy savings can be found; and that the maximum lighting load never exceed 180 W. The energy savings were due primarily to the dimming controls, occupancy sensors as well as electronic ballasts.

In another study by the same researchers, field measurements were conducted on daylighting in a fully air-conditioned daylit corridor. These included the electric lighting load, brightness of the fluorescent luminaires, daylight illuminance levels as well as the room parameters affecting daylighting design. The analyses results have indicated that up to 70% energy savings in electric lighting were attained using dimming lighting control system (Li & Lam 2003).

Onaygıl and Güler (2003) evaluated the energy saving via daylight responsive lighting control system in an office building in Istanbul. The results demonstrated that energy saving obtained by lighting control system shows differences according to the months and seasons. Energy saving which is only 20% in December increases to 47% in June and July. As seasonal differences are taken into consideration, energy saving which is 21% in winter increases to 35% in spring and 45% in summer. Energy saving in clear days is 35% and decreased to 16% in overcast days as the daily weather conditions are taken into consideration. The study further indicated a quite interesting result in that the energy saving in mixed days approximately equated to that attained in the clear days.

UNIVERSITI KEBANGSAAN MALAYSIA

Li et al. (2006) investigated the energy savings of photoelectric dimming system on a fully air-conditioned open plan office. The authors focused on the electric lighting load, indoor illuminance levels as well as daylight availability. The general features of the results such as electric lighting energy savings and transmitted daylight illuminance in the forms of frequency distributions and cumulative frequency distributions were presented. It has been found that energy savings in electric lighting were over 30% using the high frequency dimming controls. The results from the study would be useful and applicable to other office spaces with similar architectural layouts and daylight linked lighting control systems.

Although many studies presented that lighting control is highly beneficial in term of savings in the electric lighting system, several other studies also showed that there are some restrictions on the applied lighting control systems. These include the occupants' preference and the practical application of these systems.

Faber and Littlefair (1999) reported that a problem with lighting control has been user reaction to its operation. According to the authors, people tend to dislike automatic controls in that they sometimes keep the lighting on when they would have been switched off if they were manually controlled. The study went further to indicate that settings such as office buildings, classroom blocks as well as residential homes should implement manual switches even where automated switching option is available. In a series of surveys of lighting controls in offices it was reported that where photoelectric controls had been installed, they had been disconnected (Slater et al. 1996).

Ehrlich et al. (2002) admitted that the use of photo-sensor-based lighting controls has been generally unreliable because of the considerable effort is needed to ensure the proper installation and calibration the photo-sensor system and that the unreliability of such control systems constitutes a significant market barrier preventing widespread acceptance of daylight dimming controls in commercial buildings.

Regarding commissioning of lighting controls, Faber and Littlefair (1999) reported that this is mainly important because if the system does not perform properly

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there will be not only poor energy savings, but also occupant complaints and ultimately system disconnection.

Daylight is more efficient in providing light in comparison with electric light while producing less heat for the same amount of light (Robbins 1985). Zain-Ahmed et al. (2002) mentioned that minimum energy savings of 10% can be achieved by using daylighting strategies alone in Malaysia. Besides, daylight is the full-spectrum of light that matches closest to human visual response. Quality of daylight is much better than electric light. Lesser amount of daylight is needed to perform a task than performing the same task under electric light. Apart from that, daylight also gives better colour rendering and visual environment that enables the occupant to see objects properly in a room (Robbins 1985).

There can be a high potential for daylight utilization in tropical region such as Malaysia (Ahmad & Yeoman 1997) and (Lim et al. 2012). DR Ossen et al. (2005) investigated the magnitude of energy consumption for cooling and lighting when shading devices are adapted in order to analyze optimum shading as energy conservation option in high-rise office buildings. In an attempt to elucidate these complex relationships, a simple experiment of an office room is carried out using dynamic computer simulation program eQUEST- 3 (DOE 2.2). The results showed that correlation between overhang depth and energy is an important aspect compared to correlation between overhang depth with building cooling loads and daylight level, especially in tropical climate conditions. Further, total energy consumption for the designated generic office room was well below the Malaysian Standard (135 kWh/m^2) for all orientations.

2.3 DAYLIGHTING

2.3.1 Defining Daylight and Daylighting Systems

Baker and Steemers (2002) defined daylight as the combination of the diffused light from the sky and sunlight. For centuries, daylight was the only efficient source of light available. Historically, building openings had to be designed as to allow enough daylight penetration into interior spaces (IEA SHC Task 21. 2000). With the scientific

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advance in field of light, artificial lighting systems were invented, and designers occasionally neglected the importance of daylighting. Today, awareness of depleting non-renewable natural resources has again brought the potential of the use of natural light (daylight) in building design to the attention of many designers.

According to Ander (2003), the relationship between people, daylight, and architectural form is intimate. Daylighting has always an important role in the design of buildings, and research indicates the various psychological advantages of the use of daylight in building design. Baker and Steemers (2002) defined the daylighting system as "a device located near or in the openings of building envelope, whose primary function is to redirect a significant part of the incoming natural light flux in order to improve interior lighting conditions." Today, advanced delighting systems can provide daylight, user-friendly, and energy-efficient building environments.

2.3.2 Daylight Source and Availability

A predictable pattern of the quantity and direction of available daylight is achieved by the daily and seasonal movements of the sun with respect to a particular geographic location on the earth. In addition to this predictable pattern is variation resulted from changes in the weather, temperature, and air pollution. 40% of the solar energy received on the earth's surface is visible radiation. The remaining part is ultraviolet (UV) and infrared (IR) wavelengths. All of the sun's radiant energy is virtually converted to heat when absorbed. The amount of usable visible energy in the solar spectrum varies with the depth and condition of the atmosphere through which light passes (IEA SHC Task 21. 2000).

In terms of daylight, Malaysia receives plenty of natural light throughout the year. The Malaysian sky condition is classified as intermediate or average, whereby 85.7% of the time the sky is cloudy and 14.0% overcast (Zain-Ahmed et al. 2002). Figure 2.12 shows the predicted daylight levels for the selected months of March, August and December, where the peak values of illumination for maximum (in March), mean (in August) and minimum (in December) occur. The mean hourly illumination exceeds 80,000 lux in March when peak illuminances are at the highest

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levels and 60,000 lux in December when peak illuminances are at the lowest. The illuminance levels also coincide with the hottest month and coolest month, respectively. The month of August represents the average month in the year (Zain-Ahmed et al. 2002).

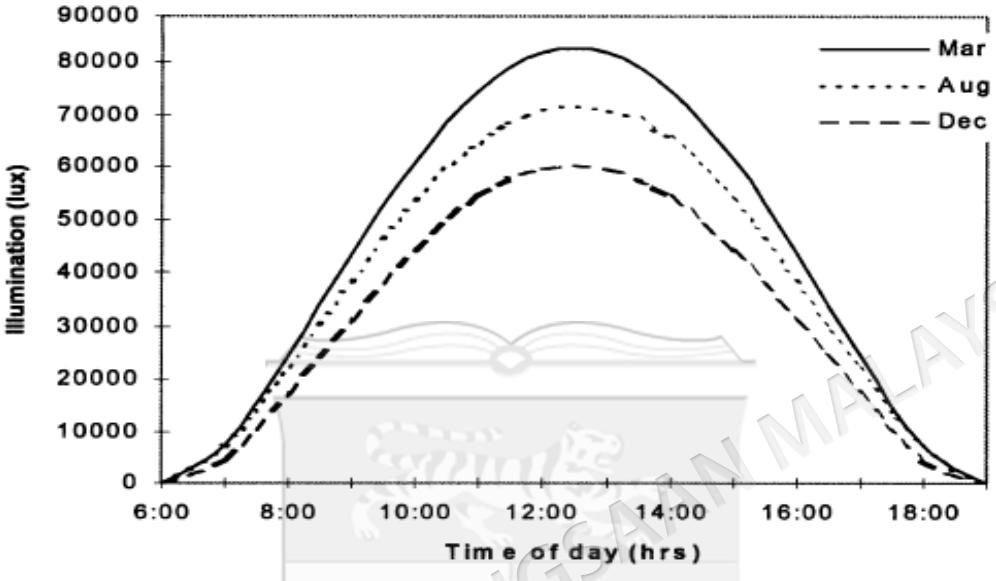

Figure 2.12 Daylight availability at Subang, Malaysia

Source: Zain-Ahmed et al. 2002

A. Daylight Sources

The sun is the source of natural light energy and the path of the sun determines the available sunlight at a particular building location. The solar altitude and the solar azimuth are the two angles through which the sun's position can be defined at a reference point on earth's surface. When sunlight is propagated across the atmosphere, part of the radiation scatters in the dust, water vapor and other suspended particles. This scattering, together with the clouds, produces the luminance of the sky. According to Rea (2000), skies are classified into three light conditions to be considered in daylighting design: the Clear Sky, Partly Cloudy Sky and Overcast Sky. In addition, Zain-Ahmed (2000), mention that several types of skies have been established and are defined below.

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The Uniform Sky. This type of sky is covered with thick, milky-white clouds and an atmosphere full of dust where the sun is not visible.

The CIE Standard Overcast Sky. The luminance of this sky is not uniform but varies with geometrical parameters. It is a sky with light cloud in a clear atmosphere where the sun is not visible. The luminance of the Overcast Sky is three times more at the zenith than at the horizon. Most parts of Europe have a Standard Overcast sky. An overcast sky normally produces illumination on the ground in the range of 5000 - 20,000 lux.

The Clear Blue Sky. This sky has a variable luminance according to geometrical factors and positions of the sun but the direct sunlight is not taken into account. The Clear Blue Sky is generally associated with mountainous regions with clean atmospheres and can generate illuminance values of between 50,000 - 100,000 lux.

Cloudy Sky. The cloudy sky is associated with skies that are partly or fully covered with clouds. They normally produce iIluminances of between 20,000 - 100,000 lux.

Intermediate Sky, Real Sky or All-Sky. The real sky does not come under any category but it is very difficult to model.

Daylight can be obtained from three basic resources:

- Diffuse light through clouds or partially cloudy skies
- Direct sunlight through clear or partially cloudy skies
- Reflected light from natural and man-made surfaces

- **The sky as a light source**

As sunlight passes through the atmosphere, a portion is scattered by dust, water vapor and other suspended particles. This scattering, acting in concert with clouds, produces sky luminance. Skies are classified to three types. This includes clear sky, partly

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cloudy sky and overcast sky. In the incompletely overcast condition, the sky luminance distribution may change rapidly and by a large amount as the sun is alternately obscured, partly obscured, or fully revealed (IESNA 2000). In the overcast condition, the sky is generally the brightest element in an outdoor scene; light reflected off other surfaces has much lower luminance. Illuminance in the completely overcast condition can exceed 2500 fc. Partly cloudy skies are even more common, constantly changing between direct sunlight and hazy daylight and fluctuating in intensity, distribution, and color temperature (Egan & Olgyay 2002).

- **Direct sunlight**

The sun is the ultimate source of natural light. Sunlight is considered as a concentrated source of light and radiant heat. Bright sunshine illumination can be as high as 100,000 lux and brings thermal radiation of about 1 kW/m^2. The sunlight arriving om earth passes through the atmosphere, being partly diffused, absorbed and scattered by the prevailing clouds and atmospheric content. Only the unobstructed portion of the sunlight will reach the interior as a direct sunlight component. Diffused light from the reflection and reflection of the sunlight will result in various forms of sky conditions (Ahmed 1996).

Solar radiation is energy from the sun and daylight is part of the energy spectrum of electromagnetic radiation emitted by the sun within the visible wave-band that is received at the surface of the earth after absorption and scattering in the earth's atmosphere. Sunlight is the direct component of light. Solar radiation and daylight possess similar physical properties and modeling of one involves the other. Modeling solar and daylight availability requires slope irradiation and illuminance on a monthly-averaged, daily or hourly basis depending on the analysis (Baker et al. 2013).

Solar radiation in Watts per square meter (W/m^2) and luminance in candelas per square meters (cd/m^2 or $Im/m^2.sr$) measure the energy intensity emanating from the sun. Luminance is the energy contained within the visible solar spectrum of wavelengths between 0.39-0.78 Jlm. Irradiation in Watt-hour per square meter (Wh/m^2) or Joules per square meter (J/m^2) is the cumulative energy incident on a

surface in a given period of time. Irradiance (W/m^2) and illuminance ($lumens/m^2$ or lux) are the instantaneous incident energy (Zain-Ahmad 2000).

- **Reflected light**

The sun illuminates surfaces, creating secondary sources of light. Light-colored surfaces reflecting sunlight are typically the second-brightest source of light in the environment. On a sunny day they can be the dominant light source in the field of view. Light reflected from the ground may be important in daylighting design. Such light is, in turn, reflected from the ceiling or walls onto other interior surfaces. On daylighted elevations, the light reflected from the ground normally represents 10 to 15% of the total daylight reaching a window. It frequently exceeds this with light-colored ground surfaces such as sand or snow. On shaded exposures, it may account for even more of the total light reaching a window, depending on the sky conditions and building design (IESNA 2000).

B. Sky luminance Distribution

The role of sky illuminance distribution is to determine the cloud presence by identifying whether the sky is clear or overcast and the solar altitude angle. In literatures related to this topic had found the reasonable agreement among recorded minimum amount for diffuse illuminance cited (Heerwagen & Connolly 2004). The outcome of the report had come up with values to meet the criterion that about 90% of the working hours throughout the year would have diffused illuminance amount greater than these minima. According to Heerwagen and Connolly (2004) the catalogued values for diffused illuminance vary between about three to ten kilolux and about 280 to 930 footcandles. Figure 2.13 and 2.14 display the relationship between sky illuminance, solar altitude angles and sky conditions; the frequency distribution for measured illuminance and daylight availability in relation to cloud cover respectively. By obtaining these values, daylight availability can be predicted.

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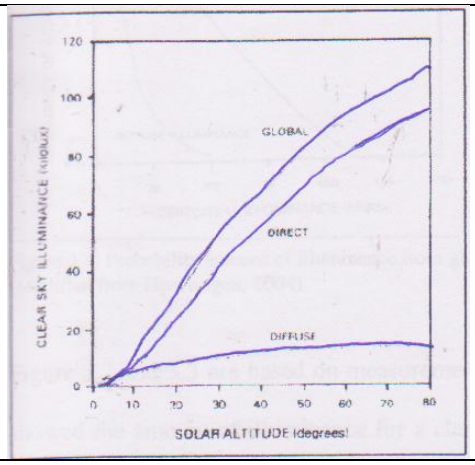

Figure 2.13 The relationship between global, direct-beam and diffuse illuminance during clear sky versus solar altitude of the sun

Source: Heerwagen 2004

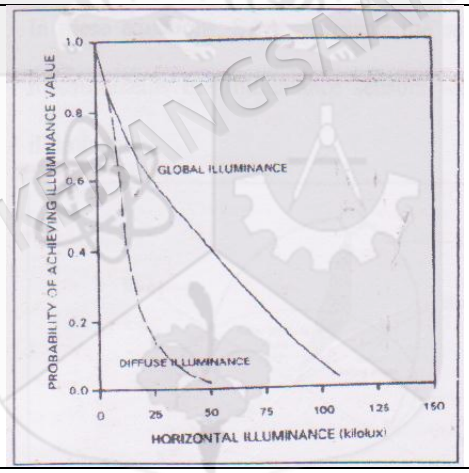

Figure 2.14 Probability amount of illuminance from global and diffused sky component

Source: Heerwagen 2004

Figures 2.1 and 2.2 are based on measurements from San Francisco. The first graph showed the amount of illuminance for a clear sky plotted versus the altitude of the sun. These illuminance amounts have been measured on a horizontal surface Heerwagen and Connolly (2004). The second graph showed the amount of illuminance for an overcast sky plotted versus the altitude of the sun and the third graph showed the probability of observing alternative amounts of illuminance from

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global and diffused sky component measurements at horizontal surface. Equations have been derived based on the data shown in these graphs. The equations were used to predict illuminance values for any solar altitude angle and either clear or overcast skies. The two equations were:

For clear skies:

Illuminance on a horizontal surface = 0.927 + 117.2 × (sin SAA)$^{1.325}$ (kilolux)

For overcast skies:

Illuminance on a horizontal surface = 0.357 + 0.578 × SAA (kilolux)

In these equations, SAA represents the solar altitude angle Figure 2.15. During the measurement the illuminance sensors were facing upward to record horizontal illuminance.

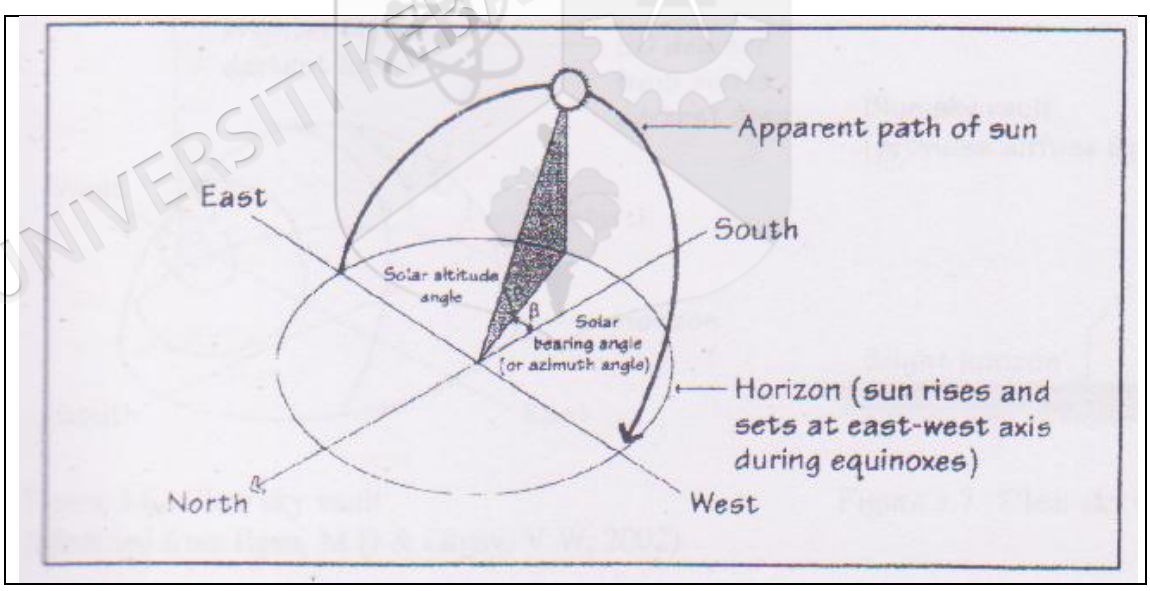

Figure 2.15 Solar Altitude Angle (SAA)

Source: Egan and Olgay 2002

The characteristic of the two sky types are explained as follow:

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- **Clear sky condition**

During a clear sky condition, the sun is the brightest source of light. The clear sky model displayed in Figure 2.16 is divided into three luminance regions. The first region is known for it brightness and is located nearest to the sun. The second region is a very large area that covers much of the sky. This region also includes a relatively dark zone which is defined by the sun and the zenith point (90 degrees from the sun). Meanwhile, the third region generally lies just above the horizontal all around the sky vault. Its brightness comes midway between the brightness and the darkest region. According to Egan and Olgay (2002), the atmosphere of the clear blue sky filters and diffused light but provided low illumination Figure 2.4. Although near the sun region has highest brightness, the majority of the blue sky provided only 2,000 to 10,000 lx, which is less bright than the overcast sky and is not properly distributed over the sky dome. The normal illuminance level values under typical clear sky will range from 50000 to 100000 lux.

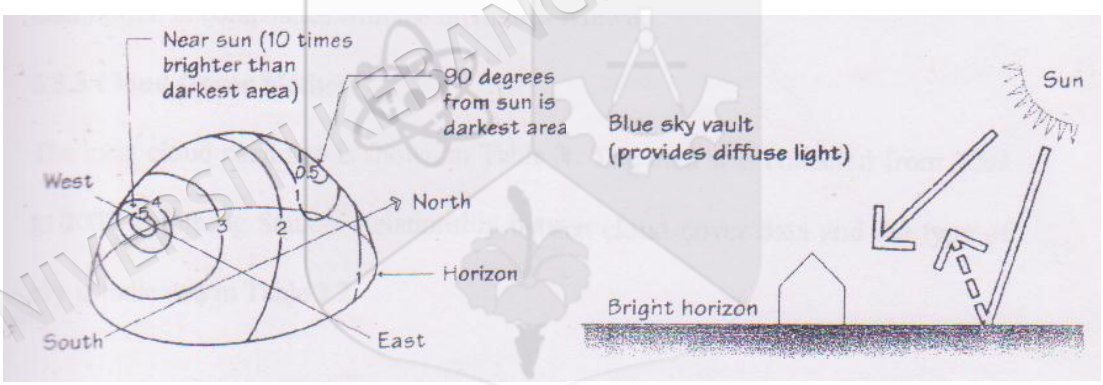

Figure 2.16 Clear sky vault and condition

Source: Egan and Olgay 2002

- **Overcast sky condition**

The overcast sky condition occurs when the cloud cover completely obscures the sun. Diffused light is produced during this particular sky condition. The sky is brightest at the zenith and decreases at the horizontal to approximately one-third of its maximum brightness as shown in Figure 2.17 (Egan & Olgay 2002). In this study, the decision

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was made to understand the Malaysian sky type in compliance with the literature reviewed.

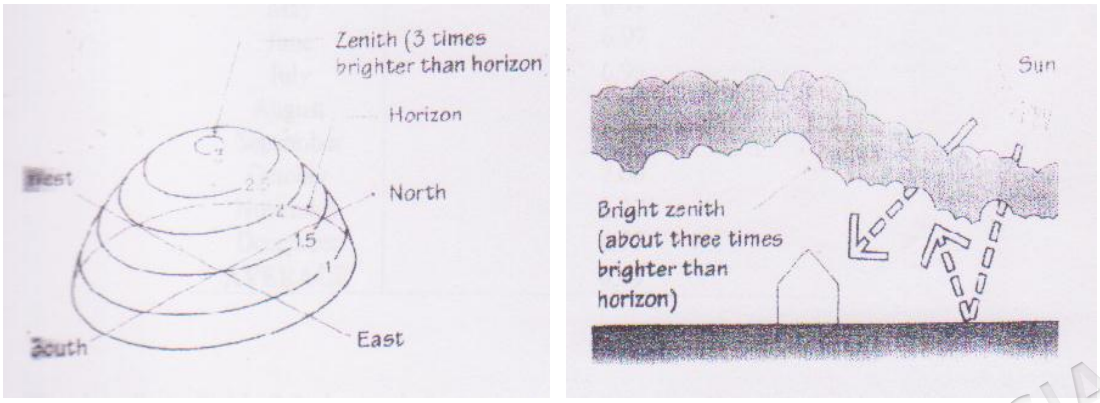

Figure 2.17 Overcast sky vault and condition

Source: Egan and Olgay 2002

2.3.3 Malaysia Sky Condition

The apparent movement of the sun across the sky can be visualized as a path in an imaginary overhead sky-dome. The sun-path throughout the year in different locations can be translated into a diagram such as a solar chart. Figure 18 and 19 showed sun-path diagram for six locations in Malaysia and showed that the sun position is almost the same for all six locations. The sun path is generally east-west with the sun approximately 25° to the north during summer solstice and 25° to the south during winter solstice for all locations in Malaysia. The sun-path diagram is a useful tool to help in the conceptual design stage of external shading devices for different orientations. The sun-path diagram is used to estimate sun angle at various time of day and year, allowing architects to design shading devices to block or allow direct sunlight at whatever dates or times (Ahmad 1996). Although, the light received from the sun is considered the ultimate source of daylight, the daylighting of an interior normally relies on the diffused light in the form of skylight. This is due to the unreliability of the sun as experienced in the temperate climates and its severe brightness in hotter regions.

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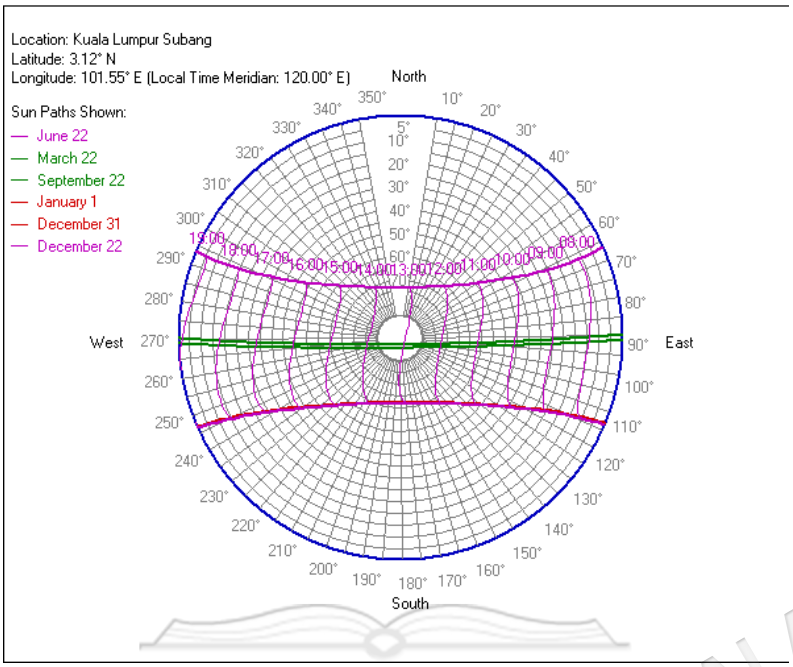
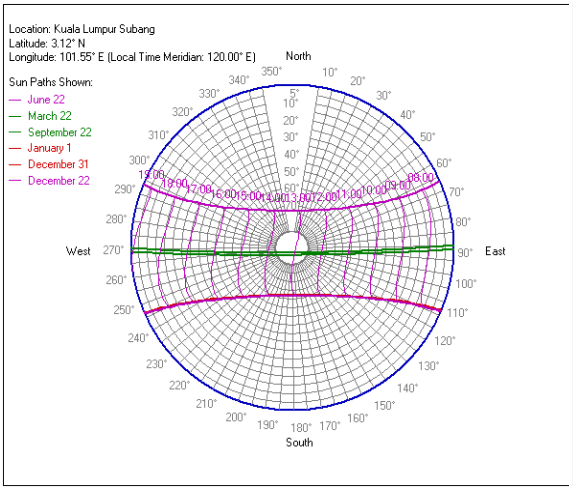


Figure 18 Kuala Lumpur's Sun-path diagram

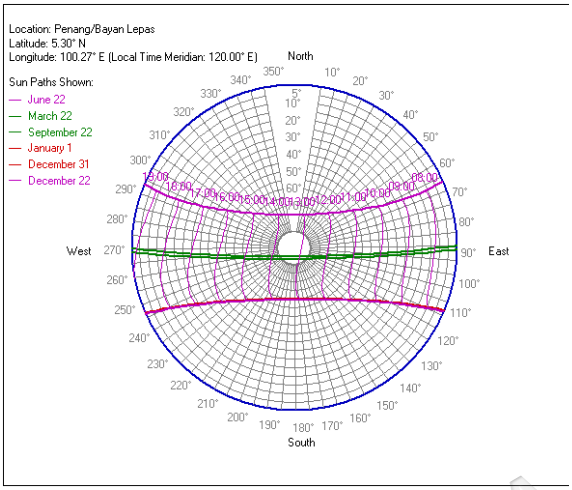
Source: IES-VE software

UNIVERSITI KEBANGSAAN MALAYSIA

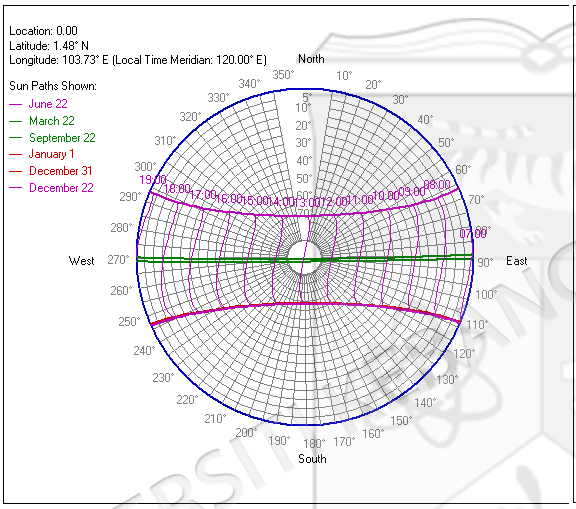
Kuala Lumpur's Sun Path



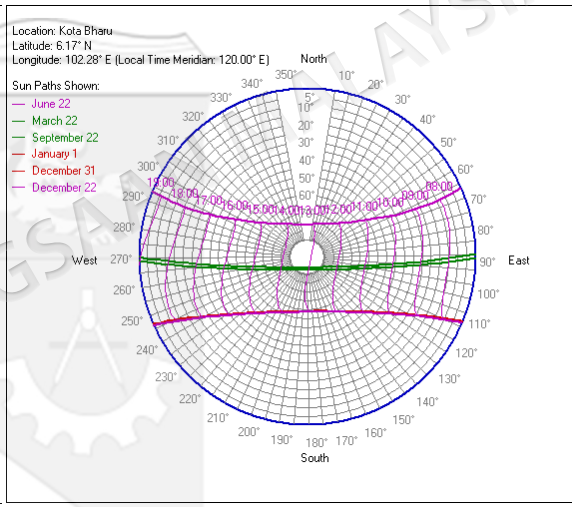
Penang'a Sun Path



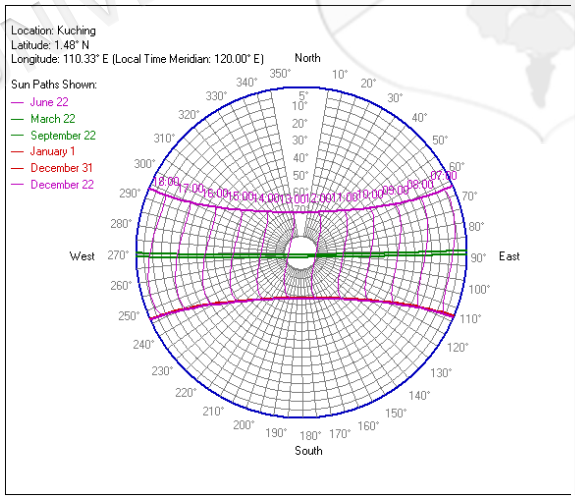
Johor Bharu's Sun path



Kota Bharu's Sun path



Kuching's Sun Path



Kota Kinabalu's Sun Path

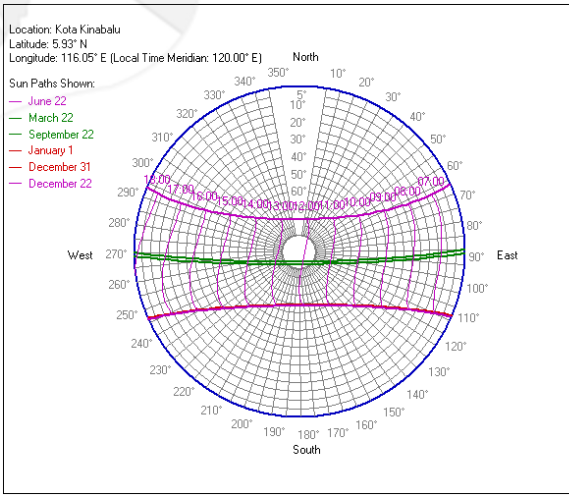


Figure 19 Sun-path diagram of Malaysian Cities

Source: IES-VE software

C. Malaysian Sky Conditions

Different types of sky result from different types of climates and geographical locations. For Malaysia in particular and warm-humid equatorial climates in general, it is difficult to choose any one of the standard design skies available (Ahmad 1996). This is because the sky condition in Malaysia can vary significantly throughout the day, due largely to the formations of clouds which are constantly moving on the sky throughout the day. When the cloud is very dense, the sun is totally obstructed resulting in the overcast sky condition. At other times, patches of clouds will permit direct sunlight to penetrate intermittently and the sky can be clear and bright with white patches around the edge of the clouds (Ahmad 1996).

According to Zain-Ahmed (2002) and Ahmed (1996) the abundance of daylight in the tropics that has not been utilized to the maximum, nor has it been considered as design criterion. The main drawback is maximum daylight availability is usually concurrent with intense solar heat gain, especially in hot and humid climates, like in Malaysia. In addition, the sky conditions in Malaysia can vary significantly throughout the day from overcast to clear sky, due to formation of clouds (Ahmed 1996). Therefore, availability of sunlight and daylight can fluctuate significantly throughout the day.

Table 2.4 illustrates the mean of cloud cover in (oktas) recorded from 1980 to 1993 by the Malaysian Meteorological Services, based on hours of observation from 8 a.m. to 8 p.m. Malaysian Standard Time in Petalling Jaya's station, near Kuala Lumpur. From the table, it can be seen that the cloud cover increases yearly, and in 1993 the recorded values were constantly above 7.0.The relationship between cloud cover data and the type of sky is indicated in Table 2.5.

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Table 2.4 Record of mean Cloud Cover record in (Oktas) based on hours of observation from 08:00 a.m. to 20:00 p.m. for the year 1980 to 1993

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1980	6.5	5.9	6.3	6.3	6.6	6.6	6.8	6.8	6.8	6.9	6.8	6.9	6.6
1981	6.9	6.6	6.4	6.8	6.7	6.6	6.4	6.8	6.9	7.0	6.9	6.3	6.7
1982	6.5	6.6	6.7	6.5	6.3	6.7	6.8	6.9	7.1	6.8	6.8	6.7	6.7
1983	6.3	6.1	6.6	6.9	6.5	6.5	6.5	6.8	6.7	6.9	7.0	7.1	6.7
1984	6.9	7.2	6.7	6.7	6.8	6.8	6.8	6.9	6.9	6.9	7.0	6.9	6.9
1985	5.9	6.9	6.9	6.9	6.9	6.1	6.7	6.1	5.7	4.9	4.5	5.0	6.0
1986	7.1	6.0	6.7	6.7	6.5	6.3	6.5	6.8	6.9	6.9	6.9	6.5	6.7
1987	6.8	6.4	6.8	6.7	6.9	6.9	6.7	6.9	7.1	6.9	7.0	7.1	6.9
1988	6.9	6.8	6.9	6.9	6.9	6.9	6.9	7.0	7.0	7.1	7.2	7.0	6.9
1989	6.9	7.0	7.1	6.8	7.0	6.7	6.9	7.0	7.0	7.1	7.0	6.7	6.9
1990	6.7	6.3	6.9	6.9	6.9	7.0	7.0	7.1	7.0	6.8	7.1	6.4	6.8
1991	6.7	6.9	6.9	6.9	6.9	6.9	7.1	7.1	7.1	NA	7.1	7.3	NA
1992	6.9	7.0	7.0	7.1	7.1	7.1	7.1	7.1	7.2	7.1	7.1	7.2	7.1
1993	7.0	7.0	7.0	7.2	7.1	7.0	7.1	7.1	7.1	7.2	NA	NA	NA

Source: Ahmad 1996

Table 2.5 Relationship between cloud cover and the type of sky

Type of Sky	Cloud Cover Justification
Heavily Cloud Sky	7.0 oktas < Cloud Total < 8.0 oktas
Intermediate Sky	1.0 oktas < Cloud Total < 7.0 oktas
Clear Sky	0.0 oktas < Cloud Total < 1.0 oktas

Source: MMD 2001

The data from Table 2.4 shows that, average annually cloud cover for twelve years at Petalling Jaya's station was 6.8 oktas. This particular value (refer to table 2.5) was within the range of 1.0 oktas < Cloud Total < 7.0 oktas, thus classifying the type of sky for Petalling Jaya's as 'intermediate Sky'.

Zain-Ahmed et al (2002) used the nebulosity index (NI) to determine sky conditions and to calculate the irradiances in Malaysia. According to different NI values, the sky conditions are categorized as shown in table 2.6 below. Based on the

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occurrences of sky types, the study concluded that the Malaysian sky is predominantly an intermediate sky. This was justified by the calculated mean NI value for Malaysian as 0.52, which lies between the range of intermediate sky 0.20 and 0.70. The definition of intermediate implies that the sky is neither clear nor overcast (Zain-Ahmed et al, 2002).

Table 2.6 Different Sky types according to Nebulosity Index, Subang Jaya, Malaysia.

Type of Sky	**Nebulosity Index (NI)**	**Frequency (%)**
Overcast Sky	0.00<0.05	14.0
Intermediate overcast	0.05<0.20	2.3
Intermediate mean	0.20<0.70	66.0
Intermediate Blue	0.70<0.95	17.3
Blue / Clear Sky	0.95<1.00	0

Source: Zain-Ahmed et al. 2002

The intensity of the direct and diffused radiation is significantly influenced by the presence of turbidity and water vapor content as well as the thickness of the clouds. But being near the equator, the daily solar radiation and its duration varies only slightly (Ahmed 1996). Figure 2.20 to 2.22 illustrate respectively the average hourly values of direct normal, diffuse horizontal and global horizontal solar radiation (Wh/m^2) and sunshine hours for Kuala Lumpur.

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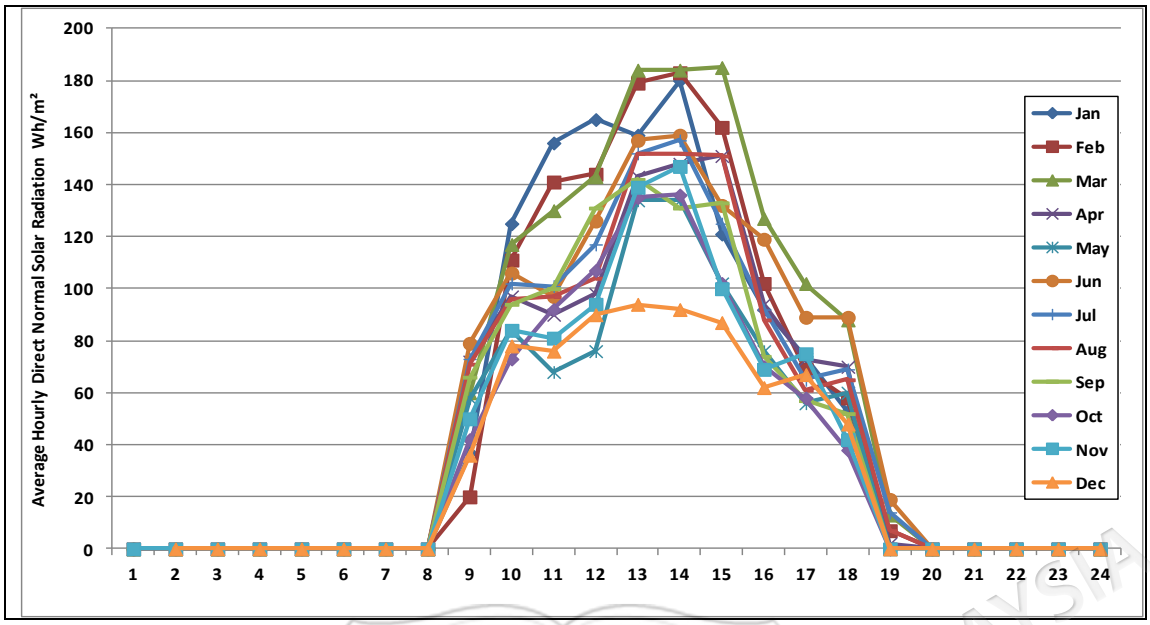

Figure 2.20 Kuala Lumpur average hourly direct normal solar radiation

Source: ASHRAE Handbook, 2009

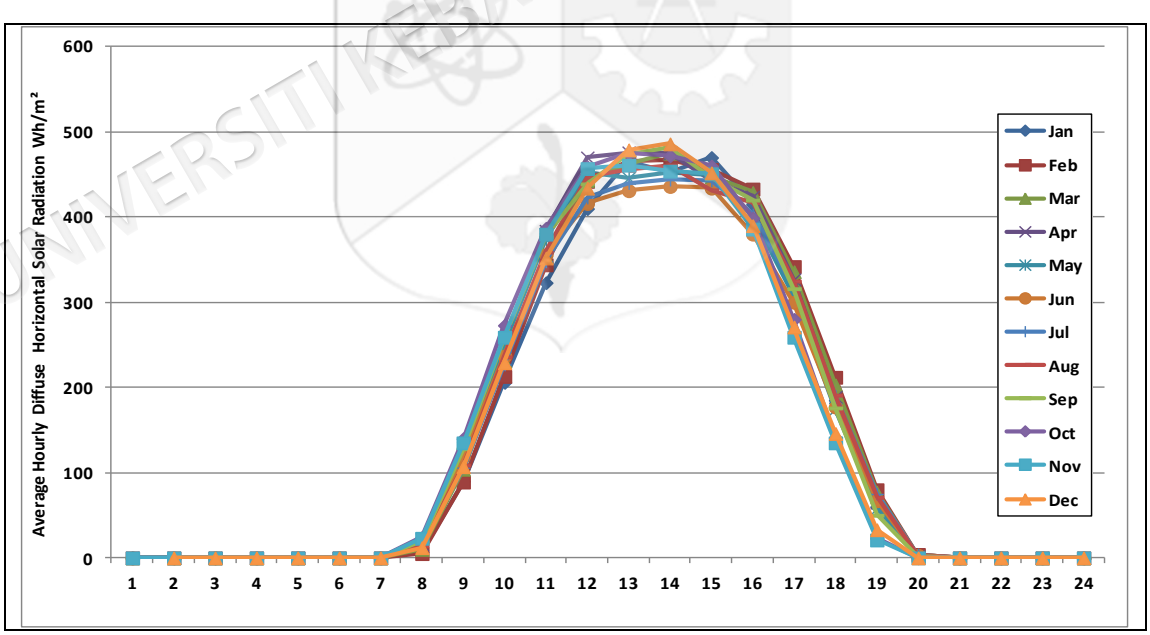

Figure 2.21 Kuala Lumpur average hourly diffuse horizontal solar radiation

Source: ASHRAE Handbook, 2009

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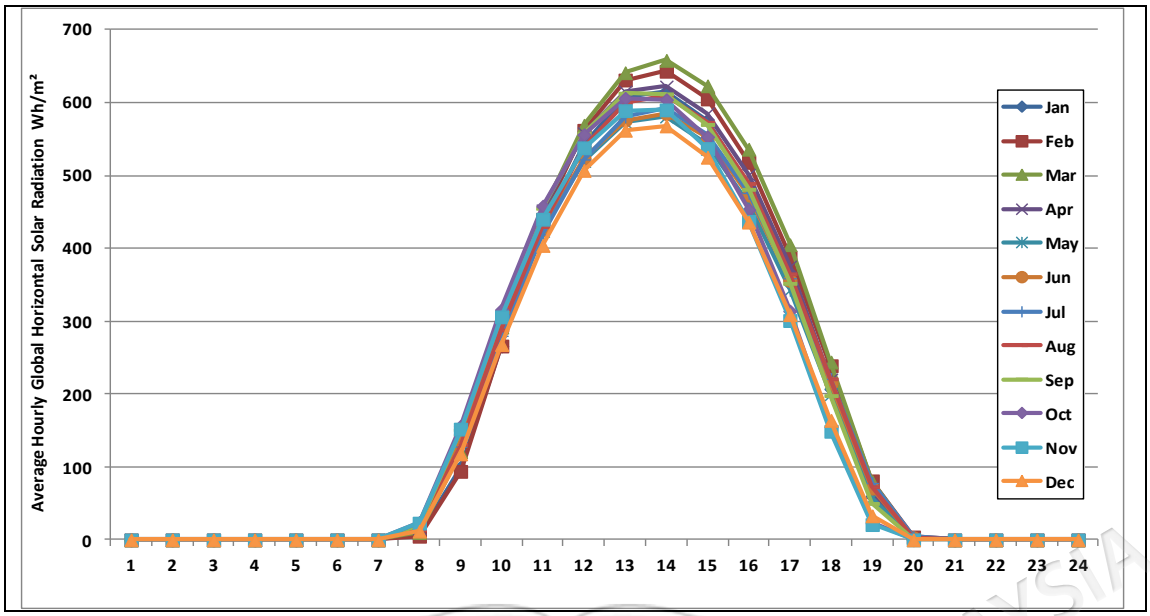

Figure 2.22 Kuala Lumpur average hourly global horizontal solar radiation

Source: ASHRAE Handbook, 2009

The major drawback to harvest daylight in tropical climate is high intensity of solar radiation which will result unwanted solar heat gain (Lim et al. 2012). Figure 2.23 illustrated the monthly average direct, diffuse, and global solar radiation for the Kuala Lumpur city. This climatic data was obtained from ASHRAE Handbook (2009) for Kuala Lumpur, Malaysia. It clearly demonstrates that the ratio of diffuse radiation to direct radiation in Kuala Lumpur is very high. The monthly average global solar radiation for Kuala Lumpur city was from 3.91 kWh/m^2 to 4.63 kWh/m^2. The highest solar radiation was estimated at 4.63 kWh/m^2 in March, February and April while the lowest was 3.91 kWh/m^2 in December. Therefore, it is so important to know how to avoid solar radiation from overheating the building spaces through daylighting systems.

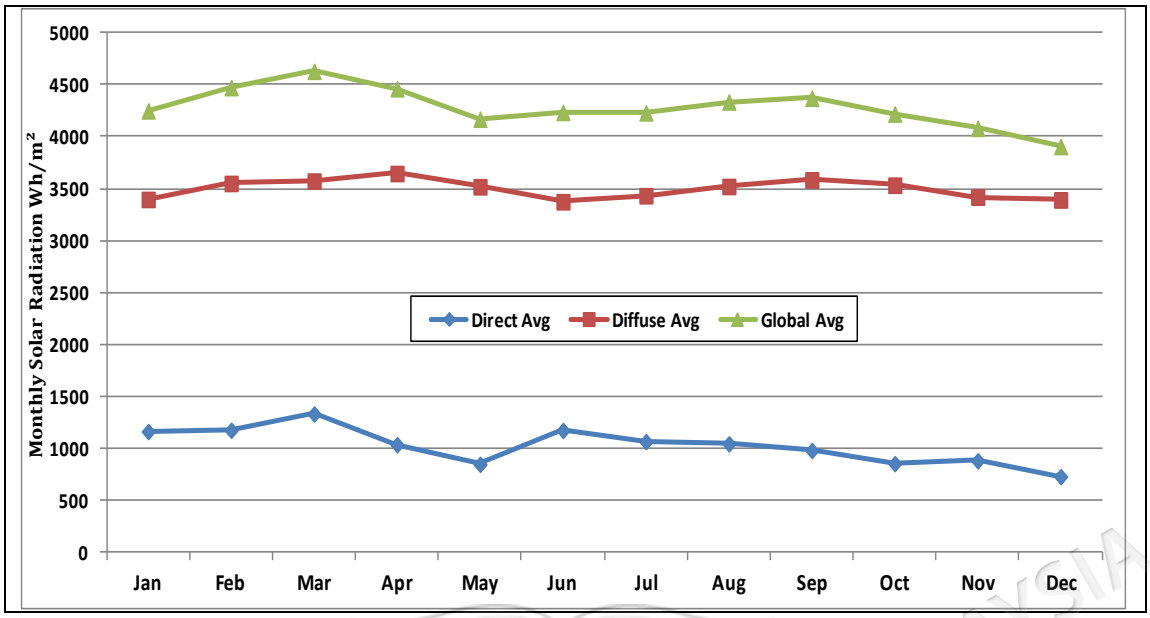

Figure 2.23 Kuala Lumpur monthly averages solar radiation (direct normal, diffuse, global horizontal)

Source: ASHRAE Handbook, 2009

D. Daylight Availability

The phrase "Daylighting availability" refers to the amount of daylight available from the sun and the sky at a specific location, time, date, and sky condition (IESNA 2000). The daily and seasonal movements of the sun with respect to a particular geographic location produce a predictable pattern of amount and direction of potentially available daylight. As such, the effect of this variation on lighting energy use in daylighting spaces has to be well studied during the preliminary study of the building design using the region's meteorological data. Traditionally, daylight resources can be analyze by first conducting extensive measures of the locale and then use this result to develop the specific illumination model (Robbins 1985). Illuminance observations for this purpose have been taken by a number of people over the past years, regional variations in climate and latitude can cause differences in the relative amounts of daylight available; yet existing methods for predicting daylight in interiors are mainly based on the daylight data diffuse sky conditions, excluding consideration of any direct sunlight entering a room (IEA SHC Task 21 2000). Daylighting availability data is recorded every minute at more than 50 stations across the world.

UNIVERSITI KEBANGSAAN MALAYSIA

Malaysia is located in the tropical region near to equator, with approximate latitude 1°N to 6°45'N and longitude 99°36'E to 104°24'E. There is no long-term measured daylight data available in this region. According to Zain-Ahmed et al. (2002), the hourly indices at Subang, West Malaysia, indicate that 85.6% of the time the sky is predominantly intermediate, 14.0% overcast and 0% blue. This finding is further agreed by Djamila et al. (2011), showing that 70–90% of the sky at Kota Kinabalu, East Malaysia, is intermediate using cloud cover ratio. However, 100% of the sky is predominantly intermediate for the whole year using nebulosity index (NI) method. Hence, Malaysian tropical sky is predominantly intermediate. Totally clear skies are impossible. Intermediate sky shall be employed for tropical daylighting study.

As tropical sky is predominant by intermediate sky with clouds (Zain-Ahmed et al. 2002) and (Djamila et al. 2011), the sky can be bright with patches around the edges of the clouds. Direct glare problem occurs when the occupants look to the high sky luminance through the windows. While the sun is not obscured by the clouds, direct sunlight patches falling on the interior spaces also cause non-uniform daylight distribution, resulting great contrast and visual discomfort. Consequently, the challenge in tropical daylighting is not about achieving the daylight quantity, but to control the daylight quality (Lim et al. 2012).

For tropical daylight availability, the global illuminance (E_G) was predicted using irradiance data and proposed luminous efficacy constant. Previous research showed that EG exceeds 80,000 lx at noon during March when solar irradiation is highest; and reaches 60,000 lx even during December when solar irradiation is less intense (Zain-Ahmed et al. 2002). From field measurements, it was found that the E_G values could exceed 140,000 lx. Meanwhile, Djamila et al. (2011) demonstrated that the predicted E_G exceeds 100,000 lx at Kota Kinabalu, East Malaysia. The review of previous research evidenced that during office working hour (9–17 h), the EG mostly exceeds 20,000 lx. Consequently, estimated E_G of 20,000 lx shall be employed for tropical daylight factor (DF) analysis in offices rather than the typical assumption of 10,000 lx for temperate climate.

Daylight availability data and the equations give mean values and do not express instantaneous values of illumination. Because of that, measured instantaneous luminance may differ widely from those obtained from calculation methods based on daylight availability. In order to calculate daylight availability at a site these values have to be determined (IESNA 2000):

- **Site location:** identified by *l* and *L* for latitude longitude respectively. These values can be obtained from any standard atlas or almanac.
- **Time:** Solar time can be determined from standard time (or daylight time) by regulating both for site longitude within the time zone and for equation of time.
- **Solar position:** Position of the sun is specified by the solar altitude and solar azimuth. The solar position is dependent on three factors: site latitude, solar time, and solar declination.
- **Sunlight:** The sun is considered to be a point source that provides a constant illuminance at a point on a plane that is normal to the direction of the sun and near the earth's orbit.
- **Skylight:** The sky is classified using one of the following: the sky-ratio method or the sky-cover method. The sky ratio is determined by dividing the horizontal sky irradiance by the global horizontal irradiance. The sky cover method uses estimates of the amount of cloud cover.

Since daylight availability is essential in the design of energy-efficient building elements, especially for daylighting systems designs. Therefore, the daylight availability data from the Kuala Lumpur IWEC weather file will be used in the proposed study to determine typical dates and times for the daylighting analysis.

2.3.4 Daylighting Design Strategies

According to the definition of Ander (2003), there are two simple daylighting design strategies: side-lighting and top-lighting.

UNIVERSITI SULTAN ZAINAL ABIDIN MALAYSIA

Side-lighting uses the walls of a building to admit daylighting into interior spaces. It is a convenient strategy for building and provides both views and options for ventilation. It gives light with a strong directionality, but which diminishes as the distance from the aperture increase. In addition, it is good for horizontal work plane surfaces. The disadvantage of sidelight is that it may cause glare, as the illuminating area is in the field of view of the occupants. And there are often high contrast ratios between the aperture and the surrounding surfaces.

Top-lighting uses the upper part of the building element: the roof or another element above the ceiling line. The advantage of top-lighting is that it gives designers flexibility in arranging the geometry and orientation of daylight apertures according to the lighting needs of the occupants and is not limited to wall orientations like side lighting (Lam 1985). As a result, the uniformity of light distribution is more easily achieved with top lighting. In addition, large quantities of light can be provided through relatively small openings.

As stated by Cabús and Pereira (1996), while toplighting can help reduce the electric energy used in artificial lighting, at the same time, potential heat gains from inappropriate design have to be avoided. This challenge in designing with top lighting has to be closely examined, especially in buildings in low-latitude, hot and humid climates without a heating period.

UNIVERSITI KEBANGSAAN MALAYSIA

2.3.4.1 Common Toplighting System Designs

Toplighting refers to the process of adding architectural apertures above the roof plan of a building to allow natural light to enter the building space. Reviewing common toplighting system designs provides accurate information and enables better understanding of overall architectural design. Figure 2.24 presents a cross section of three toplighting system designs most commonly used in commercial buildings.

The case study building was modeled in the EnergyPlus simulation program to test and compare between three types and geometries of toplighting systems in terms

of energy and daylighting performance. The selected toplighting system designs are skylight, sawtooth, and roof monitor, which are generally found in commercial buildings in Malaysia. The performance of these designs in terms of energy and daylighting has been investigated in Kuala Lumpur (latitude 3°.12' north, longitude 101°.55' east, altitude 22m).

A. Skylight Toplighting Design

The skylight toplighting design is a special opening set in the plane of a building roof covered with transparent or translucent glass or plastic to admit daylight into a building. Skylights are of three different types, namely, fixed, ventilating, and tubular, and have different designs (flat paneled, domed, and pyramidal). Skylight designs have been widely used for lighting in commercial, industrial, and residential buildings. The main problems associated with skylight design are heat gain and glare. Skylight toplighting design should be carefully installed to protect the space below against water leakage and moisture penetration. Skylights can also be designed to provide heat control and ventilation (IESNA 2000).

B. Sawtooth Toplighting Design

The sawtooth design is the part of a building set higher than the surrounding roof and with walls that have windows to light interior spaces. Sawtooth roof vertical windows are arranged in rows to form a sawtooth shape. This toplighting system is commonly used in large commercial and industrial buildings. Sawtooth fenestrations usually face north in northern countries (Rea 2000). However, the sawtooth design can be created to provide better thermal attributes than the skylight design with vertical windows and high-performance glazing.

C. Roof Monitor Toplighting Design

A roof monitor is a part of the roof raised above the rest of the surrounding roof. This raised portion of the roof is supported by a knee wall that extends the lower roof, thereby providing spaces for vertical windows on one or four sides to admit daylight.

UNIVERSITI KEBANGSAAN MALAYSIA

This toplighting design is commonly used in single-story commercial, residential, and academic buildings. Roof monitors can also be designed to limit solar heat gains to the space from direct sunlight by adding overhangs to windows.

This study focuses on the effect of the three toplighting designs, namely, the skylight, sawtooth, and roof monitor, on energy and daylighting performance in the case study academic hall in UKM, Malaysia.

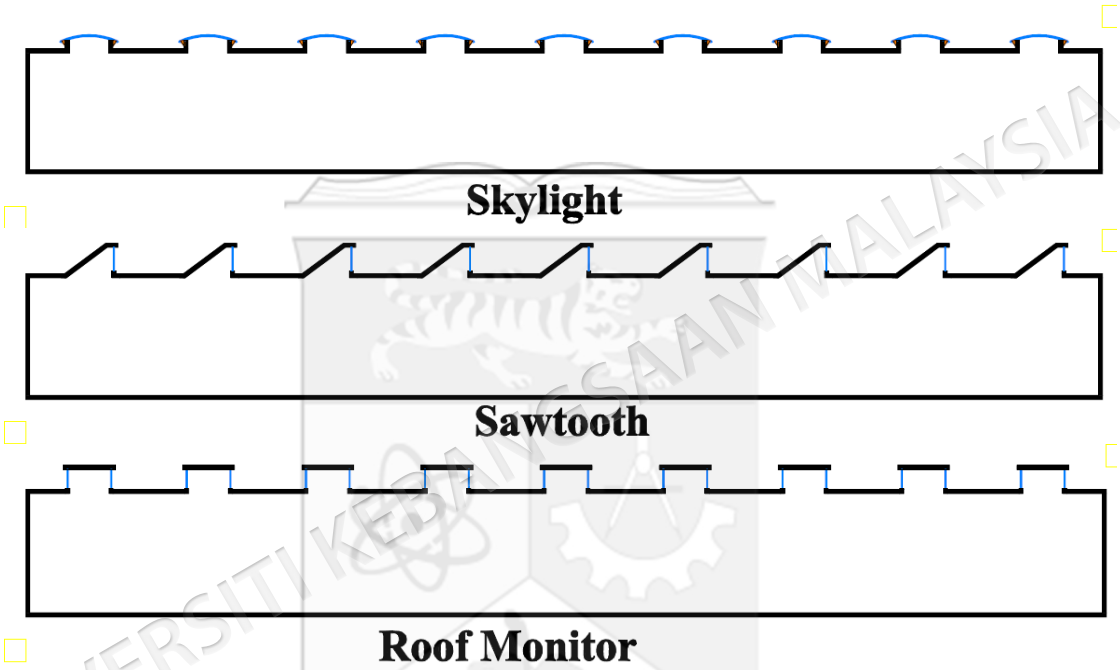

Figure 2.24 Sections of common toplighting systems designs used in buildings

2.3.5 Benefits of Daylighting

Evidence that daylight is desirable can be found in research as well as in observations of human behavior and the arrangement of office space. Windows that admit daylight in buildings are important for the view and connection they provide with the outdoors. Daylight is also associated with superior features such as quality, spectral composition, and variability (Ander 2003). A review of peoples' reactions to indoor environments suggests that daylight is desired because it fulfils two very basic human requirements: to be able to see both a task and the space well, and to experience some environmental stimulation (IEA SHC Task 21. 2000). Moreover, long hours of work

under electric lighting systems are believed to result in deteriorating health conditions, thus implying that working in daylight is comparatively stress-free.

Daylight provides high illuminance and permits excellent color discrimination and color rendering. These two properties mean that daylight provides the condition for good vision. However, daylight can also produce uncomfortable solar glare and very high luminance reflections on display screens, both of which interfere with good vision. Thus, the effect of daylight on the performance of tasks depends on how the daylight is delivered. All of these factors need to be considered in daylighting design for buildings. Daylight main advantages are discussed in detail below.

A. Occupancy Health

Many researchers have demonstrated that proper daylighting can improve the health and performance of a building's occupants. For instance, it has been reported that daylighting can improve the performance and health of students in schools. Different studies concluded that the presence of natural light can improve students' performances in schools, workers' performances in office buildings, and sales performance in retail stores (Heschong 2002).

Many studies demonstrate that the appropriate use of daylighting decreases the occurrence of headaches, Seasonal Affective Disorder (SAD), as well as eyestrain: all of which are caused by the supply of insufficient lighting. One way to curb this problem is to put in place a suitable spectral lighting system. Nevertheless, the primary health hazard associated with office lighting systems is eyestrain that can be reduced by providing best spectrum of light for the eye by the proper integration and management of daylighting in an office building. Here, the eye lacks focus on multiple distances and after a long persistence; the dilating muscles are then compelled to only be capable of focusing on a limited specific range of distances, thus resulting in shortsightedness or long sightedness (Franta & Anstead 1994).

Clark and Watson (1988) also found that daylight improves the positive mood of office building occupants. The authors argued that improved mood increases job

UNIVERSITI SAINS MALAYSIA

satisfaction, results to higher work involvement, motivation, organizational attachment, and less absenteeism by staff. On the other hand, negative staff mood was found to result in distress and distraction, while a positive mood is linked to the physical setup of the work environment as well as the nature of the routine activities therein. This includes, for example, the level of inter-employee social interaction (Edwards & Torcellini 2002).

According to review of recent study (Galasiu & Veitch, 2006), Cuttle conducted surveys in England and New Zealand to investigate the preferences of 471 office workers. Of the respondents, 99% believed that offices should have windows; 86% considered daylighting to be their preferred source of lighting. The preference for daylighting was attributed to the belief that working in daylight results in less stress and discomfort than working in electric light (Cuttle 1983).

B. Occupancy Performance

The relationship between the implemented lighting system and the students' performance has been studied by many researchers. According to (Ruck 1989), the suitable illumination have a direct bearing on people's reaction, motivation, temper as well as our perception about personal well-being. The author indicated that the issue of illumination has driven building design for centuries as evidenced by ancient architecture and its attention to natural lighting. As mentioned earlier (Ruck 1989) also argued that natural lighting not only increase employee productivity but also enhances creativity in the offices and schools environment.

Another research in a middle school by (Rouk 1997) afforded a comparative study of the relative performance of students from three different campuses and concluded that students who attend classes in large windowed classrooms or in classrooms with multiple windows showed better academic performance of up to 14 points higher. Similar argument was put forward by (Moore & Lackney 1993) who reported that windowless classrooms result in negative behaviors in both students and teachers alike; and (Ruck 1989) who also highlighted that in addition to windowlessness, limited spacing and routine tasks also result in fatigue.

UNIVERSITI KEBANGSAAN MALAYSIA

A study by Mendell and Heath (2005) reviewed available literature to confirm evidence on the effect of indoor environmental quality (IEQ) problems on student performance in U.S. schools. The results showed that some IEQ problems, including poor daylighting and ventilation did affect occupants' performance (Heath & Mendell 2002). Another study by (Sammaljärvi 1991), focused on effects of IEQ factors like dust, stuffy air, and room embellishment on physical health of children. Bad indoor air quality and dust alone caused most of the health problems (mainly respiratory) in children. These two studies indicate the importance of daylight and effectively ventilated indoor environment on children's health and performance.

C. Occupancy Productivity

In an investigation to ascertain the specific benefits associated with daylight in the academic setting, (Nicklas & Bailey 1996) compared the data generated from a naturally illuminated school and that of the schools which are artificially illuminated; and concluded that the students in the naturally illuminating school showed better reading and mathematics problem solving skills than their counterparts in artificial lighting school.

In another study, students from a school with natural illumination were found to outperform their counterparts from schools with limited or no natural lighting by 19 to 26 points higher (Hale 2002); even though the study failed to categorically state the exact feature of natural light that led to the superior performance e.g. intensity, quality or the light's physiological impact.

Despite the fact that proper lighting cannot be said to constitute the single factor for improvements in academic performance, proper classroom lighting enhances students' satisfaction which eventually results in improved student performances (Rodgers 1998). According to the design experts, the different development stages of the student must also be factored in the type of lighting system to be implemented in the classroom environment (Bushweller 1998). For these design experts, providing comfort in the academic learning environment should not be

UNIVERSITI KEBANGSAAN MALAYSIA

viewed as luxury but a part and parcel of the children's academic development; for this single factor can help the students to concentrate more in class.

In another study in Sunnyvale, California in 1983, Lockheed Martin designers developed an open office environment for improved daylighting, and reported that the new structure enhanced the collaboration among the engineers; which in turn resulted in a 15% increase in productivity. The designers further believed that this increase in productivity was what helped them to secure a huge defense contract worth over $1.5 billion. In a similar project, VeriFone, Inc. constructed Worldwide Distribution Center en route Los Angeles, California, with daylighting technology and indicated a 5% rise in productivity one and half years after operations began in the new facility while up to 28% rise in the total product output was achieved (Edwards and Torcellini 2002).

Heschong Mahone Group (1999, 2002) studied the effect of daylighting on human performance, and the field tests indicated a 20-26 percent increase in productivity in students with daylighting in their classrooms relative to classrooms having no windows or toplighting. Similarly, students in rooms with large window areas progressed 15 percent faster in mathematics and 23 percent faster in reading skills than those in classrooms with the least amount of window area. Students in classrooms with skylight and daylight controls showed an increase in test scores by 20 percent compared to the students in room lacking skylight (Heschong 1999). Also, students with operable windows in the classroom were found to progress 7-8 percent faster than students with fixed windows. Latterly, the same group studied the effect of daylighting in 73 retail store location in California (Heschong 2002). The study showed an increase in 40 percent, as maximum effect in most favorable stores, increase in retail sales in daylit areas. Also the employees reported higher satisfaction with lighting conditions in daylit stores over non-daylit stores.

D. Cost and Energy Savings

Payment of salaries, wages and overtime of employees and the initial cost of construction are high in comparison to the cost of energy and normal operations. Therefore, in order for the daylighting to pay itself, the monetary value per employee

UNIVERSITI KEBANGSAAN MALAYSIA

productivity must extend beyond the extra cost contracted as a result of introducing daylight technology. Using this model, numerous firms have reported that this increase in productivity per employee actually overshadow the rise in cost as indicated below.

One such company where improved work environment resulted in increasing gains is West Bend Mutual Insurance. Upon embarking on the improvements, the firm realized productivity increased of 2.8%, which translates to about $364,000. The firm which stood at $13 million salary base per annum, reported that some of the improvements in productivity were due to the fact that a number of their offices were relocated to daylit structures. Further dilating on the impact of employee performance on the firm's overall productivity, the report mentioned, "every minute less of wasted time per hour represents a 1.67% gain in productivity where a 2% increase in productivity equates to $3 million saved (per year)". In this way, construction constitutes about 2% of the overall building cost, 6% constitutes maintenance cost while the remaining is dedicated to employee salaries. Due to the same project, the firm reported $0.5 million dollars reduction in energy cost and reduction in employee absenteeism (Edwards & Torcellini 2002).

Study has reported that the implementation of daylighting increased the gains from rental services by up to 20% compared to buildings using the artificial lighting (Electric Power Research Institute 1998). Energy efficiency in construction has also been reported to result in increasing the value of real estate (Environmental Design & Construction, 2001); and since their maintenance cost is lower, the monetary gains from the energy savings is added to the property's income. According to (Solatube International 2004) monetizing this gain can result in up to $6 gain per square foot of the building's value.

2.3.6 Daylight Calculations and Analysis

During the last half of the nineteenth century, daylight calculation methods from natural sources first became available (Ander 2003). A number of calculation methods are used for daylight calculation. These include the Lumen Method for toplighting and

side-lighting (IESNA 2000), Computation of Illuminance (IESNA 2000), Graphic Daylighting Design Method (GDDM) (Millet and Bedrick 1980), and the Daylight Factor Method (Hopkinson et al. 1966). The Lumen Method and the Daylight Factor Method are the most widely used.

The Daylight Factor is the "illuminance received at a point indoors, expressed as a percentage of the total horizontal illuminance outdoors from an unobstructed illuminance of the same sky" (Rea 2000). Direct sunlight is excluded from both interior and exterior values of illuminance (Baker and Steemers 2002). The daylight factor method will be used for daylighting calculations in the proposed research to compare the effect of proposed top-daylighting solutions in the existing hall building. Daylight factors will be compared using actual space measurements and daylight factors calculated by the EnergyPlus simulation program.

The development of architectural styles in the 20th century, which were neither very environmentally nor very energetically conscious, tended to overlay the earlier traditions of daylight design. The availability of inexpensive fluorescent electric lighting tended to accelerate the neglect of daylighting design many buildings particularly between 1945 and 1975 have to be evaluated as failures in daylighting design conditions when compared with historic solutions (Steemers et al. 1993).

According to Johnsen (1998), daylighting has not been a very important design factor for the past decade and modern buildings have often disregarded the potential of daylighting. The three basic reasons for this attitude towards daylighting was the lack of knowledge and information on new fenestration technologies, lack of convincing evidence that daylighting could improve energy efficiency and enhance visual quality of inside spaces, and the lack of appropriate and user friendly daylighting design tools (both physical and computer). As highlighted by (Li & Lam 2001), "Energy conservation in buildings can be achieved through many strategies. One of these strategies is the integration of daylight and lighting controls to reduce the energy consumption by lighting systems. Energy savings resulting from daylighting may not only lower electric lighting expenditure and reduce peak electrical demand,

UNIVERSITI KEBANGSAAN MALAYSIA

but also decrease cooling energy consumption and potential for smaller air conditioning plants".

The use of electricity for lighting is one of the most ineffective ways of energy transformation in the building industry, and could represent 50% of energy consumption in the commercial area (Ruck 1986). Transformation of fossil fuel into electricity can represent as much as 70% of energy waste, and transformation of heat to generate light can be as inappropriate as well. Nevertheless, the high cost of electricity compared to other energy sources increases the importance of analyzing lighting use in detail.

2.3.7 Daylighting Potential in Malaysia

According to Zain-Ahmed (2002) and Ahmad (1996) the abundance of daylight in the tropics that has not been utilized to the maximum, nor has it been considered as design criterion. The main drawback is maximum daylight availability is usually concurrent with intense solar heat gain, especially in hot and humid climates, like in Malaysia. One factor that has to be taken into consideration before implementing daylighting technique to reduce energy consumption in buildings is the nature of the window plane, which has a significant effect on the daylight's incidence into the building. As a result, there exist marked disparities between energy savings from the daylight integration of one location to the other. In the tropics, the natural daylighting has been an important design feature in building construction, and has proved very effective for energy savings (Djamila et al. 2011).

The tropical sky has a lot of potential for daylighting applications due to the high daylight availability. Study conducted by Zain-Ahmad et al. (2002), identified the Malaysian sky type as intermediate sky with average cloud cover value of 6-7 oktas. Moreover, the Malaysian global, beam and diffuse illuminance values is within 10-80 Klx during office hours from 8:00am until 17:00pm. The total percentage of external illumination that falls above 10 Klx during office hours is 93% (Ahmed 2000; Zain-Ahmed et al. 2002). Only a 2.5% daylight factor is needed for the interior illuminance to reach 500 lux, which is the recommended illuminance level for

UNIVERSITI SAINS MALAYSIA

academic buildings use (IESNA 2000; MS Standard 2007). Furthermore, the study found that the differences of the illuminance availability between each month are small, as compared with those of locations far from the equator. This proposed that the application of daylighting systems for Malaysian buildings is very high.

In a study on the exterior illuminance of Kota Kinabalu in Malaysia, the researchers employed two prediction models: Perez and Du Mortier–Perraudeau–Page–Littlefair models. The study used the models to predict the vertical hourly illuminance of the city and further compared the results of the two employed models. The authors then reported that with an average illuminance of 500 lx, the vertical illuminance availability is up to 75% of the working year with room depth of 5 m. In addition, when the room depth is changed to 8 m, the average internal illuminance of up to 55% is attained (Djamila et al. 2011).

Malaysia has a high potential for energy savings resulting from the use of daylighting because of daylight availability. However, solar heat gain is a major concern in this type of climate and the use of large toplighting areas, or the use of ineffective glazing type, or incorrect toplighting orientation, could cause excessive solar heat gain, poor daylight quality, and no energy savings.

2.4 DAYLIGHTING AND ENERGY EFFICIENCY

2.4.1 Energy Consumption in Buildings

This part presents the investigation of energy consumption and energy end-uses of buildings submitted to different activities and located in different countries. The main purpose of such an analysis is to present data showing how energy is used in buildings, identifying those end-uses that are responsible for the highest energy consumption.

Energy audits carried out by Suruhanjaya Tenaga (2005) and energy surveys conducted on offices in the country indicate electricity use in commercial buildings to

UNIVERSITI KEBANGSAAN MALAYSIA

be primarily attributed to air conditioning, artificial lighting and office equipment, with 52-60%, 18-42% and about 22% of the total energy consumption respectively.

Malaysia, Indonesia, Singapore, Philippines, and Thailand are the countries that joined the Association of South East Asian Nations (ASEAN). Table 2.7, which is part of the Building Energy Conservation Project Report, presents energy end-use for buildings located in those countries (Ghisi 2002). In average, cooling end-use is about 62.4% of the energy consumption in schools, offices, hotels, hospitals, and supermarkets. Lighting end-use ranges from 20.6% to 22.5% of the energy consumption in schools, offices, and hotels. In the store analyzed in Malaysia, it reaches 46.5%. It can be noted that lighting and cooling together account for most of the energy used in buildings in those countries.

Table 2.7 Energy end-use in the ASEAN countries

Building Type	Country	Quantity	End-Use (%)		
			Cooling	Lighting	Others
Offices	Indonesia	1	80.1	11.8	8.1
	Malaysia	5	68.8	23.1	8.1
	Philippines	24	61.2	22.5	15.6
	Singapore	4	49.8	24.2	26.0
	Average	34	61.6	22.5	15.5
Hotels	Indonesia	4	57.6	18.5	23.9
	Malaysia	3	61.1	22.8	16.1
	Philippines	8	63.9	16.2	18.2
	Singapore	2	55.4	38.6	6.0
	Average	17	60.9	20.6	17.7
Hospitals	Malaysia	1	77.9	14.7	7.4
	Philippines	8	56.1	6.6	34.5
	Average	9	58.5	7.5	31.5
Stores	Malaysia	1	40.1	46.5	13.4
Schools	Singapore	1	71.0	22.0	7.0

Containued

UNIVERSITI KEBANGSAAN MALAYSIA

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Supermarkets	Philippines	4	58.9	6.6	34.5
Hospitals	Malaysia	1	77.9	14.7	7.4

Source: Ghisi 2002

The Commercial Buildings Energy Consumption Survey in the USA 1994 provides a data for Energy end-uses for buildings located in the USA which are presented in Table 2.8. The energy consumption is presented for five different end-uses, and it can be seen that lighting accounts for most of the energy consumption in most types of buildings (Ghisi 2002).

Table 2.8 Energy end-use in the USA

Building Type	End-Use (%)					
	Heating	Cooling	Ventilation	Office equipment	Lighting	Others
Theatres	10	13	14	3	34	26
Schools	5	8	11	5	53	18
Hospitals	2	20	14	4	44	16
Offices	3	10	17	21	35	14
Publics and safety	-	5	8	5	44	38
Others	-	7	-	6	38	49

Source: Ghisi 2002

In the United States as a point of reference, According to statistics presented by Plympton et al. (2000) from the National Renewable Energy Laboratory (NREL), between 2000 and 2007, an estimated 5000 new education buildings were expected to designed and constructed in the USA to meet the needs of American students in kindergarten through high school.

According to the EIA CBECS (Commercial Buildings Energy Consumption Survey), education buildings are considered as the second largest public consumer of energy in both their construction and operation should be designed in a way that enables them to make the best use of existing natural resources (EIA 2003). According

UNIVERSITI KEBANGSAAN MALAYSIA

to the Department of Energy USA, an estimated $1.5 billion could be saved annually with the implementation of minor energy saving reforms on existing and new academic buildings. High performance buildings those built with durable, environment-friendly materials and designed on the basis of life-cycle costs, rather than first cost- help reduce the use of nonrenewable resources. In addition, they are more productive places for teaching and learning, and save substantial amounts of money over the long run (Fischer et al. 2007).

Wong and Jan (2003) evaluated the Total Building Performance (TBP) of two building blocks in a typical secondary school in Singapore. The analysis involved both objective and subjective evaluation through the use of techniques like walk through, visual inspections, data logging, and on-site information processing. Tools like interviews, questionnaires, surveys, and recording instruments were used for subjective data analysis. Thermal, lighting, indoor air quality, spatial, and acoustic requirements were studied for both the building blocks using building energy codes and environmental guidelines, and were applied as base comfort levels. Temperatures and humidity levels inside the classrooms were found to be higher than the recommended maximum, and the illuminance values were lower than the recommended 500 lux, with a problem of glare near windows. Carbon dioxide levels were found to be within the recommended maximum, but still on the higher side. Acoustic and spatial values did not fit within the recommendations. The results are preliminary in nature, but are good starting point in total school building analysis. The proposed study will also use some of the methods used by Wong and Jan (2003), including walk-through, daylight measurements, and computer simulation to analyze the existing lighting conditions inside the case study building spaces.

Nicklas and Bailey (1996) evaluated the first year energy performance of three new daylit schools, Clayton and Selma Middle Schools and the K-5 Four Oaks School designed by Innovative Design. These schools were compared to with similar but non-daylit schools in their respective Counties in North Carolina. Annual energy consumption was also compared with two other daylit schools designed by the same firm. All schools were prototypical in their daylighting design, incorporating south-facing roof monitors, except one which had both south and north monitors, and all

UNIVERSITI KEBANGSAAN MALAYSIA

schools proposed to achieve daylighting levels over 70fc (700 lux) in the classrooms. The cost of added daylighting construction features was high, but was offset due to downsizing of mechanical systems. Energy consumed by the newly built schools, though included energy used for criteria like computers, advanced AV equipment and extensive evening use of gymnasiums, still indicated total annual energy cost reductions from 22 percent to 64 percent over the existing schools. Like the above, the proposed study aims to develop energy efficient daylighting solutions for education buildings relevant as the previous study.

2.4.2 Energy Savings Impact of Daylighting

Many researchers have agreed on the positive effect of daylight on energy savings (Li & lam 2003). The following findings provide the importance of the daylighting systems in order to increase energy conservation, and review the potential effectiveness of these systems by means of simulations and measurements.

In tropical countries such as Malaysia daylighting which is considered as an approach for passive energy efficiency because of its long hours of sun shine throughout the entire year in addition to the enormous daylight luminous in Malaysia. This characteristic could meet most of the luminance internal demand within a day that could direct in considerable proportion of energy saving (Ibrahim & Zain-Ahmed 2007).

A study conducted by Ibrahim and Zain-Ahmed (2007) To account daylight availability in an office interior under various fenestration options; namely window-wall-ratio (WWR), glass types and application of external shading devices of varying depth. The study used IES RADIANCE software and the Daylight Factor method to analyze its outcome. Daylight Factor (DF) was used as the basis to estimate the percentage of daylit floor area of a generic 4.5m deep office cell. The optimum WWR to achieve the maximum percentage of daylit floor area for a 4.5m deep room are 40%, 55% and 65% for clear, tinted and reflective glass, respectively. The results from the daylight availability study also shows that application of simple horizontal shades does not significantly affect the amount of daylight indoor. In fact, application

of external shades improves the daylight distribution whereby the illuminance intensity in areas closer to the windows were reduced, providing a gentle daylit indoor.

In investegation by Santamouris et al. (1994), the energy consumption pattern of 186 office structures was studied in Greece. The study specifically encompassed energy usage for heating, cooling, and lighting, and the strengths and weaknesses of the different energy saving mechanisms were highlighted. For energy savings to be achieved in each case, they either implemented the natural lighting or introduced energy efficient conventional lighting technologies in the buildings. The study found that buildings with fluorescent bulbs switched on from 7 AM to 5 PM achieved up to 40 % contributions from daylighting from a single side and up to 59% for daylight that enters from the four sides of the buildings of the overall lighting load. For cases where operations extended beyond 7 AM, the contribution of daylighting was from 29 to 68% of the total energy load for lighting.

Bodart and De Herde (2002) evaluated the effect of lighting energy saving on the building energy consumption using an integrated approach that combined daylighting and thermal aspects. They demonstrated that daylighting can reduce consumption of artificial lighting from 50% to 80%. Further, global primary energy savings of up to 40% can be achieved not only through the reduction of lighting consumption but also from the reduction of lighting internal loads, for a type of glazing typically used in office buildings in Belgium. For exceptionally high performing glazing systems, the energy savings may increase to 50% (Bodart & De Herde 2002).

In another study, Galasiu et al. (2002) investigated the effect of different setups of Venetian blind on lighting controls. Using energy usage and illumination level as the performance metrics, the result indicated that up to 60% saving in energy is achieved in clear sky conditions compared to conventional lights-on throughout from 6 AM to 6 PM (Galasiu & Atif 2002).

In a similar work, Li and Lam (2003) conducted field measurement of energy savings in an air-conditioned corridor which implemented daylighting technique. By

UNIVERSITI KEBANGSAAN MALAYSIA

computing the energy savings, the result indicated that daylighting resulted in between 3.44 to 4.29 kWh/m^2 use of conventional energy, while energy savings of up to 47.2kWh/m^2 is attained, which is about 65% savings in energy usage for the corridor illumination.

Based on review by Doulos et al. (2005), a variety of results can be found with regards to the impact of daylighting on energy savings. Based on simulation results, Doulos found that daylighting control can achieve up to 77% lighting energy savings and 14% of total energy savings. Similar work by Sullivan et al. (1992) investigated the effect of window and lighting systems on energy conservation. The results indicated that daylighting contributed up to 40% of the primary energy savings (Sullivan et al. 1992).

The study by Ghisi and Tinker (2005) integrated the daylighting system with the conventional lighting techniques using rooms with various dimensions in Leeds in the UK and Florianopolis, in Brazil. The energy analysis work was performed using the VisualDOE energy simulation program. The result of the study showed that the energy saving potential on lighting of Leeds was from 10.8% to 44% while that of Florianopolis was from 20.6% to 86.2%.

In another study by Krarti (2005), the impact of four factors of daylighting on lighting energy savings is investigated. These factors are the geometry of the building, area of the window, the type of window and the perimeter of the buildings. The result of the study found that the daylighting aperture significantly influence energy savings due to the implementation of daylighting technique. Specifically, up to 70% savings in energy was achieved (Krarti et al. 2005).

Using photoelectric dimming technique, Li et al. (2006) conducted field measurement on the energy savings of a fully air conditioned open office with daylighting technique. The study focused on the lighting load, inside illumination level, and the availability of daylighting. With this system in place, the study found between 1.1 and 1.7 kWh savings in energy every day; which translated to 365 kWh

UNIVERSITI SAINS MALAYSIA

or 33% savings in energy usage per annum on conventional lighting technique with dimming controls.

2.4.3 Building Thermal Load Impact of Daylighting

According to Ghisi (2002), it is a fact that Energy cannot be created or destroyed; only its form can be changed. As a result, energy used to operate artificial lighting systems will be changed into light and heat. It must also be understood that the visible spectrum, with wavelengths between 380 and 780nm, is situated within the thermal radiation range. In this way, part of the light will also become heat. The heat generated by artificial lighting systems that have to be removed by mechanical cooling is called "lighting cooling load," i.e. it is the heat produced that has to be removed to keep comfort levels, and "lighting heating load" when the heat helps to maintain comfort levels. Lighting load ins usually presented as a percentage of the total heating sources in the building, natural or artificial, and therefore depends on many factors, such as weather conditions, wattage installed in the building, area of windows, and the fabric of external walls and roof, number of users etc.

Daylight aids decrease the electricity use and the associated sensible cooling load because of artificial lighting. Therefore, proper daylighting design can contribute to smaller air-conditioning system and lower the peak power demand of buildings. in other words, energy savings resulting from daylighting mean not only low electric lighting and reduced peak electrical demands, but also reduced cooling loads and the potential for smaller heating, ventilating and air-conditioning systems (Li et al. 2005).

In Orlando, in the USA, Parker noted that approximately 30% of the cooling load is due to artificial lighting through simulations of a specific building located in Orlando (Parker et al. 1997). In general, it stated that the heat produced by artificial lighting contribute between 15% and 20% of the overall building cooling load (IESNA 2000).

In Japan, a project for developing semi-transparent solar windows for energy efficiency was carried out. The study found that when the lighting control is not

UNIVERSITI KEBANGSAAN MALAYSIA

implemented, the transmittance emanated from the higher solar cell led to reduction in heating energy load and a higher cooling energy load due to the higher energy gains from the solar windows. Also, the study indicated that the larger the dimensions of the windows, the higher the achieved energy savings. In the summer however, larger window dimensions caused increasing heat gains on the solar windows (Miyazaki et al. 2005).

Gratia and De Herde (2003) reported that energy radiated by lighting with incandescence corresponds to 80% of energy converted against 50% for a fluorescent lighting. With the passing of time, the generated heat saturates the surrounding materials, thus increasing the inner temperature of the room. This phenomenon can however be curbed by implementing natural lighting. Apart from minimizing internal heat gains, the use of daylight makes it possible for energy consumption reduction.

In France, a project on integrating daylighting with artificial lighting systems was conducted to study the thermal loads of office structures (Franzetti et al. 2004). The results indicated that when natural lighting was not implemented, the needs for cooling surpass that of heating. Cooling is used to evacuate the internal loads, which are mainly due to lighting in the hot period Figure 2.25. This implies a large reduction of all energy needs (except heating needs) when daylight is maintained even by a basic light control device.

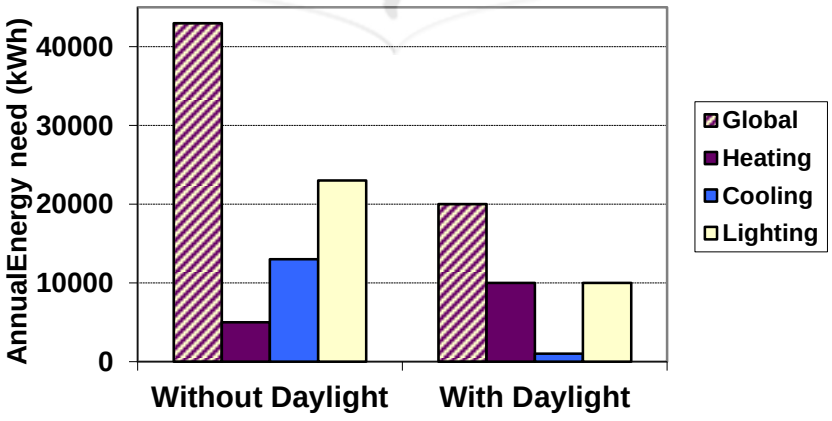


Figure 2.25 Annual energy needs (kWh)

Source: Franzetti et al. 2004

UNIVERSITI KEBANGSAAN MALAYSIA

The study by Lam and Li (1998), regarding to daylighting and energy analysis for air conditioned office buildings, reported that reduction in the sensible heat gain from artificial lighting due to daylight integration is about 32.3 kWh/m^2 for on-off lighting control and 35 kWh/m^2 for top-up lighting control.

Further researches and studies on the impact of daylighting on building thermal load were also done by Li et al. (2005) who reported that there was an insignificant difference in monthly peak cooling load reduction with and without the implementation of daylighting, ranging from 379 kW to 492 kW depending on the month of the year. Also, when daylighting was not implemented, peak load was realized on the 15th August at 14.00, which shifted to the 17th August when daylighting was introduced (Li et al. 2005).

El Mohimen et al. (2005) analyzed the importance of daylighting in office environments in Egypt and the results showed that in addition to diminution in the total annual building energy usage, daylighting reduces the peak cooling loads and the peak electricity demands. In Cairo, the reduction is estimated to be 7% for peak cooling load while for peak electicity demand, up to 15% reduction was achieved when the prototype office building has clear single-pane glazing at 20% WWR (Mohimen et al. 2005).

2.5 ENERGY AND DAYLIGHTING SIMULATION PROGRAMS

According to Ayres and Stamper (1995), a wide variety of energy simulation programs are currently available from many organizations, utilities, and private consultant. Building energy simulation programs have became fundamental design tools, which are used to quantify the annual energy use of proposed energy conservation measures in new and existing buildings. Public energy analysis programs in the U.S. are represented by three main code development efforts, including: DOE-2 (1981), BLAST (1993), and EnergyPlus (2001).

The DOE-2 is a powerful and commonly used application for analyzing and costing the energy consumption of different types of building. The application

UNIVERSITI TEKNOLOGI MALAYSIA

provides an accurate estimate of the proposed building's energy consumption and cost. By using DOE-2, designers can easily determine building parameters that will improve the energy efficiency of a building. In order to perform an hourly simulation of the building and to estimate utility bills, DOE2 requires a description of the building's layout, construction plans, operating schedules, HVAC systems, utility rates and weather data (Group 1998). DOE-2 comprises of five subprograms: one is for translation of a user's input (BDL Processor); the rest of the subprogram include LOADS, SYSTES, PLANT, and ECONOMICS. LOADS, SYSTEMS, and PLANT are executed in sequence, with the output of Loads becoming the input for Systems, and the output of Systems becoming the input for Economics. After the simulation is completed, each of the simulation subprograms produce printed reports of the results of its calculations. The DOE-2 program is considered an accurate energy simulation program in terms of capabilities and reliability and thus, will be used in the proposed study.

The Building Loads Analysis and System Thermodynamics (BLAST) is an application which predicts the energy usage of buildings due to their heating and cooling needs, and provides the estimated cost of such energy usage using the Heat Balance Loads Calculator (HBLC) (BSO 1993). BLAST can also be employed to analyze the energy efficiency of recent as well as retrofit buildings because the heat balance method has long been recognized as a fundamentally sound approach to heating and cooling load calculations. The BLAST has limitations on daylighting and illuminantion calculations and controls (Crawley et al. 2000). Therefore, the BLAST energy simulation program may not be suitable for simulating the case study academic building and will not be used in this study.

Both DOE-2 and ESP-r BLAST require time to build a model and also to carry out the simulation because they are based on a UNIX operating system, which may be a constraint. For this reason, some adaptations, such as adding interfaces to make the DOE program more friendly were undertaken by the private sector in the USA. As a result of this, a commercial version with a graphic interface VisualDOE was developed by ELEY ASSOCIATES (1995) (Visual 2003), which utilizes the DOE-2E

UNIVERSITI KEBANGSAAN MALAYSIA

simulation tool for accurate estimation of energy consumption and peak demand, and is compatible with WINDOWS operating systems.

EnergyPlus is a new building performance simulation program with features from BLAST and DOE-2, along with new capabilities, including integrated simulation and multiple time step approach simulation (Crawley et al. 2001). By using an integrated solution technique, EnergyPlus can predict more accurate space temperatures for evaluation of system and plant size, and occupant comfort. EnergyPlus is being updated with increasing capabilities by linking it to other programs, such as the COMIS (Conjunction of Multizone Infiltration Specialists) airflow program and other special purpose programs. In the future, EnergyPlus is intended to replace the DOE-2 and BLAST programs. However, currently its use is unlimited to the firms and universities that created the program because of its simplicity with user interface program such as OpenStudio and design builder. Therefore, it will not be used in this proposed research.

According to Augenbroe (2002) a number of building and daylighting energy analysis software currently exist in the industry as well as numerous high end simulation applications have been developed for different building performance assessments over the last three decades.

2.5.1 Building Energy Simulation Programs

DOE-2 and BLAST are the two most popular building energy software funded by the U. S. Department of Energy (DOE), the United States Post office, and the U. S. Department of Defense. These two softwares have undergone numerous additions and improvements over the past 20 years. The simulation research group at Lawrence Berkeley Laboratory developed the DOE-2 simulation program (Winkelmann et al. 1993a, Winkelmann et al 1993b, and LBNL 2002). The BLAST (Building Loads Analysis and System Thermodynamics) application consists of a series of computer programs used to predict the energy usage of buildings, together with their associated cost as a result of their heating and cooling needs. Along with DOE-2 and BLAST, Lawrence Berkeley Laboratory has also developed other programs like SPARK

UNIVERSITI KEBANGSAAN MALAYSIA

(simulation Problem Analysis and Research Kernel), GenOpt (Generic Optimization program), BDA (Building Design Advisor), and PowerDOE (Al-Rabghi&Hittle 2001). The latest program developed by LBL (along with a team of other research institutes) is called EnergyPlus, which combines the capabilities of DOE-2 and BLAST program. The application is a stand-alone simulation program without a 'user friendly' graphical interface and display results in text files (Crawley et al. 2001).

ECOTECT is another important application developed by Square One Research Pvt. Ltd March 2003. This application does not only have the solar, heating and lighting features, but also includes acoustic and costing features with an embedded 3D modeling interface. Along with a superior user interface, this program is ideal for pre-design and design phases for solar shading and lighting analysis.

ENERGY-10, developed by the National Renewable Energy Lab (Balcomb 1998) and ENER-WIN, developed by Larry Degelman at Texas A&M University (Degelman 2002), are two other explicit building analysis program used in the industry for building energy simulations. The advantage of DOE-2 program is that the user has a clear understanding of what the input are and can predict what kind of result are to be expected. In addition, adequate experience with this program allows the user to investigate various parameters that might affect the end result. The disadvantage of the front-end computer programs is that the user cannot know what parameters are being applied in the background code and what kind of defaults are being applied in the simulations. Here, the proposed study will not use the DOE-2.1e building energy analysis program to perform lighting, cooling, and total electricity consumption for the academic building under analysis.

EnergyPlus program is a widely used and accepted free building energy analysis program that can predict the energy use and cost for all types of buildings. The EnergyPlus program provides an accurate estimate of the proposed building's energy consumption and cost. By using EnergyPlus, designers can easily determine building parameters that will improve the energy efficiency of a building. In order to perform an hourly simulation of the building and to estimate utility bills, EnergyPlus requires a description of the building's layout, construction plans, operating schedules, HVAC

UNIVERSITI KEBANGSAAN MALAYSIA

systems, utility rates and weather data (EnergyPlus 1996-2009). EnergyPlus comprises five subprograms: one is for translation of a user's input (BDL Processor) and the remaining four are LOADS, SYSTES, PLANT, and ECONOMICS. LOADS, SYSTEMS, and PLANT are executed in sequence, with the output of Loads becoming the input for Systems, and the output of Systems becoming the input for Economics. Each of the simulation subprograms produce printed reports of the results of its calculations.

The EnergyPlus program also includes a "daylighting calculation model". The effect of daylighting on the building cooling, heating, and electricity loads can be calculated using the daylighting model in conjunction with the LOADS and SYSTEMS functions. The daylighting input is required in the LOADS portion of an input file (Figure 2.8). The Daylighting Simulator in DOE-2 has three main stages: Daylight factor preprocessor, Hourly daylighting simulation, and Hourly control simulation. Daylight factors can be determined at user-specified reference point (Winkelmann 1998).

EnergyPlus has been widely validated by comparing its results with thermal and energy consumption measurements on real buildings. EnergyPlus has undergone to validation by U.S. Department of Energy (DOE) and many other laboratories and institutions and the program show that sufficient accuracy in energy prediction. The program validation gives confidence to users that the EnergyPlus results are reliable for building energy evaluation (Witte et al. 2001).

In one of the EnergyPlus validation researches, Loutzenhiser and Manz (2007) conducted and empirical validation of four building energy simulation programs, EnergyPlus, DOE-2.1E, TRANSYS-TUD, and ESP-r. In order to test different aspects of the programs' calculations, a sensitive analysis of the results of modeling solar gain through glazing unit with external and internal shading screens were provided. EnergyPlus, DOE-2.1E, TRANSYS-TUD, and ESP-r showed average percentage errors of 6.7%, 13.8%, 5.7% and 4.3% respectively; where EnergyPlus showed excellent credibility with 94% (Loutzenhiser et al. 2007). Table 2.9 presented

UNIVERSITI KEBANGSAAN MALAYSIA

comprehensive comparisons of the capabilities of building energy simulation programs.

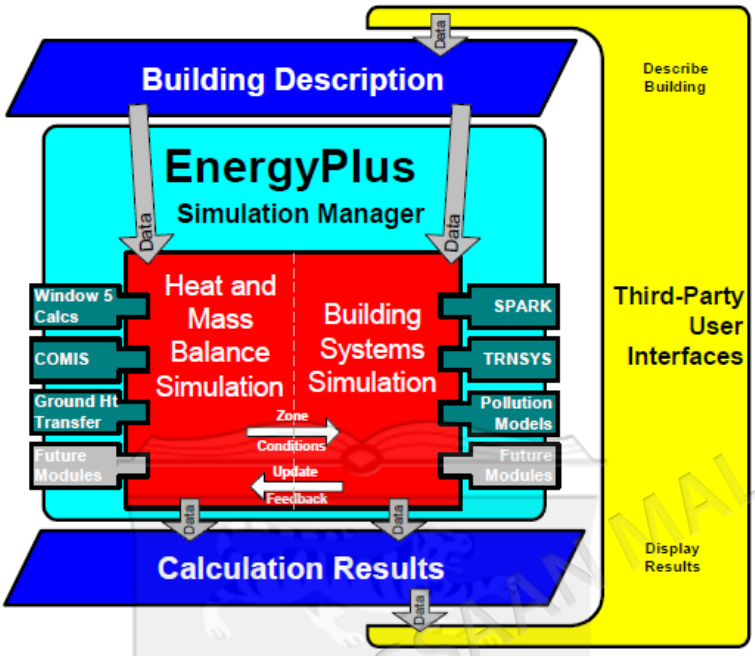


Figure 2.26 EnergyPlus overall simulation program structure

Source: Doe 2010

Thus, after reviewing the building energy and daylighting simulation programs, the proposed study will use EnergyPlus software as a building energy simulation program due to its excellent credibility and reliability for evaluating toplighting daylighting system performance.

OpenStudio7.0 is another advanced simulation application. OpenStudio uses EnergyPlus and RADIANCE to model the overall energy usage of buildings. OpenStudio includes graphical interfaces along with a Software Development Kit (SDK). The newer version of OpenStudio has SketchUp Plug-in, capability for Parametric Analysis, Run Manager, as well as an interface for viewing results. The SketchUp Plug-in enables the 3D modeling in the application. It provides a fast way of creating geometry together with the associated attributes using the inbuilt features. SketchUp is also interfaced with Google Earth, Building Maker, as well as Photo Match. The OpenStudio application is a graphical energy-modeling tool. It includes

UNIVERSITI KEBANGSAAN MALAYSIA

visualization and editing of schedules, editing of loads constructions and materials, a drag and drop interface to apply resources to spaces and zones, a visual HVAC and service water heating design tool, and high level results visualization (OpenStudio Software 2012).

Many programs have been reviewed. Among these programs the advanced simulation application OpenStudio7.0 with EnergyPlus simulation program was selected to be used in this study because of these main factors:

- It has been widely validated for accuracy and consistency.
- It offers a great capability for simulating a wide range of design features and energy conservation measures, including the integration of daylight with artificial light.
- It provides the ability for rapid development of energy simulations, reducing the time required to build a EnergyPlus model. Specifying the building geometry is much faster than other comparable software, making OpenStudio7.0 useful for schematic design studies of the building envelope or HVAC systems.
- OpenStudio7.0 also implements the daylighting calculations from EnergyPlus, making it possible to evaluate the integration of daylight with the artificial lighting system.
- The availability, sufficient training, and capability to maintain the program is another reason in the selection of OpenStudio7.0.

Therefor, the OpenStudio with EnergyPlus building energy and daylighting simulation program will be used in this study to determine the effect of toplighting shapes and geometries on the energy savings and daylight quality for an existing academic hall building in UKM, Kuala Lumpur, Malaysia.

UNIVERSITI KEBANGSAAN MALAYSIA

Table 2.9 Comprehensive comparisons of the capabilities of building energy simulation programs

General Modeling Features	**BLAST**	**DOE-2.1E**	**ECOTECT**	**Energy-10**	**ENER-WIN**	**EnergyPlus**
Full Geometric Description						
• Walls, roofs, floors	X	X	X		X	X
• Windows, skylights, doors, and external shading	X	X	X			X
• Multi-sided polygons		X	X			X
Import building geometry from CAD programs			X			X
Export building geometry from CAD programs			X			X
Import/ export model to other simulation programs			X			X
Number of surfaces, zones, systems, and equipment unlimited			X			X
Zone Loads						
Heat balance calculations	X	X			X	X
Building material moisture desorption	X					X
Element conduction solution method	X	X			X	X
Interior surface convection based on temperature	X					X
Internal thermal mass	X	X	X	X	X	X
Human thermal comfort	X		X			X
Design day sizing calculations						
• Dry bulb temperature	X	X	X	X	X	X
• Dew point temperature or relative humidity		X			X	X

Continued

UNIVERSITI KEBANGSAAN MALAYSIA

						Continued
Building Envelope, Daylighting, and Solar						
Solar analysis						
• Solar gain through blinds account for different transmittances					X	X
• Solar gain and daylighting calculations account from external building components			X			X
• Shading surface transmittance	X		X			X
• Shading device scheduling	X		X			X
• User-specified shading control			X			X
Advance fenestration						
• Controllable window blinds		X	X			X
• Electrochromic glazing			X			X
• Between glass shades and blinds			X			X
• Datasets of window types						X
• WINDOW 5 calculations						X
• Dirt correction factor for glass and visible transmittance			X			X
• Bi-directional shading devices						X
• User-specified daylighting control			X			X
• Window gas fill			X			X
Daylighting illumination and control						
• Interior illuminance from windows and skylights		X	X	X	X	X
• Stepped or dimming electric lighting control		X		X	X	X
• Glare simulation and control		X				X
• Daylighting illuminance maps			X			X
• Daylighting shelves			X		X	X
• Tubular daylighting devices						X
Continued						

UNIVERSITI KEBANGSAAN MALAYSIA

						Continued
Sky model						
• Isotropic	X		X	X		
• Anisotropic		X	X		X	X
Zone surface temperatures	X		X		X	X
Climate Data Availability						
Weather data provided						
• With the program	X		X	X	X	X
• Separately downloadable			X		X	X
Estimate diffuse radiation from global radiation		X			X	X
Weather data processing and editing	X	X	X	X	X	X
Weather data formats directly read by program						
• Any user-specified format			X		X	X
• EnergyPlus/ESP-r			X			X
• Typical Meteorological Year	X	X	X			X
• Typical Meteorological Year 2	X	X	X	X	X	X
• International Weather for Energy Calculations			X			X
• DOE- text format		X	X			X
• PLAST text format	X		X			X
• ESP-r text format						X
• ECOTECT WEA format			X			X

X feature or capability that is available and in common use

UNIVERSITI KEBANGSAAN MALAYSIA

2.5.2 Daylighting Energy Simulation Programs

A number of computer programs for daylighting energy analysis have also been developed by the Windows and Daylighting Program instituted at the Building Technologies Department, Lawrence Berkeley National Laboratory (LBNL 1994).

RADIANCE which is a high precision free application was developed in collaboration with the U. S. DOE and the Federal Government of Switzerland. The performance metrics of the application are spectral radiance/irradiance and the glare indices; and various result formats are supported such as colored images, numerical results as well as contour plots. One significant benefit of RADIANCE is its ability to simulate almost every material without any limitation on the geometry. Being a suitable choice for engineers and architects, RADIANCE helps in the prediction of illumination, visual quality, as well as the quality of innovative designs and daylighting systems. Another reason for the wide use of RADIANCE is its simulation accuracy, ability, and extension, as compared to other simulation programs (LBNL 1997).

DAYSIM (Dynamic daylight simulation) and SkyVision are also novel simulation tools developed by the National Research Council of Canada (Laouadi 2004; Reinhart&Jones 2004). According to the research team at NRC, DAYSIM is daylighting analysis software that calculates the annual daylight availability in arbitrary buildings as well as the lighting energy use automated lighting controls (occupancy sensors, photocells) compared to standard on/off switches (Reinhart & Jones 2004). SkyVision is another specialized tool for daylighting calculations using skylights and overall lighting energy analysis (Laouadi 2004).

In study by Bryan and Autif (2002), four simulation programs were compared to study their individual modeling capacities. Desktop Radiance was found to be the most accurate for lighting calculations but was termed non-user-friendly, and Lightscape performed the best rendering of interior spaces but was inaccurate in sky modeling. Lumen Micro and RadioZity were not considered good lighting programs

UNIVERSITI KEBANGSAAN MALAYSIA

due to their inaccuracies in building complex room geometries (Bryan and Autif 2002).

VisualDOE also provides analysis results on the different performance criteria of daylighting. VisualDOE provides detailed daylight factor summary report for the four sky conditions for each space in the project with daylighting. It includes most of the detailed information used by EnergyPlus in making daylighting calculations. Space daylighting summary report is also produced to give monthly-average lighting energy reduction, illuminance, and glare for each daylight space. If only one lighting reference point is specified, the entries under REFPT 2 will be zero. Average daylight illuminance, which gives the average illuminance due to daylighting reference point, is also provided. For each daylit space, a report is produced to give the monthly lighting energy reduction due to daylighting for each hour of the day, and for all hours of the day combined (including nighttime hours). The monthly daylight-illuminance frequency-of-occurrence distribution at each lighting reference point is provided. If only one lighting reference point is specified, the entries under REF PT 2 will be zero (Tools 2001).

Although a lot of daylighting software is available in the industry, most of these programs can be used only to conduct daylighting simulations, and do not include building energy analysis. The proposed study will use the OpenStudio7.0, which uses the EnergyPlus energy simulation software which developed by the U.S. Department of Energy (DOE) which incorporates a daylighting calculation tool along with the building energy analysis program.

2.6 PREVIOUS CASE STUDIES IN HOT-HUMID CLIMATES

This section is present case studies related to daylighting systems and their energy and lighting performance in Malaysia and hot-humid climate. The majority of these studies were focused in non-academic buildings, such as offices, malls, hotels, etc., and few of those studies considered the education sector.

Ahmad (1996) and Ahmad and Rasdi (2000) had identified 8 commercial buildings around Kuala Lumpur that were built with toplight and sidelight atria. The

UNIVERSITI KEBANGSAAN MALAYSIA

buildings were analyzed using DF method to evaluate the daylight level for both design type. Two modeling approaches, namely, computer modeling using Radianc and physical model evaluation under artificial sky were chosen as the research methodology. The finding showed that sidlit atria have considerable potential to be used in tropical climates because the design adapted well in both overcast and clear sky conditions. Sidlit spaces were also observed to be providing pleasant interior illumination with minimum glare compared to toplight spaces. With excessive daylighting of up to 28% of DF during clear sky condition, toplight spaces unfortunately suffer from overheating and over lit. This particular type of atria (i.e. toplight) implementation in tropical building was therefore concluded to be unfit unless mechanical environment controls were installed (Ahmad & Rasdi 2000).

Zain-Ahmad et al. (2002) discussed the effects of interior illumination of the room due to their openings. Seven sizes of window opening from 10% to 40% of the total floor area were used in a room of 3m (length) by 4m (width). The results were then made to improve energy efficient measures for the buildings. Artificial sky was used to test the model fitted with windows of different sizes of opening. The results showed that window to floor ratio (WFR) value of 0.40 will provide adequate daylight into a space and will definitely reduce energy consumption of electric lighting. Furthermore, less heat is dissipated from artificial lighting system.

Zain-Ahmad (2000) had concluded the Malaysian daylight design criteria within ten to eight kilolux during working hours from 8a.m. to 5 p.m. The illuminance range consumed 76.5% of the working hours. Meanwhile another 16.2% of working hours received sky illuminance that exceeds eight kilolux bringing the total illuminance above ten kilolux to 92.7%. Therefore she stressed that the daylight design criteria for Malaysia is recommended to be ten kilolux and fall within CIE range of intermediate sky (Zain-Ahmad 2000).

In hot and humid climate, one drawback of using shading devices is the risk to reduce natural-light (direct sunlight & daylight) level and as a consequence increases in use of artificial lighting. What makes natural-light utilization so interesting is that in terms of building energy use it reduces the electricity consumption for lighting and

UNIVERSITI KEBANGSAAN MALAYSIA

indirectly reduces the cooling demand through reduction of internal heat load from lights. However, there is abundance of natural-light in the tropics has not been utilized to the optimum or either it has not been considered as design criteria (Zain-Ahmed et al. 2002) and (Ahmed 1996). The main drawback is maximum natural-light availability is usually concurrent with solar heat gain, especially in hot humid climate like in Malaysia.

The external shade is the simplest and most effective form of controlling heat gain through windows. However, as discussed in the previous section, the potential for daylighting is severely reduced. Most window wall buildings in the sub tropics and tropics use highly reflective or tinted glass and venetian blinds to control radiant heat gain. Venetian blinds can be closed to reflect sunlight outwards or opened to admit low angle daylight and reflect sunlight inwards. However, when closed, venetians severely restrict view and reflective / tinted glass reduces the potential for daylighting (Edmonds & Greenup 2002).

Study conducted by Ossen et al. (2005), investigates the effect of six different alternatives of external horizontal shading devices on incident solar radiation, transmitted solar heat gains, natural light penetration and energy consumption. The study was carried out using a standard, single fenestration perimeter office room in a typical high-rise office building. The investigation is conducted using the eQUEST-3 dynamic energy simulation program supported by the DOE2.2 calculation engine. The results revealed that overhang ratios of 1.2, 1.6, 0.6 and 0.8 reduced the incident direct solar radiation more than 80% on the east, west, north and south orientations respectively. The target illuminance of 500lux for internal lighting was obtained for overhang ratios of 1.0, 1.3, 0.2 and 1.0 on respective orientations. The findings also revealed that optimum energy savings of 14%, 11%, 6% and 8% were achieved by optimum overhang ratios of 1.3, 1.2 and 1.0 on the east, west and north, south orientations respectively (Ossen et al. 2005).

A recent study conducted by Lim et al. (2013) investigate internal shading device to improve daylighting quality in contemporary high-rise open plan offices. A base model was derived from previous case studies for simulation using Radiance.

UNIVERSITI KEBANGSAAN MALAYSIA

Various venetian blinds, vertical blinds and light shelves were configured for the experiment. Daylight factor (DF) was evaluated for quantitative performance; work plane illuminance (WPI) distribution and vertical plane luminance ratio were investigated for qualitative performance. The findings demonstrated that generally blinds were not a good potential for daylight utilization but good in reducing luminance contrast. Light shelves improved performances in DF and WPI distribution but increased the luminance contrast. In addition, the integrations of light shelves and partial venetian blind (45° closed) were proposed as the effective designs for all orientations. The highest improvements of 31.8% in WPI distribution and 66.7% in luminance ratio were achieved for south and east orientations, respectively. Furthermore, the study demonstrates that with proper internal shading design, effective daylighting depth can be significantly improved from typically used 2.5 H rule of thumb (2.5 times of the height of window) to 3.6 H (Lim et al. 2013).

In tropical regions natural daylight has been a fundamental factor in building design. It is the most efficient way of lighting a building in the daytime and has a great potential for energy conservation in buildings (Djamila et al. 2011). Zain-Ahmed et al. (2002) proved that minimum energy saving of 10% can be achieved from simple daylighting strategies alone in Malaysia.

Many studies in Southeast Asian region shows that using of day lighting strategy in building can decrease the demanding on the energy consumption by 20% and help to overcome the problem of increasing of sensible heat load on air-conditioning (Hastings 1994). In tropical countries such as Malaysia daylighting which is considered as an approach for passive energy efficiency because of its long hours of sun shine throughout the entire year in addition to the enormous daylight luminous in Malaysia. This characteristic could meet most of the luminance internal demand within a day that could direct in considerable proportion of energy saving (Ibrahim & Zain-Ahmed 2007).

A study conducted by Ibrahim and Zain-Ahmed (2007) To account daylight availability in an office interior under various fenestration options; namely window-wall-ratio (WWR), glass types and application of external shading devices of varying

UNIVERSITI KEBANGSAAN MALAYSIA

depth. The study used IES RADIANCE software and the Daylight Factor method to analyze its outcome. Daylight Factor (DF) was used as the basis to estimate the percentage of daylit floor area of a generic 4.5m deep office cell. The optimum WWR to achieve the maximum percentage of daylit floor area for a 4.5m deep room are 40%, 55% and 65% for clear, tinted and reflective glass, respectively. The results from the daylight availability study also shows that application of simple horizontal shades does not significantly affect the amount of daylight indoor. In fact, application of external shades improves the daylight distribution whereby the illuminance intensity in areas closer to the windows were reduced, providing a gentle daylit indoor.

Recently, Mahdavi (2013) studied the impact of Window-to-Wall Ratio (WWR) as one of the passive design strategies to optimize daylighting in high-rise office buildings in Kuala Lumpur as a recommendation for building designers to use it at the early stages of design. This study was carried out by simulations on IES-VE software by using RADIANCE program for calculation of the daylight distribution due to WWR on daily basis during office hours. An investigation on the optimum amount of window size has been done by studying an office room model with 6m × 6m × 4m dimension. WWR was considered from 20% to 50% at 5% interval in two types of expanding method of window namely vertical and horizontal. The results revealed that 25% WWR is the best in vertical expanding as well as 35% WWR have more suitable daylight in horizontal expanding in sunny sky for a hypothetical office room (Mahdavi et al. 2013).

Hunn et al. (1993) also presented the results of a study of the effect of shading devices on annual heating, cooling, and total energy use, peak electric demand, and energy cost savings in a school as well as residences, a small office, and a high-rise office in Minneapolis, Minnesota. To estimate energy savings, the DOE-2 building energy simulation program was used. Surprisingly, the results showed that the annual energy savings for the school were less than 1%. This value is much less than the annual savings for the residence (4%), the small office building (5%), and the high-rise office building (5%) in the same climate.

UNIVERSITI KEBANGSAAN MALAYSIA

A study by Treado et al. (1984) tested the impact of window, skylight, and clearstory daylighting systems using building energy analysis software on the annual energy performance of buildings (Treado et al. 1984). It concluded that the skylight is the most efficient system for curtailing the overall energy used for heating, cooling, and lighting of a building. This study, however, tested the efficiency of each system for latitude 38°N i.e., Washington DC, and the results could be different if tested in other latitudes and climates.

Another study by Place et al. (1984) tested the potential lighting electricity reductions and associated thermal impacts of replacing electric light with sunlight admitted through roof aperture glazing on a single-story, prototypical office building and found that a combination of east-facing and west-facing glazing reduced energy cost more than a south-facing glazing. This study used BLAST3-0 building energy analysis program and then chose two roof lighting options in order to predict reductions in lighting electricity and the impacts on energy consumption for heating and cooling the building. It concluded that the study need for more design options, as it only tested a south-facing glazing and a combination of east-and west-facing glazing. The results also indicated that a large portion of the electricity consumed for lighting can be displaced using modest amounts of glazing on the roof. Also, both heating and cooling energy consumption reduction are possible for a daylighting system, but they are substantially smaller than the potential lighting electricity reductions.

This study, however, analyzed only the roof monitor type of daylighting option for a hypothetical office building and differs from the proposed study which will analyze skylight, saw-tooth, and roof monitor options for an existing multi-purpose hall building. Also, in this study the test location was in the U.S. in high-latitude location. The results might be different if tested in a low-latitude, hot and humid climate, since there is no heating period. Also in this study, the south-facing glazing was chosen, because it admitted more light in the winter than in summer. This criterion will be less significant in hot and humid climates, as heat is not needed at any time of year.

UNIVERSITI KEBANGSAAN MALAYSIA

Another study by Cabús and Pereira (1996) tested the performance of toplighting systems, including a skylight, clerestory, and roof monitor, along with their associated heat gain for locations in the tropics at latitude 0^0. By using the ratio of light output to heat gain (SSLE), the study showed that the skylight has the lowest SSLE ratio among the three options. In addition, the study has proven that the energy performance of daylighting system differs based on location and weather conditions. The test in this study used only clear sky conditions. Thus, the optimum system for overcast sky was not examined. In addition, lighting performance parameters were not analyzed, because the study emphasis was on energy performance rather than lighting performance.

A study by Garcia-Hansen et al. (2002) outlined possible energy savings and the better performance achieved by three toplighting systems strategies skylight, roof monitors and clerestory roof windows and element arrangements across the roof in zones of cold to temperate climates typical of central and central-southern Argentina at latitude 35^0S. Analyses were undertaken considering daylighting, thermal, and ventilation performance of the different strategies. The study concluded that, for thermal aspects, the most energy savings reached for the different strategies were 43.16% for clerestories, 41.4% for roof monitors and 38.86% for skylight for a glass area of 9% to the floor area. The study also suggests that skylight should be used for locations with predominant cloudy sky conditions but not for locations with heat gain problem. For predominant clear sky types, the authors recommended clerestories roof windows. The study also noted that roof monitors had the best combined results in terms of lighting and thermal effects and also suggested for use under variable sky conditions.

The test cases for this study, however, used only one type of glazing, which is clear glass. Thus, the optimum system for glazing type was not examined. In addition, if the test was done under constant thermal performance across the test cases, lighting performance could have been analyzed more efficiently. Because of this, the results might be different if tested under different glazing areas, types of glazing and at other latitudes.

Another study by Kim et al. (1985) analyzed daylight of classroom and atrium at Texas A&M University building through comparison of daylighting data from a computer program, a scale model of building, and a constructed full-scale building measurements to illustrate the potential of using daylighting design methods to reliably predict actual building daylighting performance. As part of the daylighting analysis for the classroom, actual daylight levels were measured at 20 points inside the spaces, and daylight factors were calculated through the use of a computer program called MICROLITE. The study showed that the computer generated daylight levels in the classroom were highly correlated or proportional to the measured daylight levels, but were almost twice the measured levels. The differences were due to the presence of actual classroom's furniture and other objects that absorb light energy. The scale model daylight levels in the atrium were overestimated by about 30%. The discrepancies between the actual measurements and the scale model measurements was attributed to high reflectance of scale model materials compared to the average reflectance in the actual building.

The research by Dewey and Littlefair (1998) investigated daylighting performance, but not the energy performance, of different toplighting systems. They focused on analyzing the performance of daylighting in terms of the uniformity of illumanance level of six toplighting systems including skylight, clerestory, and roof monitor systems. The test were employed in order to attain the standard spacing-to-height ratios of each toplighting system and which system gave the most flexibility corresponding to the interior lighting standards enshrined in the CIBSE Code. The study concluded that the roof monitor system gave the most even illumination than other systems, since it had the largest spacing-to-height ratio that still met the uniformity guidelines.Table 2.7 presented a summary for previous studies.

However, the study is for lighting performance only. Energy performance was not included; therefore, the systems are not energy comparable. In addition, the test was done under overcast sky conditions, which is the predominant sky type of the United Kingdom. Because of this, the results might be different if tested under other sky types and other latitudes.

UNIVERSITI KEBANGSAAN MALAYSIA

2.7 SUMMARY: THE GAP IN THE LITERATURE REVIEW

This literature review reveals some gaps in the literature related to toplighting daylighting systems as follows:

- Most previous researches on daylighting systems do not reflect different toplighting shapes, geometries and modern glazing attributes for using toplighting in buildings. This study evaluates various shape, geometries, and glazing types and applications.
- Most of previous researches were conducted in cold-climate countries and only a few studies in locations close to the equator like Malaysia.
- Only a few researches addressed toplighting shapes and geometries. Regardless of the potential for energy savings, integration of daylighting with artificial lighting by lighting control system is still not applied in building because of their cost and difficulty.
- Not all parameters that affect the energy savings in building have been evaluated entirely. This study expands on the previous studies by evaluating parameters such as toplighting shape, glazing area, glazing types and orientations.
- Detailed simulation researches have not been carried out with toplighting daylighting systems. This research will use EnergyPlus with OpenStudio SketchUp Plug-in as an energy and daylighting analysis program because of its credibility as software for evaluating toplighting systems performance.
- Some studies have been carried out to evaluate the performance of toplighting in terms of energy and lighting quality. However, a few researches have been carried out for tropical climates like Malaysia. The conclusions could be different for the tropical climates, because of the shortage of a heating season.

UNIVERSITI KEBANGSAAN MALAYSIA

Table 2.7 Summary Table for Previous Studies

No	Author	Classification	Application	Climate Zone	# Bldgs Analyzed	Size (m^2)	Energy Use Analysis	Energy savings	Comment
1	Zain-Ahmed et al. 2002	Daylighting strategies	Size of windows	Malaysia Tropical	1	6741	M,S	10%	Total energy savings
2	Ibrahim and Zain-Ahmed 2007	Various fenestration options	External shading devices	Malaysia Tropical	1	18	S	N/A	Optimum WWR are 40% and 55%
3	Ahmad and Rasdi 2000	Toplight and sidelight atria	Commercial buildings	Malaysia Tropical	8	N/A	M,S	N/A	Sidelight atria adapted in tropical climates
4	DR Ossen et al. 2005	Shading devices	Office room	Malaysia Tropical	1	36	S	6%-14%	Total energy savings
5	Lim et al. 2013	Shading device	High-rise open plan offices	Malaysia Tropical	1	69.12	S	N/A	Improvements of 31.8% in WPI and 66.7% in luminance ratio
6	Djamila et al. 2011	Daylighting in building	Room	Malaysia Tropical	1	17.5	S	N/A	Highlights the importance of Sun path diagram
7	Mahdavi et al. 2013	Window-to-Wall Ratio (WWR)	High-rise office buildings	Malaysia Tropical	1	36	S	N/A	25% WWR is the best and 35% WWR more suitable daylight
8	Hunn et al. 1993	Shading device	School residences, and office	Cold and Humid	4	5086	S	1%-5%	Total energy savings
Continued									

UNIVERSITI KEBANGSAAN MALAYSIA

									Continued
9	Treado et al. 1984	skylights, windows, and clerestories	Commercial single floor	U.S.A.	1	232.3	S	65%	Lighting energy savings
10	Place et al. 1984	Roof aperture glazing	Single-story commercial building	U.S.A.	1	930.3	S	N/A	East-facing and west-facing glazing reduced energy cost more than a south-facing glazing
11	Cabús and Pereira 1996	Toplighting Skylight, clerestory, and roof monitor	Room model	Brazil Tropics at latitude 0^0	3	35	S	N/A	Energy performance of toplighting differs based on location
12	Garcia-Hansen et al. 2002	Toplighting skylight, roof monitors and clerestory	Rectangular room	Argentina cold to temperate	1	42	M	N/A	SSR 43.16% for clerestories, 41.4% for roof monitors and 38.86% for skylight
13	Dewey and Littlefair 1998	Toplighting systems skylight, clerestory, and roof monitor	A single-story scale model	UK	1	1350	M	N/A	Generate recommended spacing-to-height ratio corresponding to CIBSE Code

** M: Actual measurement*
S: Simulation

UNIVERSITI KEBANGSAAN MALAYSIA

CHAPTER III

RESEARCH METHODOLOGY

3.1 INTRODUCTION

This chapter describes the simulation methodology used in this study. This chapter is comprised of sections on developing a computer simulation model of the case study building using EnergyPlus version 7.0, validating the case study simulation results, comparing the actual building utility bills with the computer simulation results, and modeling toplighting systems options, alternatives simulation parameters, the energy performance evaluation methodology, and the daylighting performance evaluation methodology. A flow chart of the methodology used in this study is presented in Figure 3.1. The methodology used is explained in details in the next sections of this chapter.

3.2 STEPS OF THE METHODOLOGY

3.2.1 Case Study Building Data Collection

The UKM academic hall building investigated is one of the four academic halls at the Universiti Kebangsaan Malaysia (UKM). Monthly electricity consumption data (based on utility bills) for the past two years were obtained from the Department of Development Management at the UKM campus. As-built architectural, electrical, and mechanical drawings were also obtained from the same Department. Relevant hourly weather data for Kuala Lumpur city and the university campus, occupancy schedules, system schedules, occupants' density, lighting power density, equipment power density, and mechanical systems information for the selected hall were also

UNIVERSITI KEBANGSAAN MALAYSIA

obtained. These drawing and schedules helped determine all of the systems used in the case study building, and the data and schedules formed a major part of the building energy simulation program input data.

Building construction, mechanical, and electrical details were obtained from the Jabatan Pengurusan Pembangunan (JPP or Department of Development Management) office after official interviews. The Department office had well-documented original drawings and building specifications of the selected building. Black-and-white prints of these architectural, mechanical, and electrical design drawings and construction details were provided by the Department and formed the basis part of modeling the case study input file for the EnergyPlusV0.7 energy simulation program. The architectural, mechanical, and electrical drawings were further verified with the actual case study building through a series of visits to the selected academic hall building.

Permission to conduct the study at the Dewan Tun Abdullah Mohd Salleh academic hall was obtained from the 'Research Administration' of the Department of Development Management. This permission included site inspection (walk-through) and regular visits to the hall building to verify the building drawings, and to measure daylight level inside the case study building for daylighting analysis. A representative of the academic hall was present during the visits and daylighting measurements. This study would have remained in-complete without the permission of the JPP because the walk-through and visits to the case study building are a very important part of our research.

3.2.2 Case Study Building Description for Simulation

Data on the academic hall under consideration data were used to model the case study building and the schedules and systems information for the loads and systems inputs in the OpenStudio V-7 input file. These data will be useful in calibrating the base case simulation model in OpenStudio V-7. Monthly data on the total building electric energy consumption (utility bills) for the selected case study building of the past two years were also obtained from JPP. The case study modeling was adjusted to the

UNIVERSITI KEBANGSAAN MALAYSIA

monthly data for the building energy consumption and exact lighting, cooling, equipment, and occupancy schedules. These schedules were an essential part of the calibration process for the base case model. Two other sensitive input parameters specific to building an envelope, namely U-value for the walls and roof and infiltration rate were also tested to calibrate the base case. A final case study simulation model was created by adjusting certain building parameters and then comparing the OpenStudio V-7 simulation result with the actual utility bills.

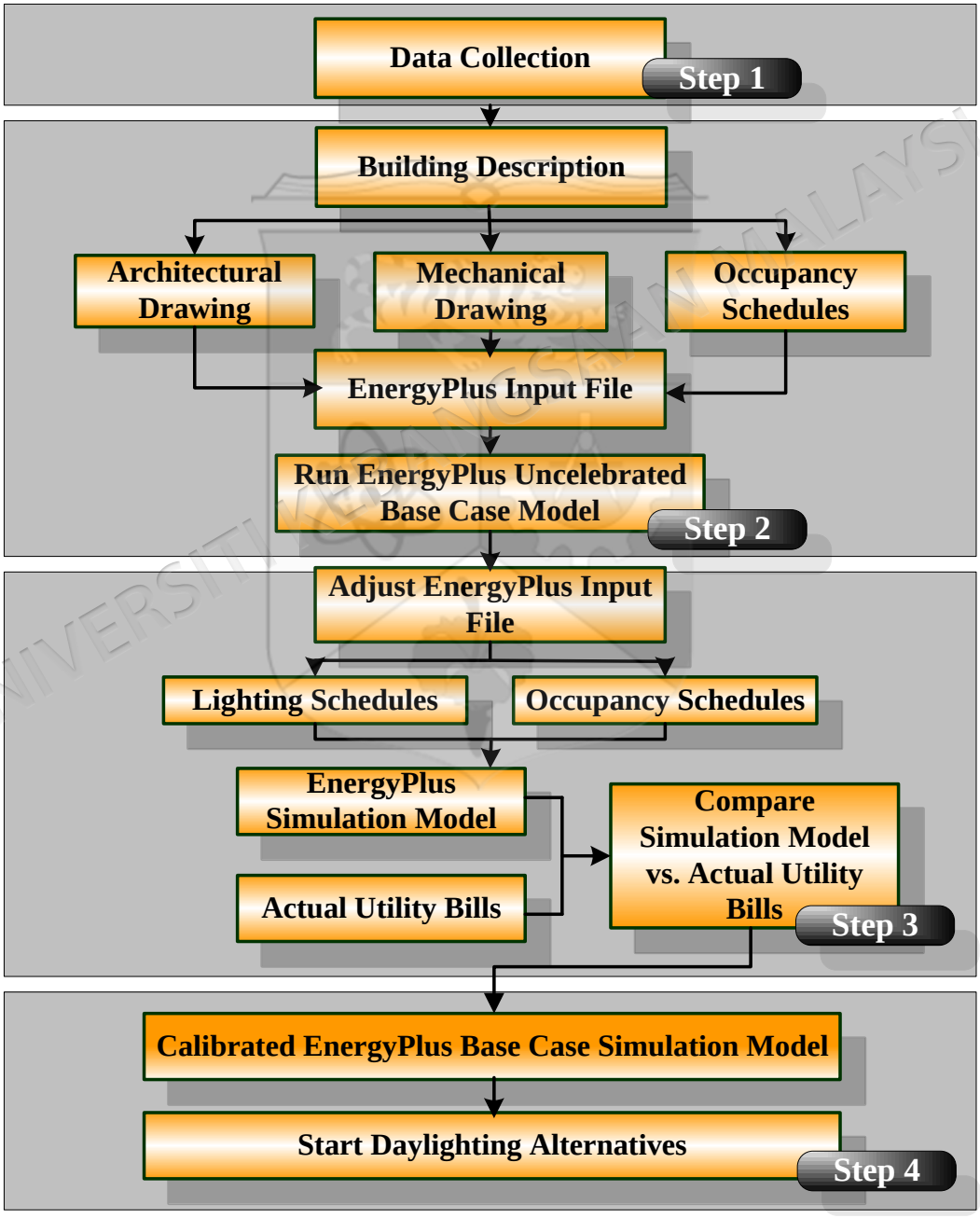


Figure 3.1 Basic flow chart guide of research methodology

3.3 CASE STUDY BUILDING DESCRIPTIONS

3.3.1 General Building Description

The academic hall under analysis has a total area of 2078 m^2. The hall building has an exterior wall structure, with a 151 mm-thick brick wall with cement, 15 mm plaster, and paint on both sides. The roofing is a built-up type with a metal roof installation deck equivalent 0.48 mm in thickness, colored, and 50 mm-thick fiberglass insulation as well as a layer of chicken wire mesh. The floor is a lightweight 4" concrete slab construction with 20 mm terrazzo tiles with cement in the corridors and space hall. The entire building is single story, and the front elevation faces south. Figure 3.2 presents a floor plan of the academic hall building. Figure 3.3 presents the east and west elevations of the academic hall.

3.3.2 Case Study Building Description for the Simulation

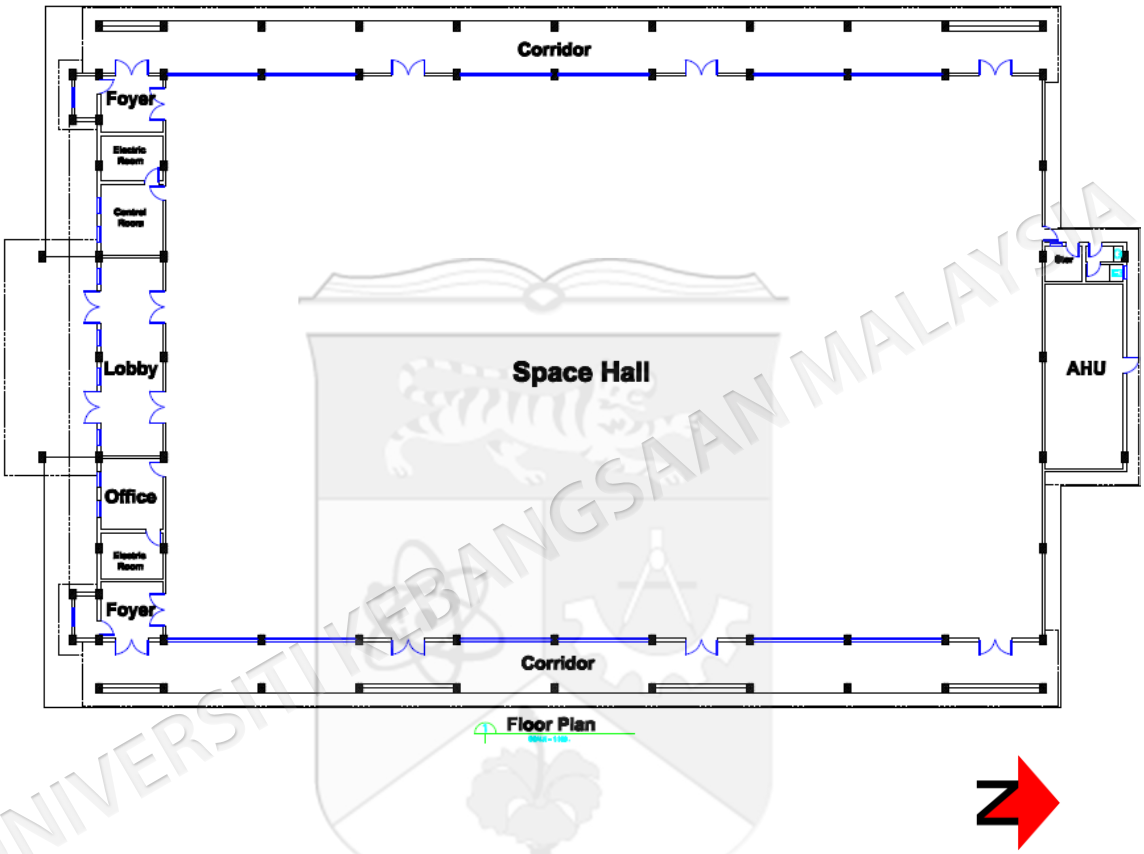
This study primarily aims to determine the effect of daylighting coming into the working surface through various shapes and geometries of toplighting systems on the total building energy consumption and its effect on interior daylight levels. The UKM hall case study represents a base case for the simulation parametric analysis to be conducted to evaluate the effect of various shapes of toplighting design parameters on energy and daylighting performance.

The energy and daylighting performance evaluation focused on the hall shown in the core academic building plan. The long side of the UKM hall building was at 0 degrees to the north-south axis, and the main entrance side of the building faced south. A plan of the UKM hall academic building is presented in Figure 3.2, and prespective, east and west elevations are presented in Figure 3.3.

The total floor area of the case study building under analysis was 1890 m^2. This area represented approximately 91% of the total hall area. The dimensions of the hall space under analysis were 35 m width x 54 m length x 6 m floor-to-ceiling height. Interior photographs of the case study building were taken with permission from the

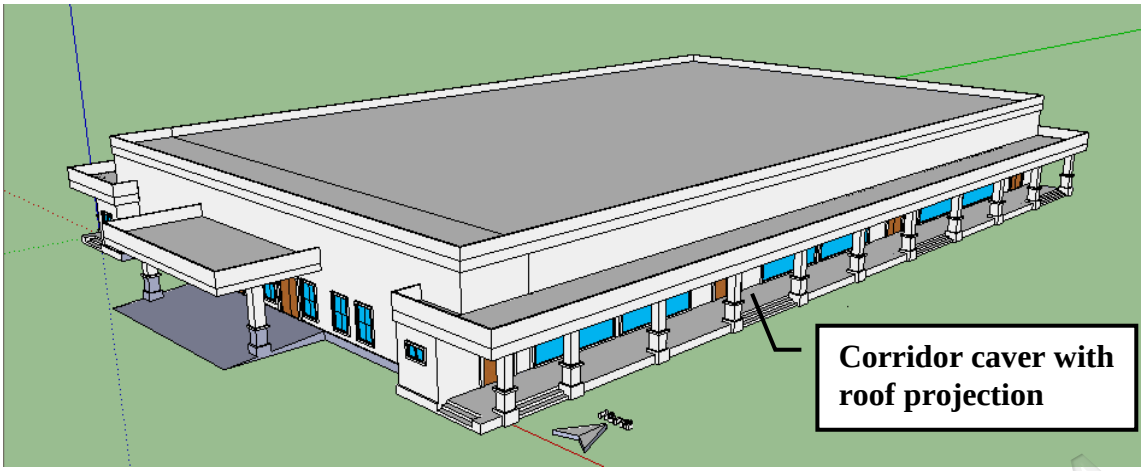
UNIVERSITI KEBANGSAAN MALAYSIA

JPP and are presented in Figure 3.4. The exterior walls and roof system specifications of the case study building were obtained from the JPP, and the U-values of the exterior walls and roof system were measured using EnergyPlusV-7. The case study building main characteristics are described in Table 3.1.

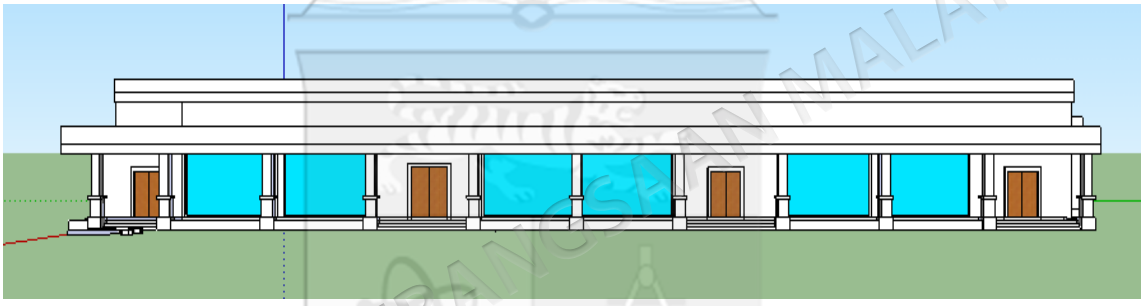


UNIVERSITI KEBANGSAAN MALAYSIA

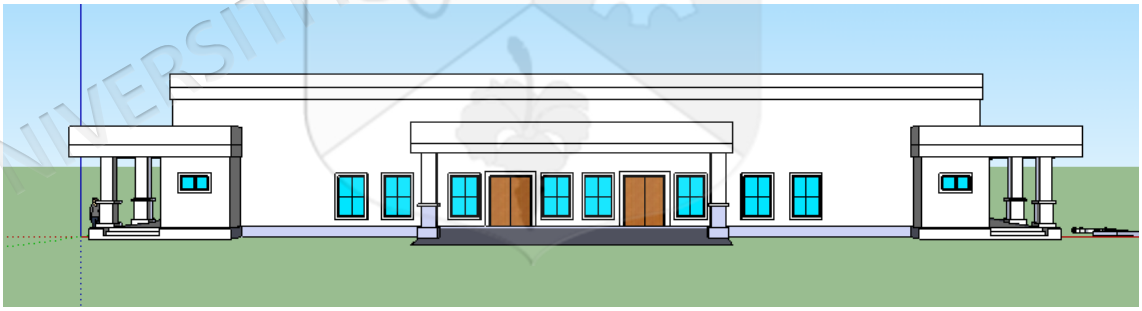
Figure 3.2 Floor plan of case study UKM academic hall



(a) Perspective



(b) East elevation



(c) South elevation (main entrance)

Figure 3.3 Perspective and elevations of UKM academic hall: Perspective (a) east elevation (b) and south elevation(c)

UNIVERSITI KEBANGSAAN MALAYSIA

(a) The case study hall when artificial lighting is ON

(b) The case study hall when artificial lighting is Off

(c) Case study exterior corridor and sidelight system photographs

(d) Case study interior sidelight system photographs

Figure 3.4 Interior and exterior photographs of UKM case study building: (a) when artificial lighting is ON (b) when artificial lighting is Off, (c) photographs for exterior corridor and sidelight system, and photographs for interior sidelight system

Table 3.1 EnergyPlus input case study building characteristics used for simulation modeling

Component	Description				
Location	Kuala Lumpur (Latitude 3°.12' North, Longitude -101°.55' East, Time Zone +8, Altitude. 22 m)				
Plan Shape	Rectangular				
Number of Floors	One-story building				
Window-Wall-Ratio [%]	**Total**	**North**	**East**	**South**	**West**
	24.27	0	40	0	40
Corridor Roof Projection	3.7 m on east and west exposures				
Corridor Roof Height	3.7 m				
Construction Date	2004 from actual data				
Floor-to-Ceiling Height	6 m from actual data				
Floor Dimension	54 m × 35 m × 6.0 m from actual data				
Net Building Area	1890 m^2 estimate from actual data				
Number of Zones	One zone from actual data				
Zone Type	Conditioned				
Number of People (Max)	630 students				
Lighting System Type	Holophane Crystal G. 400 watt from the actual data				
Exterior Wall Structure	151 mm thick. Brick wall with cement 15 mm plaster and paint on both sides Calculated U-value = 2.19 $W/m^2.^{\circ}C$				
Roof Structure	Metal roof deck equivalent 0.48 mm thick, colored 50 mm thick. Fiber glass insulation 1 layer of chicken wire mesh Calculated U-Value = 0.6 $W/m^2.^0C$				
Ground Floor Structure	100 mm concrete slabs 20mm terrazzo tile with cement Waterproof layer Calculated U-value = 1.21$W/m^2.^{\circ}C$				
Continued					

UNIVERSITI KEBANGSAAN MALAYSIA

Continued

Window Glazing Attributes	**Single Bronze 6mm**	
	Number of Panes	Single pane
	Tint	Bronze
	U-Factor	5.778 W/m^2-K
	Solar Heat Gain Coefficient	0.62
	Visible Light Transmittance	0.534
	Shading Coefficient	0.72
Surface Reflectance	80% for ceiling, 50% for walls, and 20% for floor	
Occupant Density	4 m^2/person, from actual data	
Lighting Power Density	13.5625 W/m^2, from actual data	
Equipment Power Density	2.906 W/m^2 , approximate value	
Infiltration (Air-changes/hour)	0.5 ACH average tightness building EnergyPlus 7.0 reference manual	

The case study building air-conditioning system and artificial lighting system are essential systems in building design that directly affect building energy consumption. The case study building under analysis uses the package terminal air-conditioner system and is selected in the EnergyPlus object as a terminal unit for case study modeling spaces. The package air-conditioning system object supplies either cooling or heating to the space in sufficient quality to meet the space loads. The air-conditioning system uses electricity for operations. The cooling design temperature (thermostat) was set to 24°C during occupied hours and 27°C at night. Cooling was only available year round. For the weather file, this study uses the Kuala Lumpur weather file available in the EnergyPlus website as a weather file selection. The main features of the case study air-conditioning system are presented in Table 3.2. The daylight hours of Kuala Lumpur, Malaysia is presented in Table 3.3

UNIVERSITI KEBANGSAAN MALAYSIA

Table 3.2 Main characteristics of case study building air-conditioning system

Characteristics	**System Description**
System Type	2 Packaged System
Total Capacity	2* 965,000 BTU/HR
Supply Air (Air Flow)	2* 24,300 CFM
Cooling Set Point Temp.	24 °C
Cooling Only	Available year round, and heating may not be required
Weather File	Kuala Lumpur weather file available in EnergyPlus webside
Climate Type	Tropical wet (no dry season, rainforest, hot all year)

Table 3.3 Daylight Hours of Kuala Lumpur, Malaysia

Month	Sun Rise Time		Sun Set Time		Daylight Hours		Average Daylight Hours
	1st Day	Last Day	1st Day	Last Day	1st Day	Last Day	
January	7:19	7:27	19:12	19:23	11:53	11:56	**11:57**
February	7:27	7:24	19:24	19:26	11:57	12:02	12:01
March	7:24	7:13	19:26	19:22	12:02	12:09	12:05
April	7:12	7:05	19:21	19:18	12:09	12:13	12:11
May	7:02	6:59	19:17	19:20	12:15	12:21	12:15
June	6:59	7:04	19:20	19:26	12:21	12:22	12:17
July	7:05	7:09	19:27	19:28	12:22	12:19	12:16
August	7:09	7:07	19:28	19:20	12:19	12:13	12:12
September	7:07	7:00	19:18	19:06	12:11	12:06	12:07
October	7:00	6:56	19:05	18:55	12:05	11:59	12:02
November	6:57	7:03	18:55	18:57	11:58	11:54	**11:58**
December	7:04	7:18	18:58	19:11	11:54	11:53	**11:56**

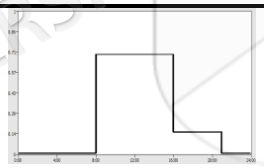
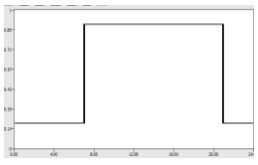
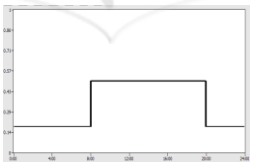
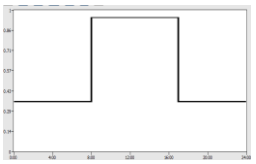
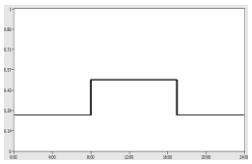
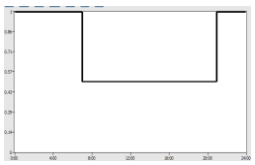
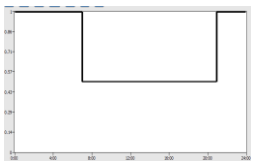
Source: www.clamatemap.com

The building occupancy schedules are critical factors in the simulation modeling because they directly affect building energy consumption. The building occupancy schedules and operation for this study are those of the UKM academic building obtained from the JPP, which is assumed to be operated 12 hours from 8:00

AM to 8:00 PM during regular UKM weekdays and 5% to 10% on weekends and holidays. Both artificial lighting, air-conditioning, and equipment systems follow this operation schedules.

Schedules of operations indicate how the building is being used. The information includes; when the building occupancy begins and ends (time, days of the week and seasonal variations), occupied indoor thermostat set points and internal equipment operational schedules. Most academic buildings have similar pattern of use where they are typically occupied during regular day time working hours, from 8:00 am to 20:00 pm. Working days are considered to be from Monday to Friday and weekends were assumed as holidays. During the night and weekends it is considered as unoccupied or partially occupied. Based on above assumption the default values of operating schedules for the air-conditioning system and internal equipment operation schedules are used in the software. Table 3.4 illustrates the case study building occupancy schedules used in the energy simulation modeling.

Table 3.4 EnergyPlus input: Case study building occupancy and operation schedules

Schedule	**Weekdays**		**Schedule Description**
Date	01/09 to 30/06	01/07 to 01/09	
Occupancy			70% during occupied periods, and 0 % during unoccupied periods, weekends, and holidays
Lighting			90 % during occupied periods, and 17 % during unoccupied periods, weekends, and holidays
Equipment			95% during occupied periods, and 35% during unoccupied periods, weekends, and holidays
Infiltration			50 % during occupied periods, 100% during unoccupied periods, weekends, and holidays

The artificial lighting system operation can be optimized through the use of daylight control systems and through the integration of daylighting with lighting systems. Such a strategy reduces not only the energy consumption by lighting systems but also that by cooling systems because of reductions in artificial lighting loads.

Principally, there are two types of daylight control systems: an on/off control system and a dimming system. The first system allows artificial lights to be turned on or off depending on the exterior illuminance. The on/off system has one limitation: the reaction and operation. Further, another problem that arises is the rapid switching on and off of lights when the daylight levels are fluctuating. This is not only frustrating for the occupants but also reduces lamp life (Doulos et al. 2005).

The second daylight control system works by dimming the lights. In this case, the artificial lights are dimmed or brightened in response to sunlight in order to maintain the set indoor illuminance level. A sensor, which is located at the station point, reads the exterior illuminance; if the exterior illuminance is greater than the target illuminance, then the artificial lights are dimmed, and vice versa. Thus, daylight responsive dimming systems are controlled by photosensors that adjust the electric lighting level according to the amount of daylighting on the photosensor. These systems are more expensive, requiring special lamps and ballasts but are best suited for offices (Doulos et al. 2005).

Schrum & Parker (2003) worked on a validation of DOE-2.1E related to the application of daylight dimming systems and the effect of window orientation and blinds on energy savings. The research was carried out using the Daylighting Test Facility located in Florida, USA. To evaluate the impact of blinds on dimming savings, the energy consumption was compared in two pairs of offices for all four window orientations: north, south, east and west. The study showed that daylight dimming systems can provide significant energy savings ranging from 24% to 51% depending on the orientation and whether the office had blinds. The simulation of the offices using DOE-2.1E agreed with measurements to within 17.4%. For offices with no blinds the percent difference between measured and simulated energy consumption

UNIVERSITI KEBANGSAAN MALAYSIA

ranged between –7.9% and 6.0%; and for offices with blinds, it ranged between 3.9% and 17.4%.

Laouadi investigate two daylight control strategies: ON/OFF automatic and continuous dimming with a base load of 10%. The lighting energy savings were calculated relative to when there was no lighting control (lights were on during building occupancy). The cost savings were based on an electricity rate of $0.10/kWh. The energy savings increase with the glazed surface area ratio. The dimming system provides up to 28% better energy saving than the on/off automatic control (Laouadi 2004). The TIAX Controls and Diagnostics Report found that dimming electric lights in daylit spaces could reduce annual lighting energy consumption in existing commercial buildings by 40-60% (Lawrence & Roth 2008).

According to previous researches, daylighting system of buildings is an important component; it plays a key role in saving energy and daylight. Further, several researches have reported that from the viewpoint of energy and cost saving, daylight is a great source of energy, particularly with the implementation of a daylight dimming control system (Dong-Hwan 2009).

Further, Galasiu and Veitch evaluated the impact of window blinds control on two different daylight control systems. Energy savings using an open loop dimming control system and another controlled shading system varied from 5% to 45% (Galasiu & Veitch. 2006). Lee and Selkowits evaluated the performances of daylight dimming control systems and on/off control systems. They concluded that daylight dimming systems reduce the energy consumption by 33% (Lee & Selkowits 2006).

For the purposes of this study, dimming daylighting control was selected. This daylighting control uses continuous dimming to maintain the design illuminance level. If the lighting level in the zone exceeds the design illuminance level, the electric lights are dimmed until the exact design illuminance level is maintained. Dimming control performance is based on electronic dimming ballast that works linearly between 100% and 10% minimum light outputs. Within this range, input power ranges between 100% and 10%, thereby indicating that 10% of full power (13.652 W/m^2) is applied at 10%

UNIVERSITI KEBANGSAAN MALAYSIA

lights output just before the electric light is switched off. Without daylighting contribution, the artificial lighting system is assumed to provide the design illuminance level when the lights are operated. Table 3.5 describes the main performance and attributes of the daylighting control used in the simulation modeling. For daylight sensors, the maximum allowable discomfort glare index is 22, which indicates that daylight will be switched off if the glare index is greater than the design value. A glare index describes the subjective magnitude of glare discomfort with high values illustrating uncomfortable or intolerable sensation of discomfort (Johnsen et al. 2006). In EnergyPlus, blinds will be employed if the glare index is above 22, which is considered to cause glare. Shading devices are opened as soon as glare no longer exist (DOE 2010). Two daylight sensors are assumed to be placed at the work plane height in the middle of the zone. In the simulation modeling, the reflectance levels of the internal surfaces are assumed to be 80% for the ceilings, 50% for the walls and 20% for the floors. The process of reflection and inter-reflection is complex and the amount of inter-reflected daylight varies according to the distance of the reference point from the window. However, as stated in BRE (1986), for most purposes it is sufficient to assume an average internally reflected component. Therefore, Interior reflectance values of 80% for the ceiling, 50% for the walls, and 20% for the floor in the case study building at UKM are set in the simulation on the basis of IESNA (2000) recommended surface reflectance.

Table 3.5 EnergyPlus input: Daylight control attributes

Characteristics	Description
Daylighting Control Type	Continuous Dimming Control
Illuminance Set Point Level	500 (lux) (MS 2007) and (IESNA 2000)
Minimum light Output Fraction	0.1 before switch off
Minimum Input Power Fraction	0.1 before switch off
Maximum Allowable Discomfort Glare Index	22 before switch off
Daylight Control Sensors	Two daylight sensors are assumed to be placed at work plane height 0.76m in the middle of the building space

UNIVERSITI KEBANGSAAN MALAYSIA

3.3.3 OpenStudio Plug-in Clarification of Case Study Building

Graphic illustrations of the base case simulation modeling are presented in Figure 3.5 with the OpenStudio SketchUp Plug-In graphic interface computer software developed by the National Renewable Energy Laboratory (NREL) of the US Department of Energy. The EnergyPlus V7.0 base case simulation modeling was modified after the base case calibration section to include the selected toplighting options of the skylight, sawtooth, and roof monitor to evaluate their effects on energy savings and daylight quality.

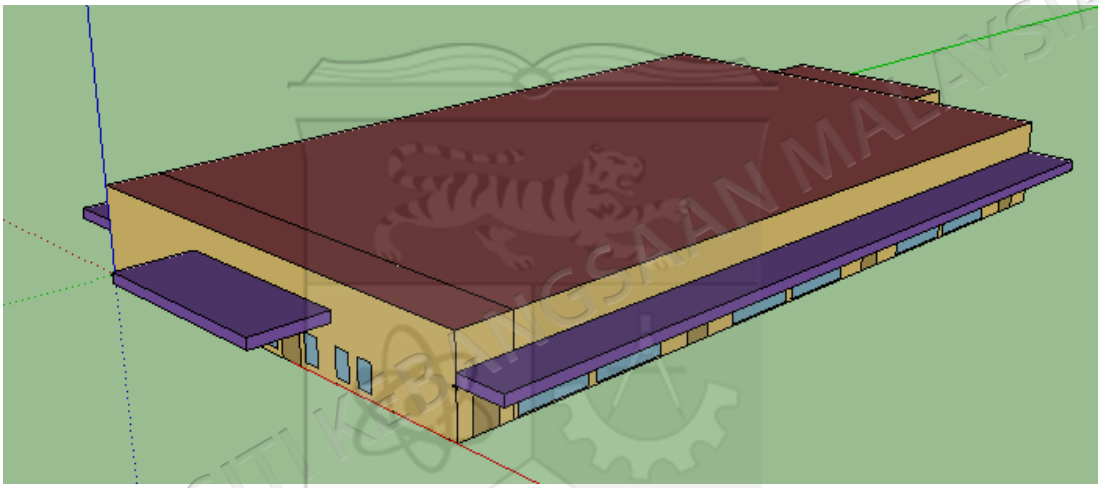


Figure 3.5 Perspective of base case model using EnergyPlus with OpenStudio Plug-in software

With all information and data about the case study building components and operation gathered, the case study building was modeled in EnergyPlus 7.0 simulation software. This step was conducted after the case study building geometry was modeled and the building dimensions, glazing size, characteristics of building components, occupancy schedules, and operation of the building were specified in EnergyPlus 7.0 software.

3.4 SIMULATION PARAMETERS IN ENERGYPLUS

This section explains in detail the main characteristics of the simulation parameters used in the EnergyPlus software.

UNIVERSITI KEBANGSAAN MALAYSIA

3.4.1 Kuala Lumpur Climate

According to ASHRAE (ASHRAE Handbook 2009), climatic zones are categorized into eight zones for building climatic envelope standards. Building systems and construction vary based on the ASHRAE recommendation for each climatic zone. The current study applies only to Kuala Lumpur location. This location was chosen to represent the hot and humid climate and daylight availability of Malaysia. Table 3.5 describes the ASHRAE thermal and daylighting climatic design condition attributes for Kuala Lumpur. ASHRAE design conditions are carefully generated from a period of record (typically 30 years) to be representative of that location and to be suitable for use in heating or cooling load calculations. The cooling set-point temperature for the air conditioning system in the simulation modeling is set to 24°C during occupied hours as the characteristics of the case study air conditioning system presented in Table 3.6. Table 3.7 showed in details the monthly (weather file) heating/cooling degree-days/hours for Kuala Lumpur city.

Table 3.6 Thermal and daylighting main climatic attributes for the Kuala Lumpur city (test case study)

Station	Heating Degree-Days	Cooling Degree-Days	Heating Design Temperature, (°C)	Cooling Design Temperature (°C)	
Kuala Lumpur	HDD10°C	CDD10°C	Dry-Bulb 99.6%	Dry-Bulb 1%	Wet-Bulb 1%
	0	6262	22	34.22	27.5
	HDD18°C	CDD18°C			
	0	3342			
	Kuala Lumpur Annual Cloudiness				
	Clear		Intermediate		Overcast
	0.0%		87.25%		12.75.0%

Source: ASHRAE Handbook 2009

UNIVERSITI KEBANGSAAN MALAYSIA

Table 3.7 Monthly Weather File Heating/Cooling Degree Days/Hours for Kuala Lumpur

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Heating degree-days base 10°C	0	0	0	0	0	0	0	0	0	0	0	0
Heating degree-days base 18°C	0	0	0	0	0	0	0	0	0	0	0	0
Cooling degree-days base 10°C	523	477	541	527	547	537	537	530	516	518	502	509
Cooling degree-days base 18°C	275	253	293	287	299	297	289	282	276	270	262	261
Cooling degree-hours base 20°C	5103	4722	5540	5440	5686	5678	5459	5281	5183	4991	4848	4766
Cooling degree-hours base 23°C	2887	2707	3308	3283	3454	3522	3227	3050	3024	2766	2691	2542
Cooling degree-hours base 27°C	877	747	1078	1006	1019	1274	1007	920	902	823	700	543

6262 annual (weather file) cooling degree-days (10°C baseline)

0 annual (weather file) heating degree-days (10°C baseline)

3342 annual (weather file) cooling degree-days (18°C baseline)

0 annual (weather file) heating degree-days (18°C baseline)

Source: ASHRAE Handbook 2009

UNIVERSITI KEBANGSAAN MALAYSIA

Weather data for Kuala Lumpur city were obtained from the International Weather for Energy Calculations (IWEC). IWEC data files are “typical” weather files suitable for use with building energy simulation programs for 227 locations outside the US and Canada (Doe 2010b). These files can be downloaded from the EnergyPlus weather data website at http://apps1.eere.energy.gov/buildings/energyplus/weatherdata. The files are derived from up to 18 years of hourly weather data originally archived at the US National Climatic Data Center. Individual IWEC files in converted format are suitable for EnergyPlus (EPW). Thus, the IWEC for Kuala Lumpur city was used in this study.

3.4.1.1 EnergyPlus Weather Data Format Definition

The weather data for EnergyPlus is a text-based format derived from the Typical Meteorological Year 2 (TMY2) weather format. The EnergyPlus Weather Converter advantage that is installed when install EnergyPlus and translates TMY2, TMY3 (Typical Meteorological Year 3 (TMY3), IWEC (International Weather for Energy Calculations format from ASHRAE), as well as ESP-r, DOE-2 and BLAST weather text format files and custom format weather files into the EnergyPlus weather format at (http://apps1.eere.energy.gov/buildings/energyplus/weatherdata_format.cfm).

3.4.1.2 EnergyPlus Weather Data Sources

The weather data provided in EnergyPlus weather format on the EnergyPlus website are derived from 20 sources. The IWEC are the result of ASHRAE Research Project 1015 by Numerical Logics and Bodycote Materials Testing Canada for ASHRAE Technical Committee 4.2 Weather Information. The IWEC data files are 'typical' weather files suitable for use with building energy simulation programs for 227 locations outside the USA and Canada. All 227 locations in the IWEC data set are available for download in EnergyPlus weather format. More information about the sources of weather data is available on the Weather Data Sources at (Doe 2010c).

Due to cost and weather data availability in EnergyPlus weather file website, this study applied simulated weather data for four Malaysian cities, namely, Kuchang,

UNIVERSITI KEBANGSAAN MALAYSIA

George Town, Kuala Lumpur and Kota Bharu that represent most of the climatic and daylight utilization conditions in Malaysia. The results might not accurately reflect electric energy savings within other Malaysian regions because of climate and daylight availability differences.

The files are derived from up to 18 years of DATSAV3 hourly weather data originally archived at the U. S. National Climatic Data Center. The weather data is supplemented by solar radiation estimated on an hourly basis from earth-sun geometry and hourly weather elements, particularly cloud amount information. The IWEC CD-ROM is available from ASHRAE. The reference for the IWEC is: ASHRAE. 2001. International Weather for Energy Calculations (IWEC Weather Files) Users Manual and CD-ROM, Atlanta: ASHRAE (Doe 2010c). The U.S. Department of Energy has licensed the IWEC data from ASHRAE. The license with ASHRAE allows DOE to:

- Distribute versions of the individual IWEC files in converted format suitable for EnergyPlus (EPW).
- Make the EnergyPlus versions of the IWEC files available to users at no cost via EnergyPlus website.

Therefore, the IWEC weather files Table 3.7 are used in this study.

Table 3.8 Location information and the IWEC stations reference numbers

Location	Latitude	Longitude	Time zone	Elevation	IWEC ref. no.
Kuala Lumpur	N 3° 12'	E 101° 55'	GMT +8.0	22m above sea level	Station 486470
George Town	N 5° 3'	E 100° 27'	GMT +8.0	4m above sea level	Station 486010
Kota Baharu	N 6° 17'	E 102° 28'	GMT +8.0	5m above sea level	Station 486150
Kuching	N 1° 48'	E 110° 33'	GMT +8.0	27m above sea level	Station 964130

UNIVERSITI KEBANGSAAN MALAYSIA

According to Mohd Hamdan (1996), the real sky conditions in Malaysia has not really been established except for a rough generalization that it is overcast based on cloud cover information. Furthermore, daylight data is not measured at any meteorological station in Malaysia and therefore daylight data is absolutely unavailable (Mohd Hamdan 1996). The Malaysia cloud condition is shown in Table 3.9. The data was recorded from 2001 to 2003 at Subang Station. Relationship between cloud cover data and the type of sky is indicated in Table 3.10.

Table 3.9 Relationship between type of skies and the cloud cover

Type of Sky	Cloud cover
Overcast Sky	7.0 oktas < Cloud Total< 8.0 oktas
Intermediate Sky	1.0 oktas < Cloud Total< 7.0 oktas
Clear Sky	0.0 oktas < Cloud Total< 1.0 oktas

Source: Malaysian Meteorological Department, 2001

Table 3.10 Average Cloud Cover for Subang from 2001-2003

Month	Average Cloud Cover (Oktas)
	Station: Subang (2001-2003) Latitude: 3°.7'N Longitude: 101°33'E
January	6.97
February	7.10
March	7.03
April	7.00
May	6.97
June	6.97
July	6.93
August	7.00
September	6.97
Containued	

UNIVERSITI KEBANGSAAN MALAYSIA

	Containued
October	7.00
November	6.97
December	6.97
Average	**6.99 ≈ 7.0**

Source: Malaysian Meteorological Department 2001

The data from Table 3.9 shows that, average cloud cover for three years at Subang was 6.99 oktas. This particular value (refer to table 3.8) was within the range of 1.0 oktas < Cloud Total< 7.0 oktas, thus classifying the type of sky for Subang as 'Intermediate'.

Zain-Ahmed et al (2002) used the nebulosity index (NI) to determine sky conditions and to calculate the irradiances in Malaysia. According to different NI values, the sky conditions are categorized as shown in table 3.11 below. Based on the occurrences of sky types, the study concluded that the Malaysian sky is predominantly an intermediate sky. This was justified by the calculated mean NI value for Malaysian as 0.52, which lies between the range of intermediate sky 0.20 and 0.70. The definition of intermediate implies that the sky is neither clear nor overcast (Zain-Ahmed et al, 2002).

Table 3.11 Different Sky types according to Nebulosity Index, Subang Jaya, Malaysia.

Type of Sky	Nebulosity Index (NI)	Frequency (%)
Overcast Sky	0.00<0.05 14.0	14.0
Intermediate overcast	0.05<0.20	2.3
Intermediate mean	0.20<0.70	**66.0**
Intermediate Blue	0.70<0.95	17.3
Blue / Clear Sky	0.95<1.00	0

Source: Zain-Ahmed et al. 2002

UNIVERSITI KEBANGSAAN MALAYSIA

3.4.2 Toplighting Shapes, Geometries and Orientations

A. Toplighting Shapes

Skylights, saw-tooth, and roof monitor shapes were proposed as the three toplighting alternatives for the case study building, and their effects were evaluated for building energy savings and interior daylighting quality.

B. Toplighting geometries

To evaluate the effect of the geometry (size) of the toplighting on the daylight supply, 12 toplighting sizes, varying from 5% to 60% of the roof area, were assessed as separate test cases for the evaluation with the test case study building. To avoid the random selection of toplighting sizes, the toplighting dimensions were calculated as a ratio of the space roof. The evaluation includes the effect of the toplighting geometries for each alternative on building energy savings and later focuses on interior daylighting quality. The toplighting area is based on the toplighting area-to-floor area ratio (TFR) of 5% to 60%.

The toplighting options with opining size up to 60% toplighting area-to-floor area (TFR) was chosen because it responds with the maximum opening size, that the design of the roof structure (slabs and beams) take up to 35% to 40% of the roof area. Therefore, our investigation, toplighting openings sizes range from 5% to 60% were used to evaluate the energy and daylighting performance of the simulated cases. Table 3.12 presents the toplighting dimensions for each toplighting alternative. The overall height of the case study test space is 6 m, and the work plane surface height is 0.762 m above space floor level.

Table 3.12 Toplighting dimensions for each toplighting alternative

TFR 5% : 0.33 m × 32 m	TFR 10% : 0.66 m × 32 m
TFR 15% : 0.98 m × 32 m	TFR 20% : 1.31 m × 32 m
TFR 25% : 1.64 m × 32 m	TFR 30% : 1.96 m × 32 m
TFR 35% : 2.29 m × 32 m	TFR 40% : 2.62 m × 32 m
TFR 45% : 2.95 m × 32 m	TFR 50% : 3.28 m × 32 m
TFR 55% : 3.60 m × 32 m	TFR 60% : 3.93 m × 32 m

C. Toplighting Orientations

The skylight, sawtooth, and roof monitor daylighting system alternatives for the case study building are considered to face the four main orientations (north, south, east, and west).

3.4.3 Spacing-to-ceiling height ratio

Multi-unit linear toplighting openings with 1-to-1 spacing-to-height ratio were evaluated first. IESNA (2000) proposes that a rule of thumb for top-daylighting systems is a spacing-to-height ratio of 1 to 1. Thus, the spacing-to-height ratio is evaluated first. However, Dewey and Littlefair (1998) reported that skylight and sawtooth toplighting systems with a spacing-to-height ratio of 1 to 1.5 provide daylight uniformity that meets the criteria set by the Chartered Institution of Building Services Engineers (CIBSE). Although the toplighting alternatives for the case study building do not have exactly the same geometry as those in the Dewey and Littlefair experiment, this spacing-to-height ratio is evaluated as well. Figure 3.6 and 3.7 show the roof plans of the selected toplighting alternatives and distribution with a 1-to-1 spacing-to-height ratio, and the sections are presented in Figure 3.8. The OpenStudio plans and perspectives of each toplighting alternative and distribution for this spacing-to-height ratio are shown in Figure 3.9 and 3.10. Figure 3.11 and 3.12 presents the roof plans of the selected toplighting alternatives with 1-to-1.5 spacing-to-height ratio, and the sections are presented in Figure 3.13. The OpenStudio roof plans and perspectives of each toplighting alternative of a 1-to-1.5 spacing-to-height ratio are illustrated in Figure 3.14 and 3.15.

The energy and daylighting performance of the selected toplighting alternatives was evaluated using the EnergyPlus simulation program. The energy savings and daylight quality of all toplighting alternatives were evaluated based on the results of the EnergyPlus program. All of the toplighting alternatives used similar weather data, geometric areas, types of glazing, orientations, spacing-to-height ratios, and construction materials. Thus, the variation is only the shape of the toplighting system.

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It is not an easy task to find the suitable program when detailed simulation methods are required, even though many energy simulation programs are currently available. It is most likely hard to suggest a clear procedure for selecting a simulation program that is suitable for everyone. Many factors, such as accuracy, sensitivity, speed and cost, reproducibility, usability, input complexity, output quality, and weather data availability are generally considered during the selection process (ASHRAE Handbook 2009). Other factors associated with the users should also be considered. These factors can be classified into three main factors: the need or the purpose corresponding to the program capability, the financial resources (to purchase, training, use, and maintain the software), and the availability of existing computer facilities (Hong 2000).

Many programs have been reviewed. Among these programs the EnergyPlus with a graphic interface OpenStudio plug-in in Google Skectchup program were selected to be used in this study because of these main factors:

- It has been widely validated for accuracy and consistency.
- It offers a great capability for simulating a wide range of design features and energy conservation measures, including the integration of daylight with artificial light.
- It provides the ability for rapid development of energy simulations, reducing the time required to build EnergyPlus model. Specifying the building geometry is much faster than other comparable software, making EnergyPlus with OpenStudio plug-in in Google Skectchup useful for schematic design studies of the building envelope or HVAC systems.
- OpenStudio also implements the daylighting calculations from EnergyPlus, making it possible to evaluate the integration of daylight with the artificial lighting system.
- The availability, sufficient training, and capability to maintain the program is another reason in the selection of EnergyPlus with OpenStudio.

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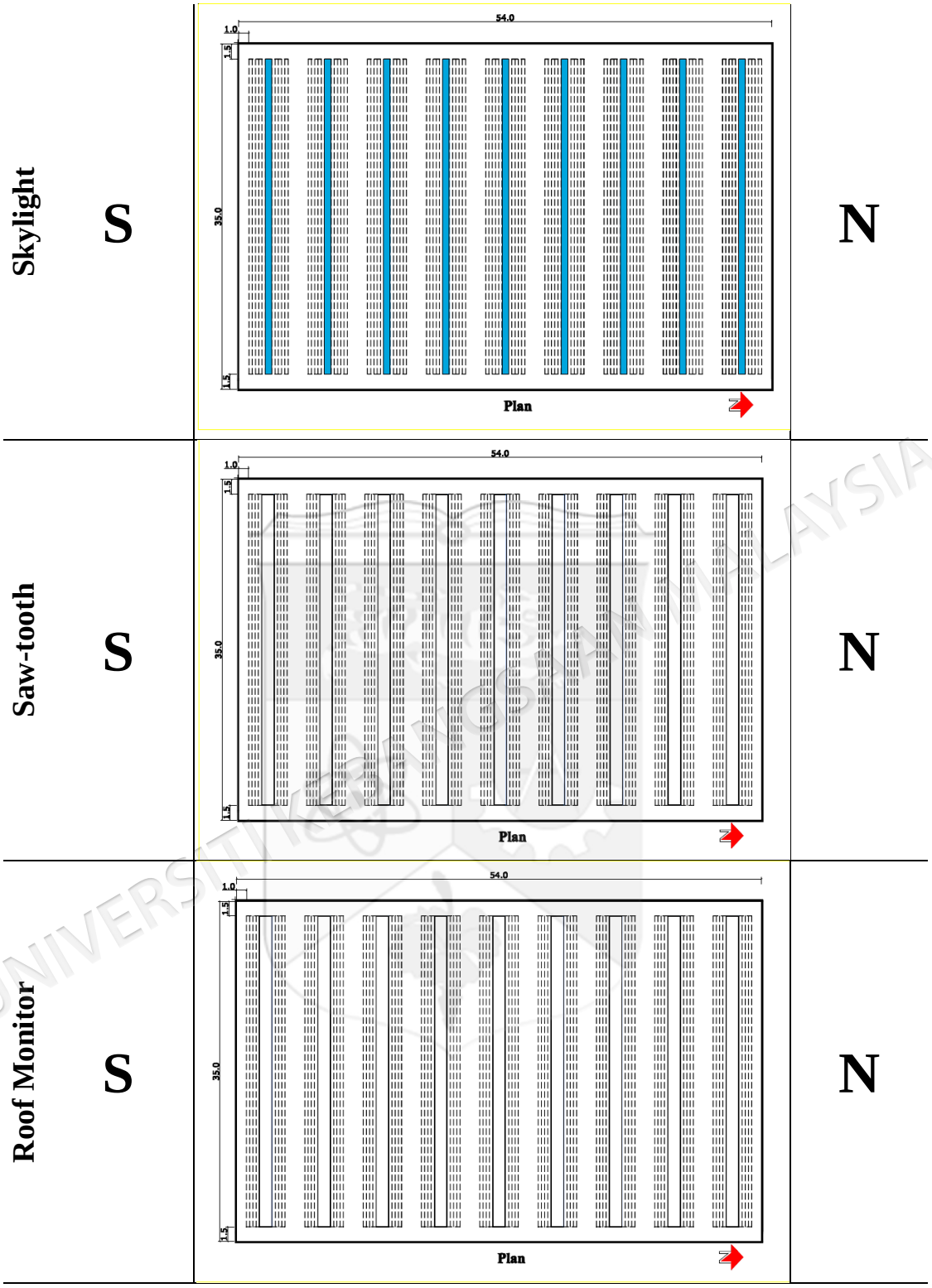

Figure 3.6 Roof plans of selected toplighting alternatives and distribution of 1 to 1 spacing-to-ceiling height ratio varying from 5% to 60% of the roof area

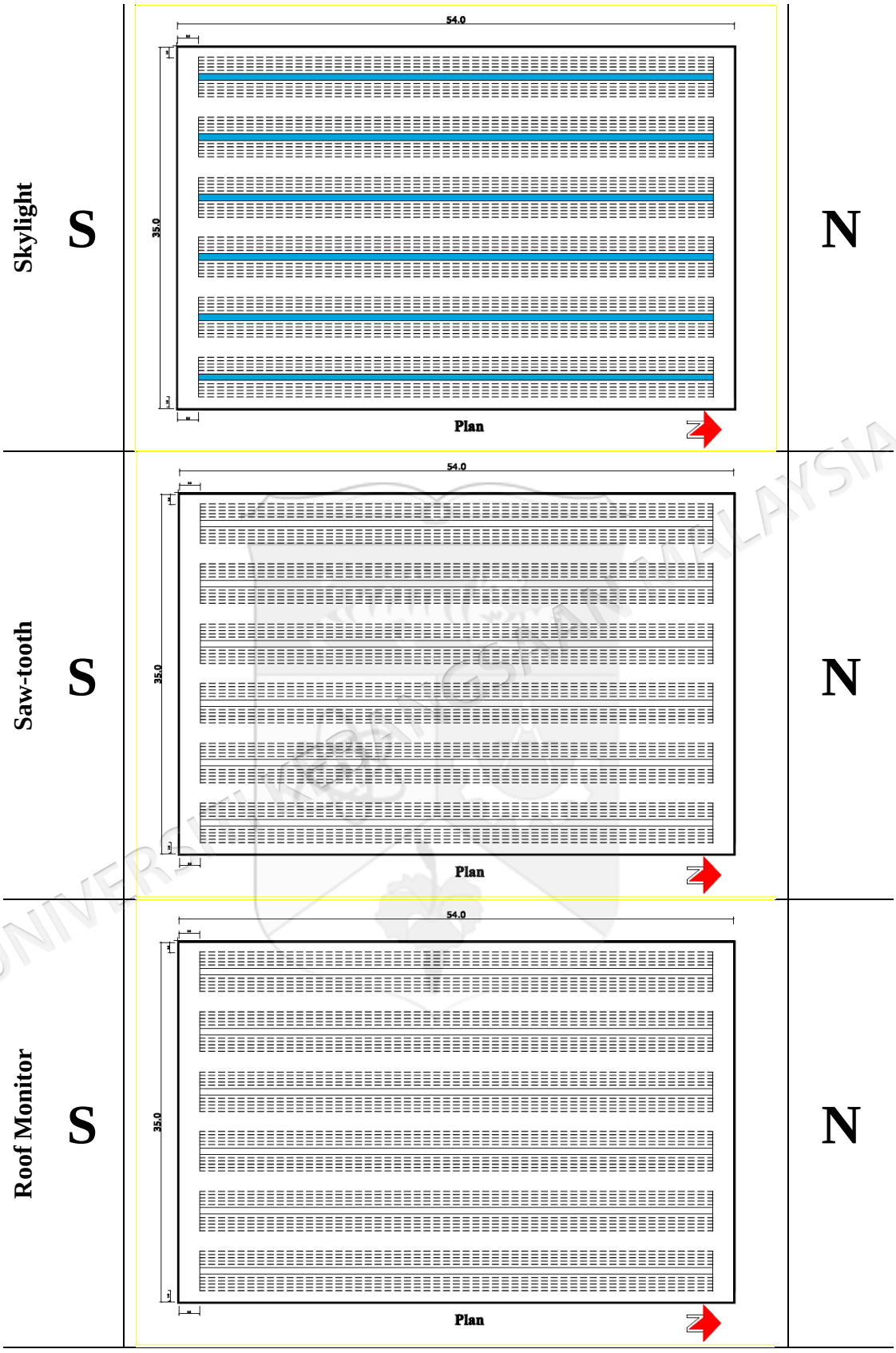

Figure 3.7 Roof plans of selected toplighting alternatives and distribution of 1to 1 spacing-to-ceiling height ratio varying from 5% to 60% of the roof area

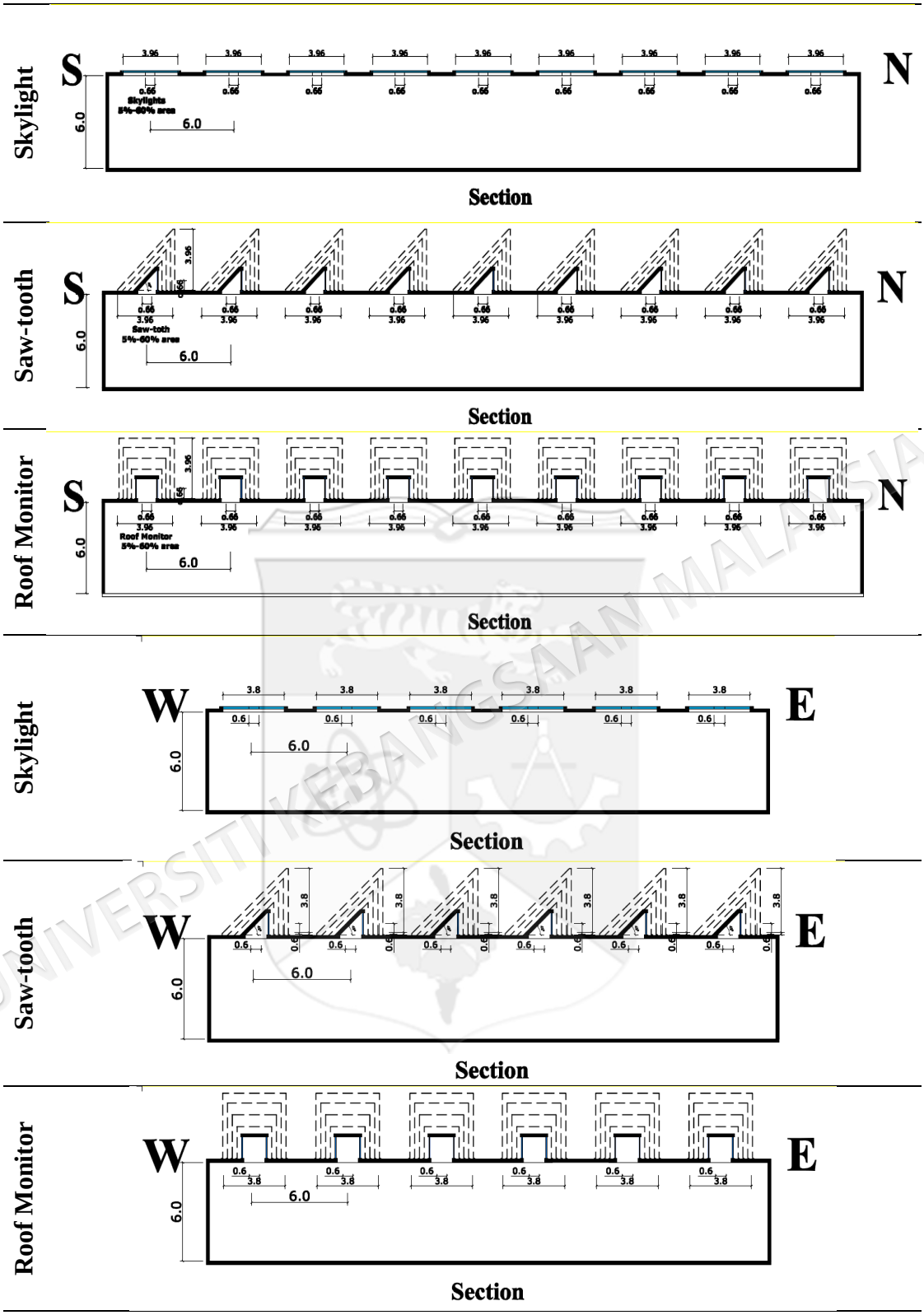

Figure 3.8 Sections of selected toplighting alternatives and distribution of 1 to 1 spacing-to-ceiling height ratio varying from 5% to 60% of the roof area

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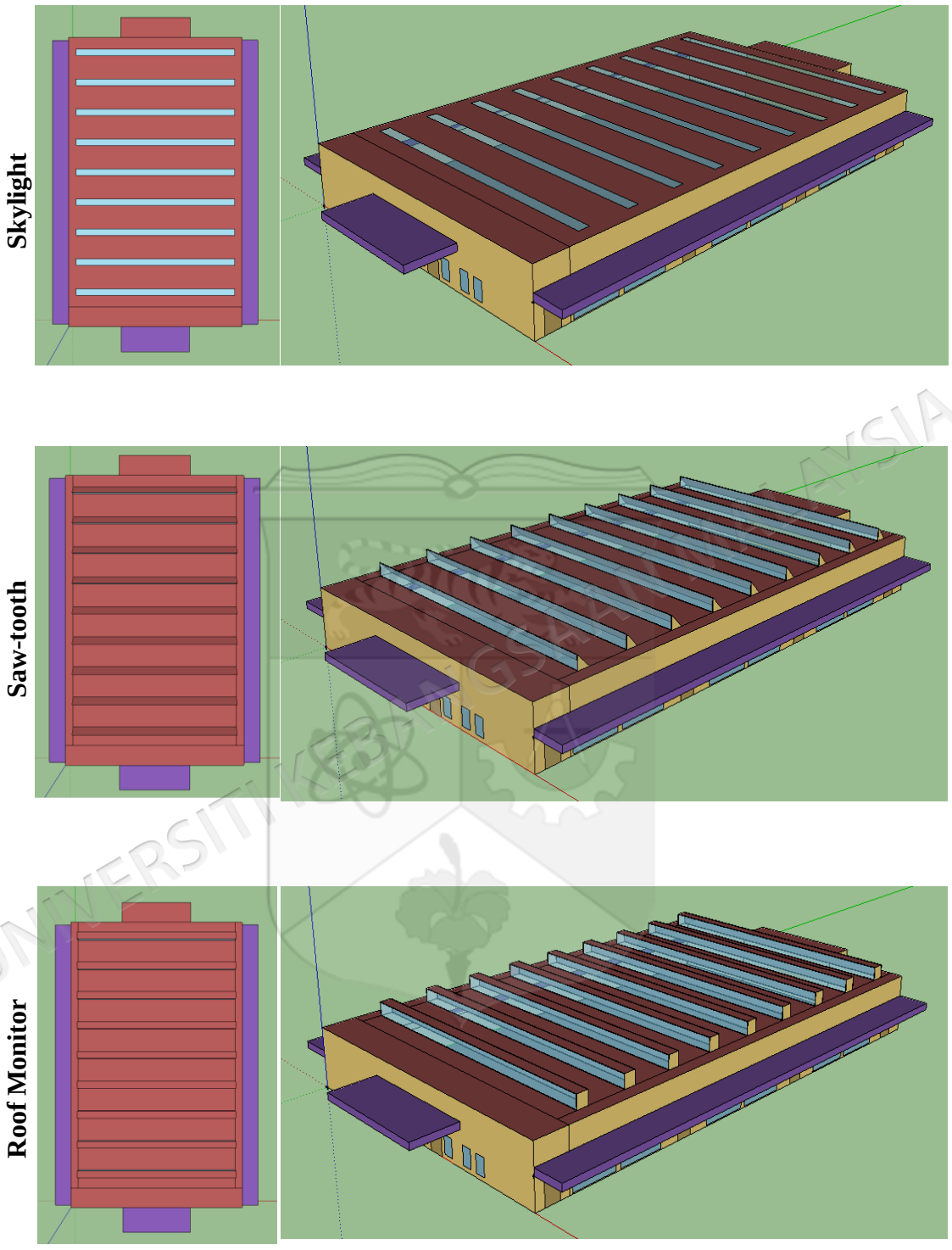

Figure 3.10 OpenStudio roof plans and perspectives of selected toplighting design alternatives and distribution of 1 to 1 spacing-to-ceiling height ratio (North/South Orientation)

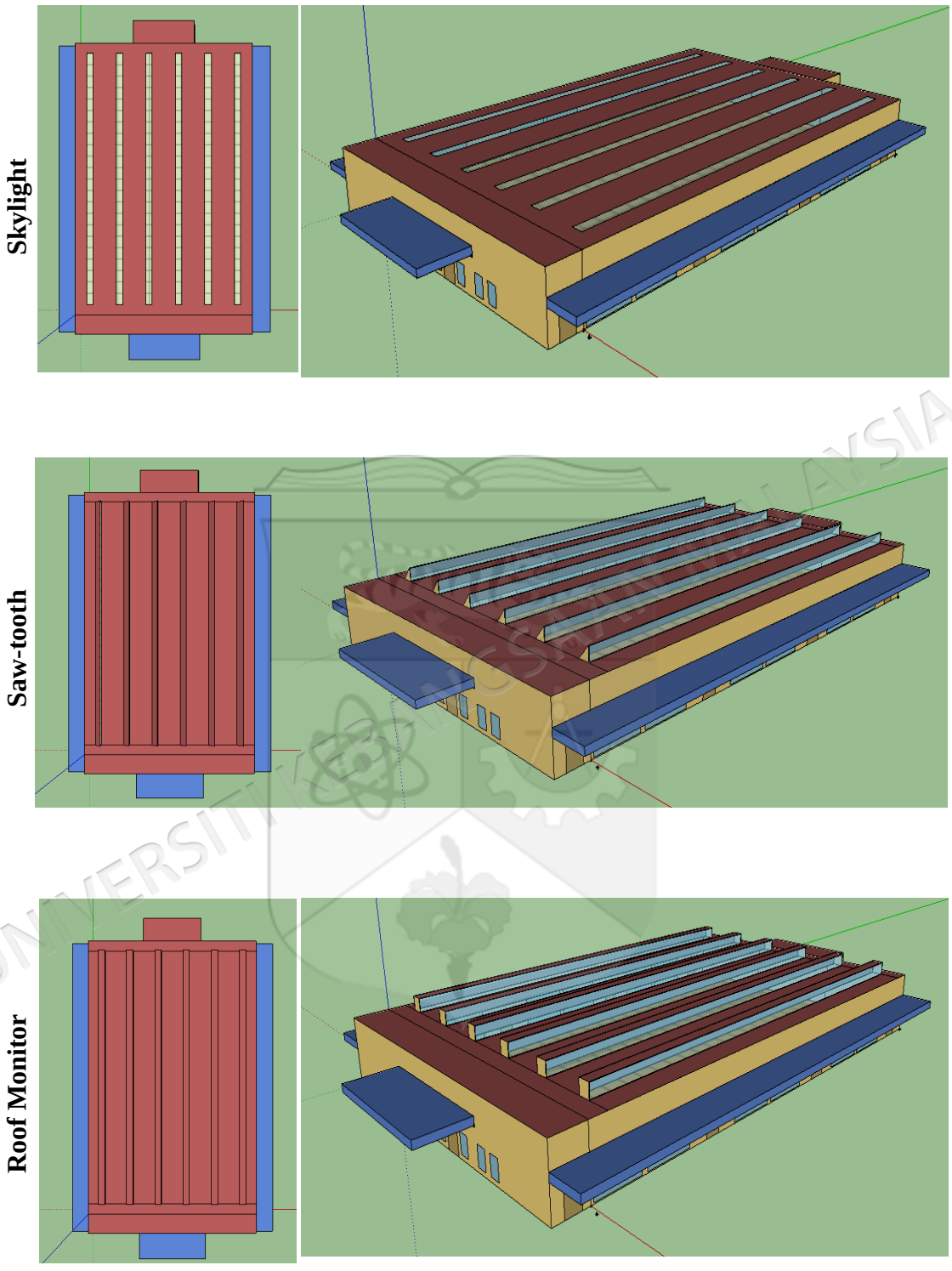

Figure 3.10 OpenStudio roof plans and perspectives of selected toplighting design alternatives of 1 to 1 spacing-to-ceiling height ratio (East/West orientation)

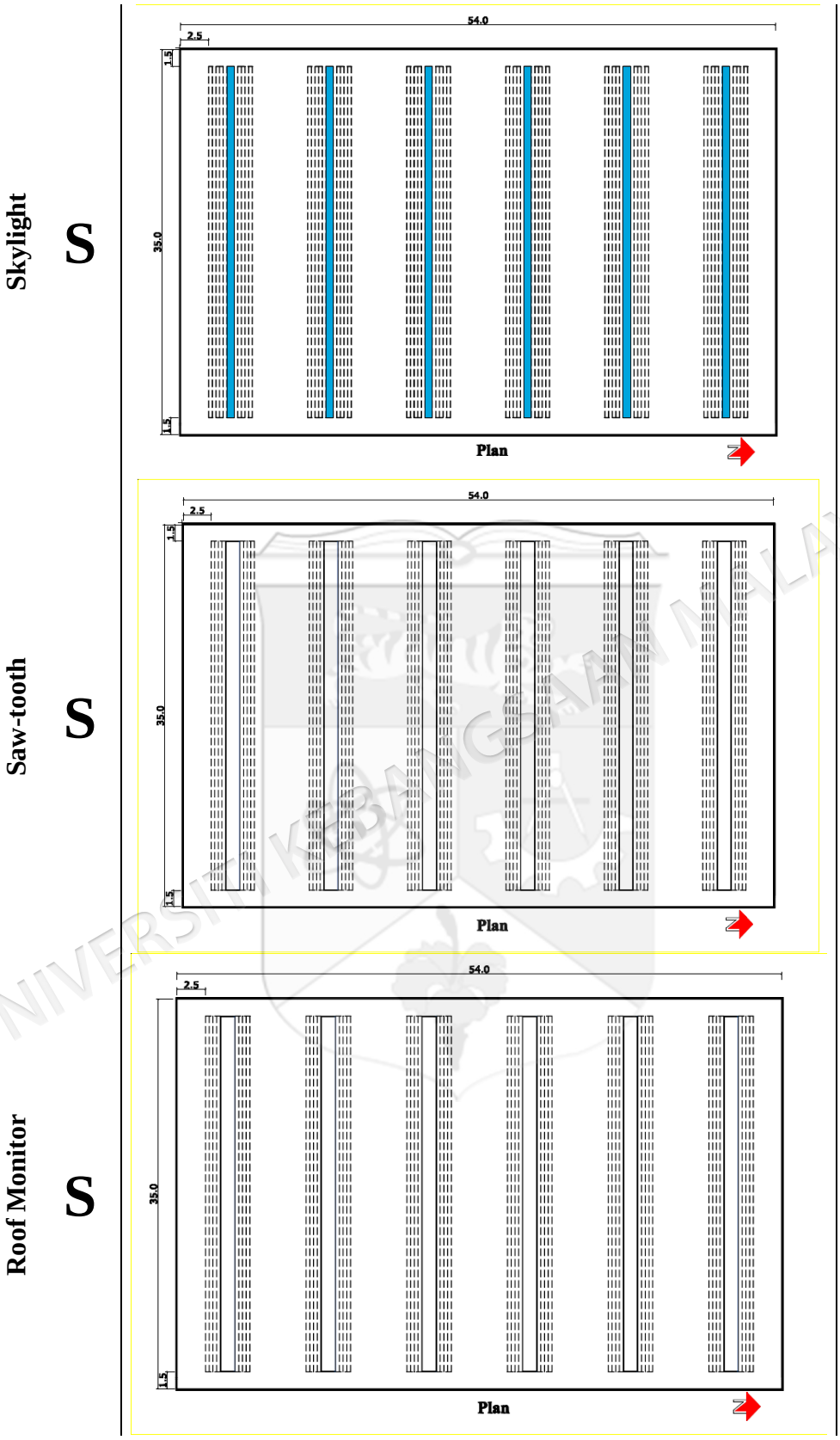

Figure 3.11 Roof plans of selected toplighting alternatives strategies and distribution of 1 to 1.5 spacing-to-ceiling height ratio varying from 5% to 60% of roof area

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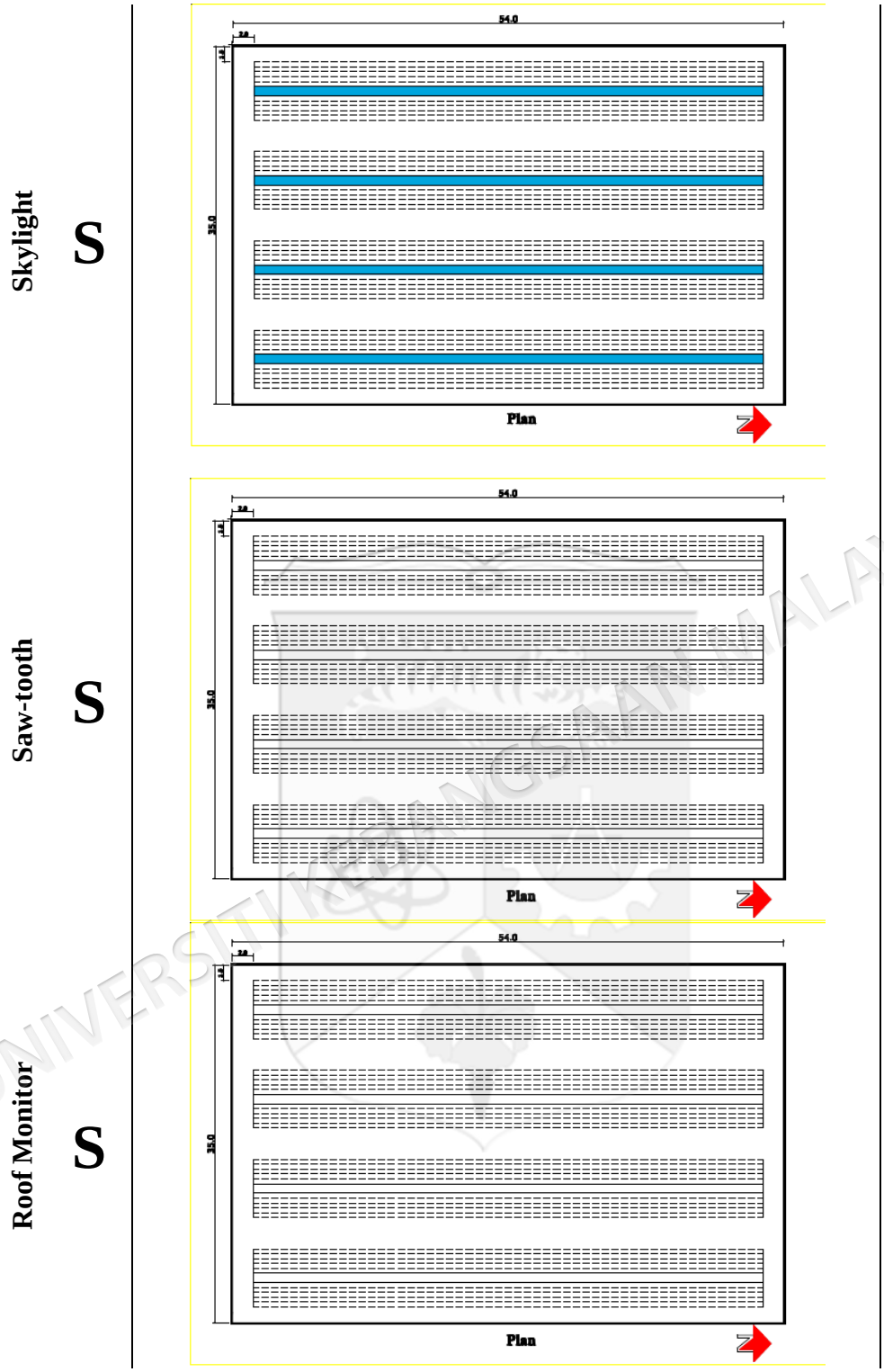

Figure 3.12 Roof plans of selected toplighting alternatives and distribution of 1 to 1.5 spacing-to-ceiling height ratio varying from 5% to 60% of roof area

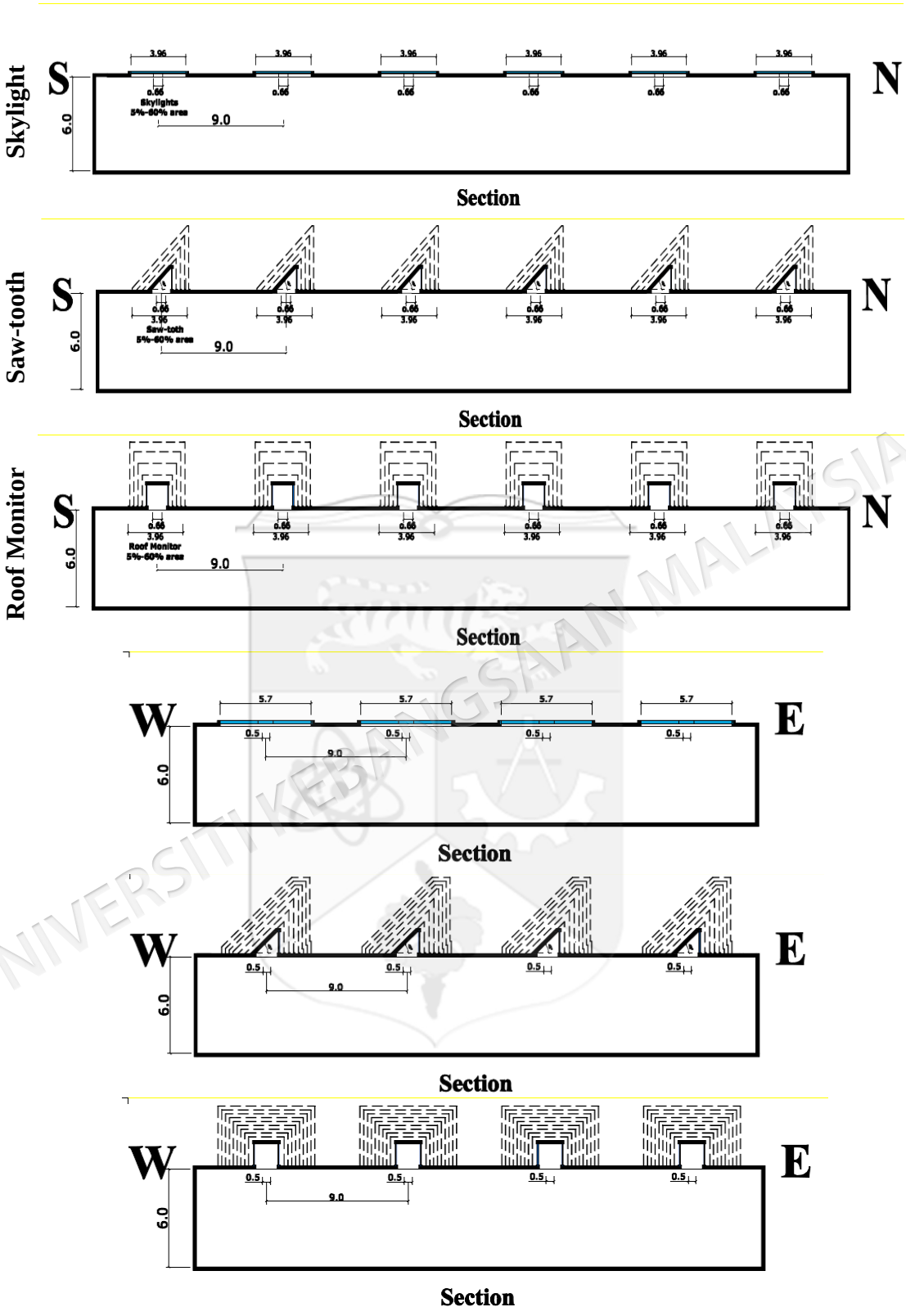

Figure 3.13 Sections of selected toplighting alternatives and distribution of 1 to 1.5 spacing-to-ceiling height ratio varying from 5% to 60% of roof area

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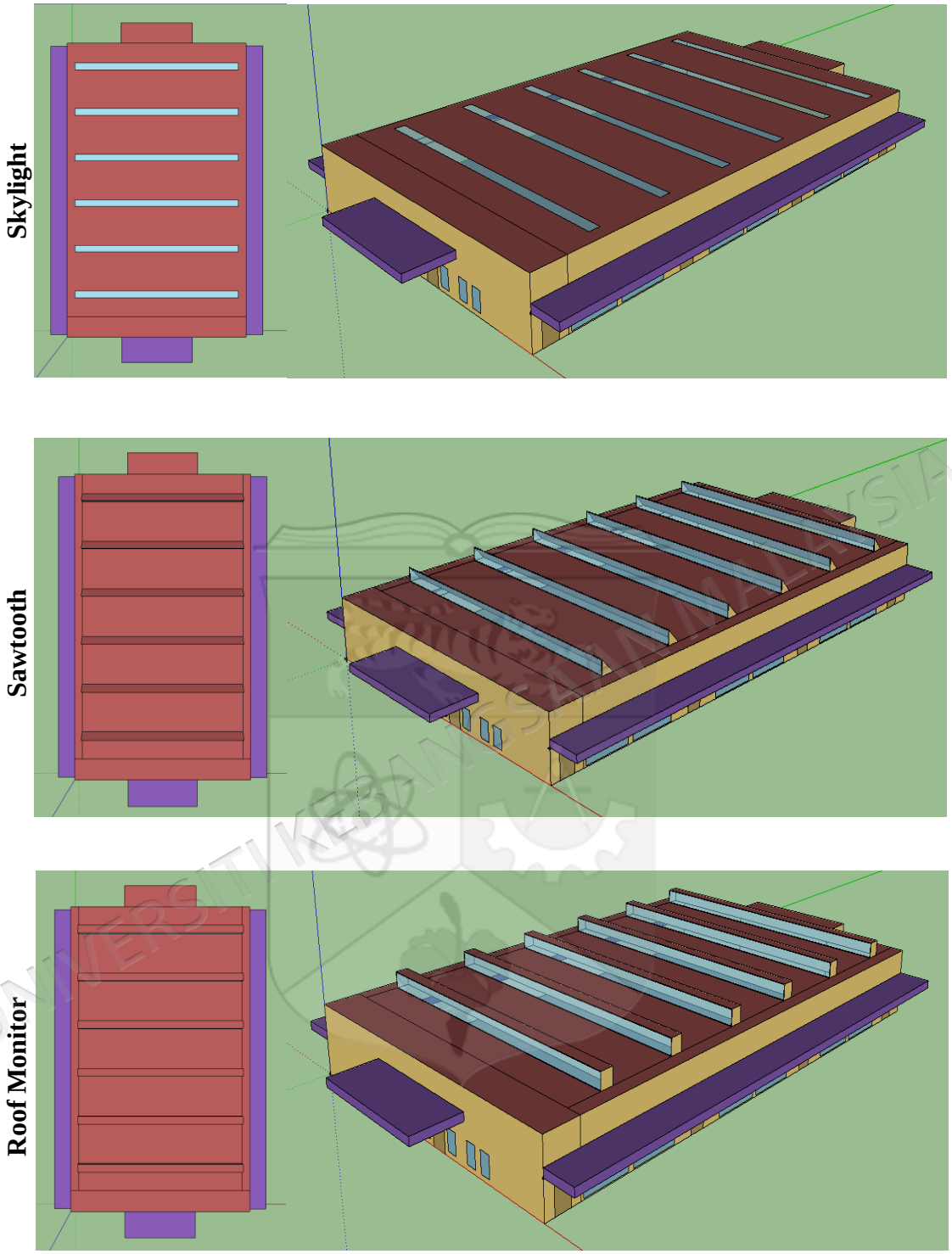

Figure 3.14 OpenStudio roof plans and perspectives of selected toplighting alternatives and distribution of 1 to 1.5 spacing-to-ceiling height ratio (North/South Orientation)

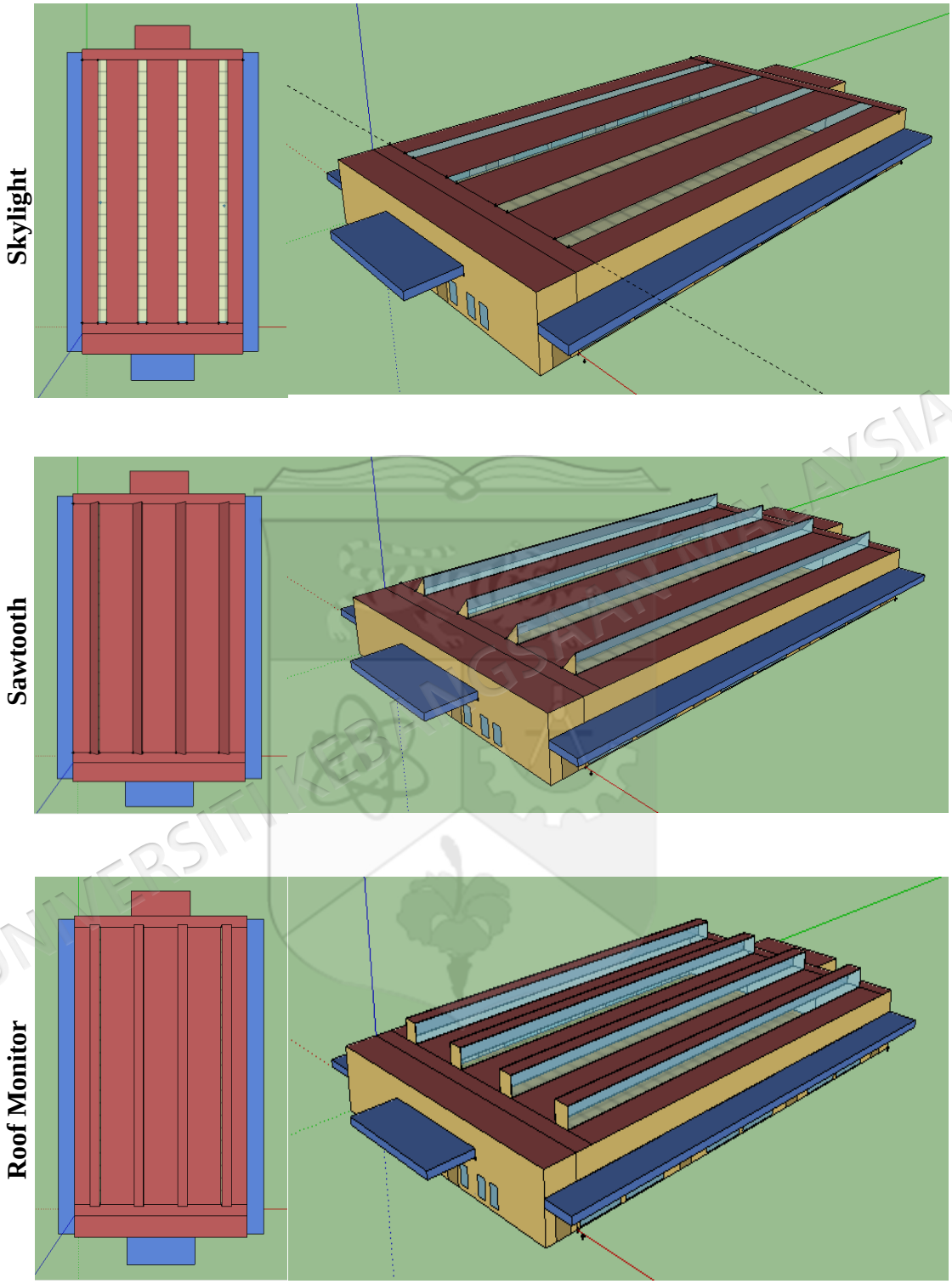

Figure 3.15 OpenStudio roof plans and perspectives of selected toplighting alternatives and distribution of 1 to 1.5 spacing-to-ceiling height ratio (East/West orientation)

3.4.4 Glazing Types

The solar heat gain coefficient (SHGC), rate of heat transmission U-factor (U-value), and visible light transmittance (Tvis/VT) are the crucial glazing attributes that quantify building energy and daylighting performance. The descriptions of these glazing attributes are obtained from the Building Component Library on the NREL website. The selected glass types for parametric analysis are available in the market and are popular choices for modern commercial and institution buildings. The visible light transmittance of the tested glazing types (single clear 6 mm, double clear 6 mm to 13 mm air, double reflect clear 6 mm to 13 mm air, and double low-emissivity clear 6 mm to 13 mm air) ranges from 0.308 to 0.881. The optical and thermal attributes of the selected glazing types used in the simulation parametric analysis in this study are presented in Table 3.13.

Table 3.13 Optical and thermal attributes of glazing types used in this study for performance comparison

Glass Type	Single Clear 6 mm-	Double Clear 6mm-13mm Air-	Double Reflect Clear 6mm-13mm Air-	Double Low-e Clear 6mm-13mm Air-
Glass Abbreviation	**Sgl Clr**	**Dbl Clr**	**Dbl Ref**	**Dbl LoE**
Number of Panes	Single pane	Double pane	Double pane	Double pane
Gas Fill	--	Air	Air	Air
Tint	Clear	Clear	Clear	Clear
U-factor W/m2-K	5.778	2.670	2.653	1.626
Solar Heat Gain Coefficient	0.819	0.703	0.426	0.421
Visible Light Transmittance	0.881	0.781	0.308	0.682

The performance of the selected glazing can be evaluated using the ratio between the visible light transmission (VT) and solar heat gain coefficient (SHGC). Light-to-solar gain (LSG) represents the relative efficiency of a glazing material transmitting daylight while blocking heat gain. Figure 3.16 shows the LSG for the

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glazing types used in this study. Higher glass's visible light transmittance VT and lower solar heat gain coefficient are suitable for hot climate regions.

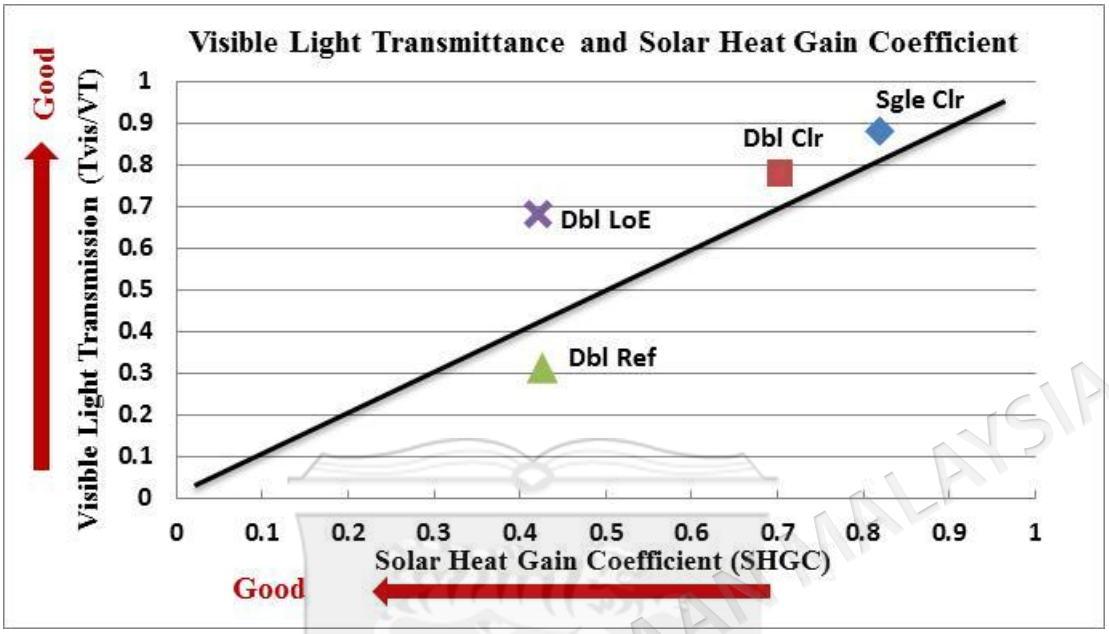

Figure 3.16 Visible light transmittance and solar heat gain coefficient for glazing types used in this study

3.5 DAYLIGHTING PERFORMANCE METHODOLOGY

A daylighting performance test was conducted using OpenStudio plug-in with EnergyPlus 7.0 to compare the output results from EnergyPlus and the real case study building illuminance level measurements. OpenStudio plug-in with EnergyPlus is used in detailed daylighting evaluations and rendering. OpenStudio with EnergyPlus daylighting calculations account for available solar radiation, site conditions, daylighting control strategies, glare and reflections, window and blind management, glazing light transmittance, glazing size, and external and internal shading devices. The daylighting evaluation parameters for the EnergyPlus simulation program are illustrated in this section. The toplighting options were tested using EnergyPlus with 1-to-1 and 1-to-1.5 spacing-to-ceiling height ratios of the skylight, sawtooth, and roof monitor with double low-e glazing type. This glazing type is assumed to have the same thermal and optical characteristics for all skylight, sawtooth, and roof monitor cases to make the cases comparable in terms of daylighting performance.

3.5.1 Intermediate and Overcast Sky Conditions

The case study model with toplighting options using EnergyPlus software was tested under intermediate sky and overcast sky conditions in Kuala Lumpur, Malaysia. In the EnergyPlus simulation program, intermediate sky and overcast sky conditions were specified for the dates and times of the case study building measurement. The intermediate sky was simulated for March 21, June 21, and December 21 at 9:00 am, 12:00 pm, and 3:00 pm solar time. The simulation times and dates were based on the article published by the Lawrence Berkeley National Laboratory (LBNL) on toplighting daylighting systems (Ong et al. 2011). The simulation also specified Kuala Lumpur (3°.12' north latitude, -101°.55' east longitude, +8 time zone, 22 m altitude) and the real case study building orientation (0° north).

3.5.2 Instrumentation: EnergyPlus

EnergyPlus is a building energy analysis and thermal load simulation program created by LBNL and sponsored by the US Department of Energy. Two building energy simulation programs were developed: DOE-2 and BLAST. The first was developed and supported by the US DOE (Crawley et al. 2001), and the second (Building Load Analysis and System Thermodynamics) was developed and supported by the US DOE. Both simulation programs were released in the late 1970s and early 1980s.

EnergyPlus is selected for this study because it can precisely simulate and calculate based on daylighting controls interior daylight illuminance, glare simulation from windows, glare controls, and lighting controls (continuous dimming, on/off, stopped), as well as calculate the effect of artificial lighting reduction on cooling and heating loads based on the most popular features and capabilities of DOE-2 and WINDOW 4 calculations (Chandran et al. 2010; Muneer 2012). EnergyPlus has more than 400 window types (e.g., gas-fill, conventional, reflective, low-e, and electrochromic layer-by-layer input) for custom glazing (Crawley et al. 2001). The software can model a complex building geometry, precisely simulate daylight performance within the building space, and predict the interior illuminance level with a high degree of accuracy with numerical results and a daylighting illuminance map.

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EnergyPlus can also model advanced fenestration calculations, controllable window blinds, and electrochromic glazing.

This study uses EnergyPlus with the OpenStudio SketchUp Plug-In interface program to predict the interior illuminance level for various toplighting options and to generate an hourly daylighting illuminance map and numerical results for each toplighting option. The OpenStudio SketchUp Plug-In is used to create the case study building model because the case study building can easily be modeled using OpenStudio 0.7 with the Google SketchUp 8 interface. OpenStudio 0.8, 0.9, and 0.10 and Google SketchUp 9 can also be used with EnergyPlus 7.0.

3.5.3 Daylight Measurement Instruments

Two portable illuminance meters, model LX-1108 (Figure 3.17), were used to measure the illuminance level inside the case study space. This illuminance meter has a measuring range of 0.01 lux to 400,000 lux, a value accuracy of ± (3% + 4 digits) as well as a large LCD display to digitally display the measurement. This meter has a small receptor head that makes it suitable for professional quality light measurement. The illuminance meter is convenient to use in on-site applications that require quick and easy light measurements. The LX-1108 illuminance meter was mounted flat on a work plane at a height of 0.76 m (2.5 feet) above the floor level with the light sensor facing up and located according to 2.5 m × 2.5 m linear grid points marked on the floor within the case study building space. The illumination levels were recorded by the instrument. The LX-1108 meter was used to measure the illuminance level inside the building space in units of lux. Daylight measurement was conducted outside the building to measure the exterior illuminance level with another illuminance meter instrument having the same specifications as LX-1108. The daylight factor was then calculated as the ratio of the work plane illuminance level (at a given point) inside the building space to the exterior illuminance level outside the building space.

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Figure 3.17: Illuminance meter model LX-1108 used in daylight measurements

Figure 3.18 LX-1108 Light Meter Sensor

The LX-1108 Light Meter sensor, as shown in Figure 3.18, has a spectral response that falls within ±5% of the CIE Standard Observer Curve. The human eye responds differently to different wavelengths of light. The CIE Standard Observer Curve defines the response of an average human eye to natural light. Figure 3.19 shows the CIE curve compared to the LX-1108 sensor curve, as provided by Lutron.

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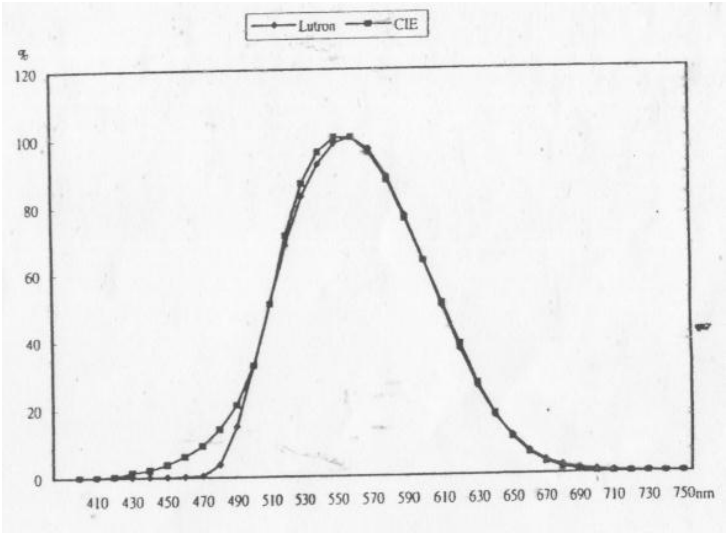

Figure 3.19 LX-1108 Lutron light Sensor Spectral Response Curve vs CIE Curve
Source: Specifications Sheet for LX-1108 light sensor provided by Lutron

For precision measurement, only the 40.00 Lux range need Zero Adjustment. Zero adjustment steps include: 1) cover the "Light Sensor" using "sensor Cover", 2) set to 40.00 Lux range, 3) pushing the "Zero Button", LCD will reach to zero values, 4) upon completion, remove the sensor cover.

The two LX-1108 light meters were obtained from Solar Energy Research Institute (SERI) UKM, with the original intent of using one light meter inside the case study hall and one light meter outside to gather the outdoor level of illuminance. The light meter measure the illuminance in lux, which can be easily converted to the English units of footcandles (see Appendix D for Light Meter features and specifications). Each light meter includes accessories of operation manual, manufactures calibration certificate, and sensor probe. Due to that both light meters purchased by Solar Energy Research Institute (SERI) UKM, the dates of the calibration certificate of both light meters are unknown.

3.5.4 On-site Daylight Measurements

Preparation for Measurements

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Before starting the illuminance level measurements (daylighting and artificial lighting) inside the case study building space, the following care were taken:

- Remove all papers and stickers from the windows, especially windows in the west elevation.
- All case study windows are cleaned and no glasses are dirty or stained.
- All case study lamps are operating and no luminaires are dirty.
- There are no major obstructions to the flow of light from sidelighting or artificial lighting systems throughout the interior, especially at the measuring points (work plane).

Procedure for case study illuminance measurements

Sufficient number and arrangement of measurement points within the interior space of the case study are suitable to obtain a reasonably accurate assessment of the average illuminance level (daylighting or artificial lighting) throughout the interior space.

The interior space of the case study building is divided into a number of equal areas (2.5m * 2.4m), as square as possible. A total of 330 equal square areas are made throughout the interior space. The illuminance level (daylighting =Yes and Daylighting =No) at the center of each square area is measured and the average illuminance level value calculated. This gives an estimate of the average illuminance on the horizontal working plane.

To determine the **minimum number** and positions of measurement points, the Room Index was calculated as the equation below (CIBSE Code, 1994):

$$\text{Room Index: RI} = \frac{L \times W}{Hm(L + W)}$$

Where:

L = length of interior space of the case study building 54m

W = width of interior space of the case study building 35m

Hm = the mounting height 5.24m, which is the height of the lighting fittings above the horizontal working plane. The working plane is measured to be 0.76m above the floor

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in case study space areas. Table 3.8 presents the determination of minimum number of measurement points.

Table 3.8 Determination of minimum number of measurement points

Room Index	**Minimum number of measurement points**
Below 1	9
1 and below 2	16
2 and below 3	25
3 and above	36

Source: CIBSE Code, 1994

To obtain an approximately "square array", i.e. the spacing between the points on each axis to be approximately the same, it may be necessary to increase the number of points (CIBSE Code, 1994).

The dimensions of the interior case study building are:

Length = 54m, Width = 35m, Height of luminaires above working plane (Hm) = 5.24m

$$\text{The Room Index calculation: RI} = \frac{54 \times 35}{5.24(54 + 35)} = 4.055$$

From Table 3.8 the **minimum number of measurement points** is 36 and above.

According to Canada Occupational Health and Safety Regulations (COHSR) the distance between each measurement point should be equal to 3m or less (COHSR, 2009). In addition, refer to “Code for Lighting 2006", published by the Chartered Institution of Building Services Engineers, more small squares are preferred for a larger work area (CIBSE, 2006). To get a good accuracy of reading, it is necessary to increase the number of points as much as possible. As it is not possible to approximate

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a "square array" of 35 and above points within such a rectangle it is necessary to increase the number of points to say 330, i.e. 22 x 15. For the case study interior space of dimensions 54 m x 35m, illuminance measurements at the centers of 330 equally divided squares were taken. Figure 3.20 presents the spaced between illuminanace measurement points.

Therefore, for the UKM case study building the spacing between points along rows across the length of the interior space = 54 ÷ 22 = 2.45m and the distance of the 'end' points from the wall = 2.45 ÷ 2 = 1.23m.

Similarly the distance between points along the width of the interior space = 35 ÷ 15 = 2.35m with half this value, 1.17m, between the 'end' points and the walls.

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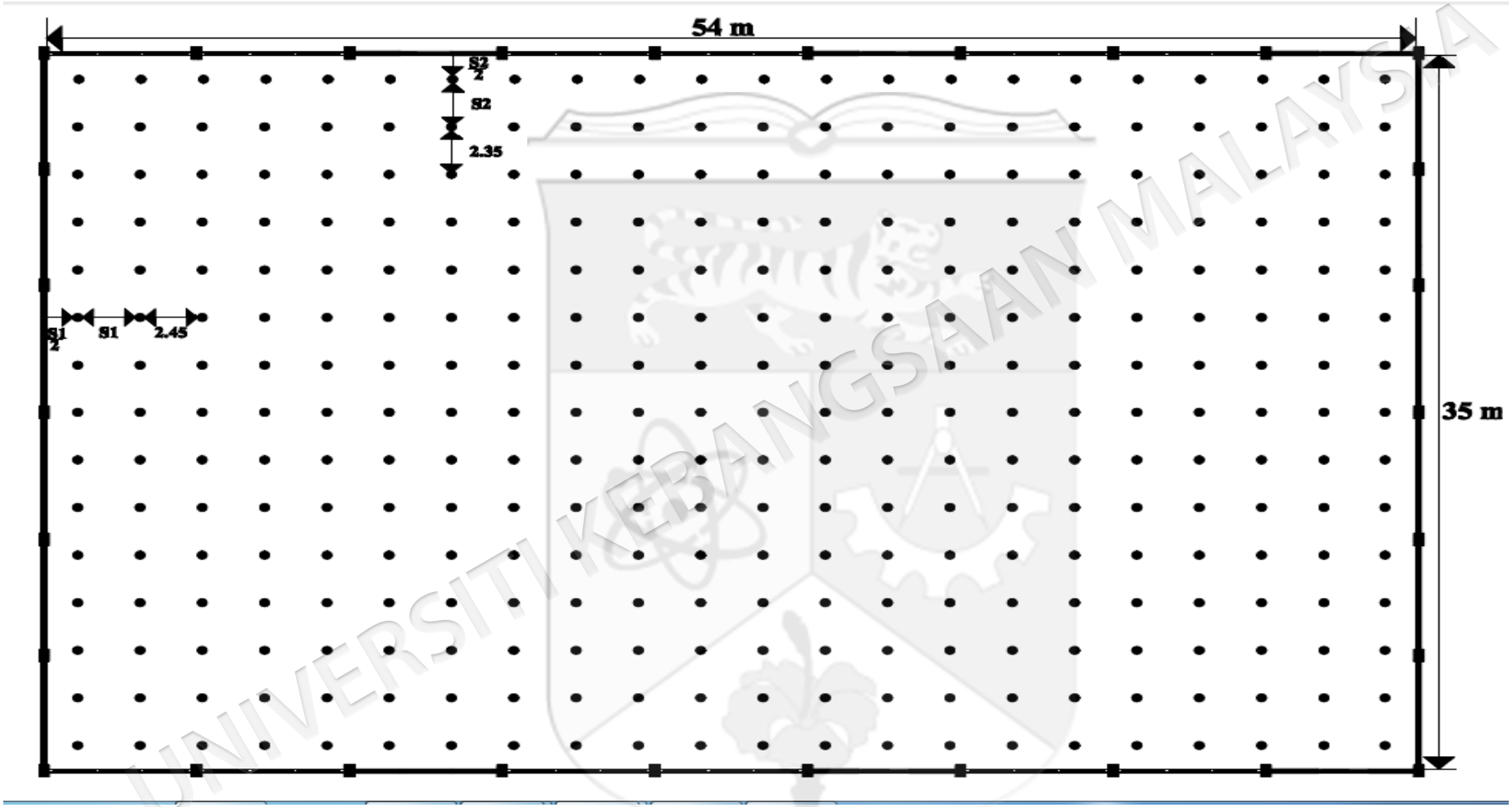

Figure 3.20 Floor plan of the grid layout of the case study building illuminance level measurement points

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Measurement instrument

The instrument that used for the case study lighting level measurement is the Lutron LX-1108 light meter. The instrument has a large LCD display with bar graph display and resolution accuracy of 0.01 Lux to 100 Lux and 0.01 Ft-cd to 10 Ft-cd according to its manufacturer. The light meter allows the user to select between 4 different light types; tungsten, fluorescent, sodium or mercury. The instrument has 5 ranges: 40.00/400.0/4,000/40,000/400,000 Lux. The instrument also has Zero Adjusting button, spectrum meet C.I.E, separate light sensor allows user to measure the light at an optimum position, Lux and Foot-candle unit selection, data hold and peak hold, and memory function with recall. The instrument includes accessories such as manufactures calibration certificate, sensor probe, and user manual.

Measurement technique

The range selector switch of the light meter was set to the lowest range possible (the one giving the accurate reading). This procedure was done to ensure that the accurate reading within the capabilities of the instrument. When measurements were taking inside the case study hall, the light meter was laid horizontally on the workplane surface, 0.76m above the floor, with the light sensor facing up. Also, during reading the meter, the light sensitive cell was insure that not be shield by the analyst's head, because this would result in low reading (so the analyst use the "hold" button so the reading can be suspended and not affected by the analyst's head).

Illuminance level Measurements

After setting the small squares, the illuminance measurements at the center of each square were taken using Lutron LX-1108 light meter with detachable sensor and cable (see figure 3.14 above). The measurements points are a linear grid of 330 equally spaced points on a straight line, separated by 2.45m, starting from the wall and ending at the opposite wall. Figure 3.17 above indicates the points of measuring lighting levels in the case study work space. The 330 measurements points were taken at different points to represents the level of lighting at the work plane in the case study interior space, 0.76m above the floor of the space. The sum of the 330 measurements is then divided by 330 to get the average. The selected measurement points represent

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the average lighting level of daylighting or artificial lighting for the whole the case study work space. The windows curtains for the case study space were totally closed during the artificial lighting illuminance level measurements.

Anather two light meters (Lutron LX-1108 light meter) were used to measure the daylight factors inside the spaces. Both the light meters had a measuring range of 0.01 to 400,000 lux. The Lutron LX-1108 instrument was laid flat at the desk level (in this case 0.76 m from the floor) with the sensor facing up, and was used to measure the interior illuminance in units of lux. A simultaneous measurement was taken outside the case study space using the Lutron LX-1108 instrument to measure exterior illuminance at exactly the same time. Daylight factor (%) was determined as the ratio of the 'interior illuminance at a point inside the experimental space due to daylight' with the 'simultaneous exterior illuminance outside the experimental space on a horizontal plane from an unobstructed hemisphere of overcast sky'.

Actual building daylight was measured under worst-case conditions based on Climate Model Year Data (Group 1998) between March 21 and 27, 2011 (the hottest month), with no wind, inside the case study hall building at UKM. The selection of times was based on the university occupancy schedules as much as possible. The measurement times were 9:00 am, 12:00 pm, and 5:00 pm. However, during the 5:00 pm to 6:30 pm measurement, the results indicated an extremely low daylight illuminance level of 80 lux and below even at a 1.0 meter distance from the case study windows because of the 3.7 m (large) corridor width in the east and west façades of the building. An example of the condition of daylight illuminance level measured on March 21, 2011 without artificial lighting is shown in Figure 3.15. A total of 330 daylight illuminance measurements were made inside the building space for the different times of the day, and each measurement took one and a half hours under real sky conditions.

From the Figure 3.21, it can be seen that the daylight illuminance lux reading near the windows had large variation with lux reading near the wall between the windows or in the center of the case study interior space even though the points are in the same row. This due to that the east façade has nine bays (6 meter each); six of

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these bays have six windows (5.6m x 3.6m) and the rest three bays have walls with a wooding door (1.8m x 2.1m) in each wall.

Similarly to calculate the average artificial lighting illuminance level of the internal space of the case study building, another 330 measurements (at the same points measured previously) were taken inside the case study building. Figure 3.22 shown artificial lighting illuminance levels (lux) measured inside case study building space (March 23, 2011). The artificial lighting illuminance level at every point was measured in the same manner of delighting measurements and the average value was found to be 402 lux.

UNIVERSITI KEBANGSAAN MALAYSIA

300	90	92	140	285	280	270	290	89	91	93	285	283	290	280	126	90	87	300	90	92	140
175	91	94	160	240	242	215	197	115	95	107	215	232	251	210	163	95	93	175	91	94	160
124	107	94	102	120	126	122	115	100	98	106	135	130	147	125	119	103	99	124	107	94	102
108	100	97	105	106	108	109	106	107	105	105	107	117	120	120	116	105	102	108	100	97	105
106	110	108	101	100	100	98	100	106	103	100	97	96	98	105	102	100	98	106	110	108	101
102	101	98	98	98	97	96	97	96	99	99	97	97	98	101	100	99	100	102	101	98	98
101	99	96	96	93	93	93	93	97	95	94	95	96	99	97	95	96	98	101	99	96	96
90	87	86	86	86	86	86	86	86	86	87	87	89	89	89	88	87	87	90	87	86	86
95	94	93	94	94	96	93	93	92	93	96	96	99	101	101	102	102	103	95	94	93	94
98	97	97	98	99	99	97	96	95	96	97	97	101	102	102	101	101	100	98	97	97	98
98	95	95	99	103	108	101	98	101	100	101	108	107	112	108	106	103	99	98	95	95	99
113	99	98	102	109	110	110	105	105	102	104	110	121	117	125	114	104	99	113	99	98	102
119	102	94	107	117	123	125	120	105	95	103	121	149	131	130	115	101	95	119	102	94	107
167	98	90	130	182	175	179	184	110	92	110	240	242	215	197	171	94	91	167	98	90	130
293	91	90	131	211	248	293	296	91	89	90	288	283	264	284	144	91	89	293	91	90	131

Figure 3.21: Measured internal daylight illuminance levels (lux) in case study building space without artificial lighting (March 21, 2011; 12:00 pm to 13.30 pm)

216	272	253	386	319	263	273	312	260	338	355	286	277	296	263	304	274	334	367	250	252	223
283	316	364	383	347	330	348	363	366	364	342	364	369	380	398	375	376	388	368	353	310	264
273	336	355	404	381	378	404	370	396	376	391	385	365	371	367	407	387	378	363	333	329	299
277	373	396	423	410	423	444	405	419	390	394	386	372	400	388	415	414	388	387	348	350	323
308	397	423	468	457	441	459	452	448	416	409	397	399	420	418	435	426	410	429	398	380	335
366	414	422	447	444	443	441	428	426	405	409	413	405	455	425	428	414	420	432	411	418	389
345	348	423	457	432	445	444	421	440	420	407	402	401	437	400	432	405	401	431	407	442	440
350	430	411	455	423	418	425	420	432	393	405	425	427	455	430	441	414	406	432	444	430	402
325	385	398	424	397	429	426	382	408	378	405	434	410	450	411	435	432	423	432	425	493	420
373	420	433	489	468	476	467	448	477	399	408	427	440	484	458	451	450	459	460	455	452	388
370	412	429	464	460	461	455	428	427	431	474	484	510	542	527	555	539	505	508	495	495	472
315	390	403	427	414	396	395	392	395	395	434	461	506	533	504	515	513	506	505	485	457	420
275	330	336	376	360	396	375	313	322	328	378	412	404	444	425	480	464	433	450	428	406	369
320	335	412	421	432	454	454	423	409	389	388	366	321	274	280	300	327	357	355	358	357	288
315	404	388	393	414	234	260	254	303	311	402	415	282	320	301	501	475	412	480	432	290	275

Figure 3.22: Artificial lighting illuminance levels (lux) measured inside case study building space (March 23, 2011)

The identified areas of the case study building space with adequate daylight illuminance level in the work plane are located in halls and auditoriums in academic buildings where the artificial lighting can be switched off, as recommended by the IESNS Lighting Handbook (IESNA 2000).

3.5.5 Daylighting Analysis Parameters

Multiple parameters must be met for good daylight quality. The following parameters and methods are used to evaluate daylighting performance in a space of each toplighting options in this study.

- **Daylight factor (%)**

The daylight factor is the ratio of indoors illuminance level at a given point to outdoors horizontal illuminance level from an unobstructed illuminance of the sky (IESNA 2000). This parameter is used with overcast sky conditions.

- **Daylight illuminance levels (Lux)**

Daylight illuminance level is defined as the total luminous power of light incident on a surface. Illuminance level is measured in lux or footcandles. The Malaysia Standard (MS) and IESNA recommend illuminance levels for different building types and tasks (Standard 2007; IESNA 2000).

- **Daylight distribution and uniformity**

Daylight distribution and uniformity can be described as the uniformity of daylighting levels throughout the space. If the daylighting level varies considerably in the space, it might cause eye strain.

The CIBSE code for interior lighting (Loutzenhiser et al. 2007) is used as a standard to evaluate the daylighting performance of daylighting system design. Dewey and Littlefair (1998) used CIBSE standards parameters for the uniformity of daylight

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distribution to investigate the uniformity and distribution of daylight in roof light single-story model.

The CIBSE code provides guidance on measuring daylight uniformity and distribution. The uniformity of daylight illuminance is defined as the ratio of minimum illuminance to average illuminance over any task area and should not be less than 0.8.

- **Daylight illuminance diversity**

Another daylight analysis parameter is the diversity of daylight illuminance which is the ratio of maximum illuminance level to minimum illuminance level at any point of the space having a boundary of 0.5 m from the wall. The diversity of daylight illuminance should not exceed 5:1. The code and standards are concentrated on horizontal illuminance levels as measure of the uniformity of daylight distribution.

3.5.6 Location of Lighting Control System

In order to record the daylighting levels inside the case study space, lighting control sensor points (called light reference points in the EnergyPlus simulation program) were introduced inside the case study space. The first sensor was typically located at a distance of 27m from the exterior wall and at 17.5m from the other two side walls. The second sensor was typically located at a distance of 2.75m from the exterior wall and at 17.5m from the other two side walls. Two reference points were specified for the case study space; a total of two (2) reference points for the whole case study space. An EnergyPlus with OpenStudio Google SketchUp Plug-in representation of the lighting control sensor locations inside the case study space presented in Figure 3.23.

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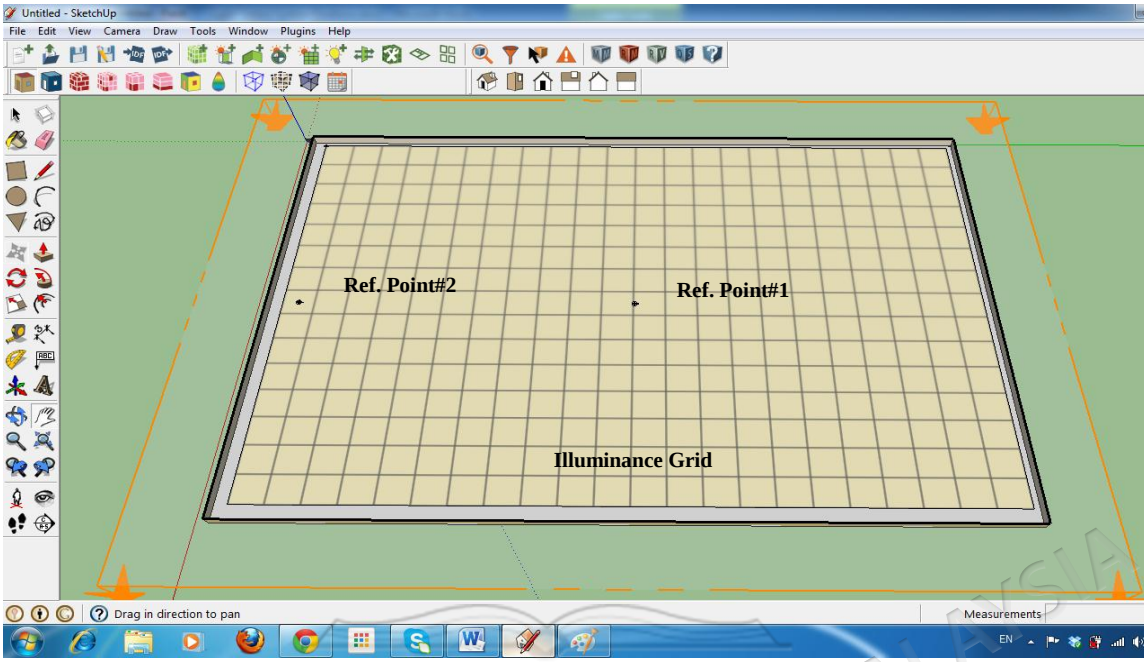

Figure 3.23 EnergyPlus with OpenStudio Plug-in in Google SketchUp representation of the reference points locations inside the case study space

3.6 CALIBRATION OF THE ENERGYPLUS7.0 BASE CASE MODEL

The methodology also comprised EnergyPlus 7.0 base case model calibration for the case study building, which is a major part of this study. The following section describes the processes of generating an EnergyPlus base case simulation model for the UKM case study building. The succeeding section describes the procedure of calibrating the energy the predicted by EnergyPlus simulation program of the base case model to the actual energy consumption.

- **Billing History**

For existing buildings, monthly electricity energy use for each month is required. This data is obtained from utility bills. Electricity energy is expressed as kWh/month. The simulation results for the base case building will be compared to this utility data. If there are significant differences between the billing history and the simulation results for the base case building, then the base case model should be modified to achieve better agreement.

For the existing UKM case study hall building, monthly electricity energy consumption (based on utility bills) for the year 2010 were obtained from the Jabatan Pengurusan Pembangunan (JPP or Department of Development Management) at the UKM campus. the actual monthly electricity energy use for the UKM hall case study building is presented in Table 3.15, where it can be seen that the energy consumption ranges from approximately 30000-35000kWh in the months of Februry, April, May, August, September, November and December, and from approximately 35000-40000kWh in the months of January, March, Jun, July and October.

Table 3.15 UKM case study hall building monthly electricity energy consumption

Month/year	**Actual Energy Consumption (kWh)**
January 2010	36731
February 2010	33006
March 2010	40958
April 2010	34175
May 2010	34307
Jun 2010	37423
July 2010	35148
August 2010	34252
September 2010	31435
October 2010	35959
November 2010	32754
December 2010	31968
Annual energy use	418116

3.6.1 Initial Simulation Results of the Base Case Model

Investigation of the base case simulation result is crucial to understand the segregated energy use of each building component. The initial simulation result (annual energy consumption) predicted by the EnergyPlus software was compared with the actual building energy consumption (monthly electricity energy use). Table 3.16 presents the initial energy simulation results of the base case model.

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Table 3.16 Initial base case model simulation results versus measured energy consumption

	Actual Energy Consumption	Initial Simulated Results	Difference
Annual energy use (kWh)	418116	505920	21%
Annual energy use (kWh/m^2)	221	268	21.3%
Annual energy cost (RM)	120417.4	145705	-

** Peak period from 7am to 7pm = 0.288 sen/kWh*
Off peak period from 7pm to 7am = 0.177 sen/kWh
Maximum demand during peak =35.6 RM/kWh

The initial annual energy consumption of the base case model predicted by the simulation program was 505,920 kWh compared with the actual energy consumption (utility bills) of 418,116 kWh. However, the energy consumption predicted by the EnergyPlus simulation program was high relative to the actual energy consumption, with a difference close to 21% which exceed the annual acceptable range between measured and simulated of ± 15%. The actual energy consumption of the case study building was obtained from the UKM JPP. Billing history (based on utility bills) provides valuable information about the building energy consumption, which can then be compared with that on a similar building in similar or different climates. For most buildings, actual energy use (utility bills) provide information about total building energy consumption, including lighting, cooling, heating, equipment, and domestic hot water. Figure 3.24 presents the actual monthly energy consumption of the case study building.

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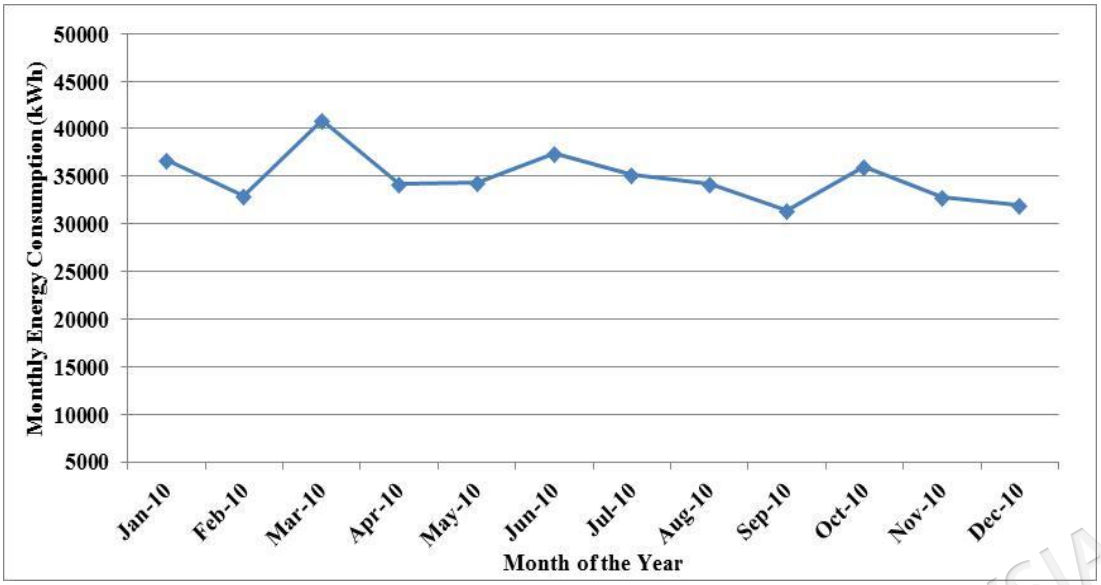

Figure 3.24 Actual monthly energy consumption of case study building

With the initial base case model simulation results, the base case model should be calibrated in EnergyPlus to achieve better agreement, monthly acceptable range value ± 25% and yearly acceptable range value ± 15% (Slade 2010), with the actual energy consumption of the case study building.

3.6.2 Calibrating to Actual Building Energy Consumption

The case study building occupancy schedules, measured energy consumption, and as-built drawings were used to create the input information file for the EnergyPlus7.0 simulation model, and this input files was then adjusted several times to the input files of the occupancy schedules and operations as needed to achieve a better agreement between the simulated results and the actual building energy use (utility bills). The principal rule for comparison between the simulation results and the actual measured data was the monthly building electricity consumption. No data for hourly electricity consumption were found; thus, the calibration for the base case computer model was based only on the monthly building energy consumption. However, to date, no consensus standards have been published on calibration procedures and methods that can generically be used on a wide variety of buildings (Haberl and Bou-Saada 1998).

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For existing buildings, it is recommended that the base case building be completely described and calibrated with the billing history before creating the alternative designs. This will make it easier to keep track of the differences between the suggested design and the base case building. If the base case model has an error, this error will be copied to all the design alternatives, so it is best to get the base case model right before alternatives are created.

- **Calibration**

Many studies have reported on various efforts to calibrate building energy simulation from a real building (Haberl et al. 1993).two studies of particular notice were those of Kaplan et al. 1991 and Hsieh 1988 who showed that calibrations at the hourly level seem to offer the best alignment between the simulation program and the measured data. However, hourly calibration present enormous calibrations problems for the energy analyst, who is usually operating under cost constraints (Haberl et al. 1993). Thus, the difficulties from measurement equipments' cost and extra data availability often make it very difficult to implement the hourly data to calibrate the building energy computer model. The calibration of a simulation to measured monthly utility data has been the preferred method for many years (Diamond & Hunn 1981; Haberl & Claridge 1 985; McLain et al. 1993).

After the base case building model has been created and debugged, a comparison between the energy projected by the model to that of monthly utility bills are made. The utility billing data should be used in the analysis. The analyst may use either monthly utility bills, or measured hourly data to calibrate the model when available (Slade 2010).

Hourly Data Calibration

In hourly calibration, two statistical indices are required to declare a model "calibrated": monthly mean bias error (MBE) and the coefficient of variation of the root mean squared error (CV (RMSE) (Kreider & Haberl 1994; Haberl & Bou-Saada 1998; Haberl & Thamilseran 1996). Equations related with the calculation of MBE

and CV (RMSE) are listed below. The acceptable tolerances for these values when using hourly data calibration are shown in Table 3.17.

$$\text{MBE (\%)} = \frac{\sum_{month}(M-S)_{hr}}{\sum_{month} M_{hr}} \times 100$$

Where:

M_{hr} = the measured kWh for any hour during the month

S_{hr} = the simulated kWh for any hour during the month

$$\text{CVE (RMSE}_{month}) = \frac{\sqrt{\sum_{month}(M-S)^2 hr \times N_{hr}}}{\sum_{month} M_{hr}} \times 100$$

Where:

M_{hr} = the measured kWh for any hour during the month

S_{hr} = the simulated kWh for any hour during the month

N_{hr} = the number of hours in the month

Table 3.17 Acceptable Tolerances for Hourly Data Calibration

Source : Slade, 2010

Calibration Type	Index	Acceptable Value
Hourly	MBE_{month}	± 10%
	$CV(RMS_{Emonth})$	± 30%

*Lower values indicate better calibration

Monthly Data Calibration

Comparing energy use projected by simulation to monthly utility bills is straightforward. After the model is developed and run, monthly-simulated energy consumption and monthly utility billing data are plotted against each other for every month. Equations calculating the error in the monthly and annual energy consumption are given below. The acceptable tolerances for these values when using monthly data calibration are shown in Table 3.11.

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$$ERR_{month}\ (\%) = \frac{(M - S)_{month}}{M_{month}} \times 100$$

Where:

M_{month}= the measured kWh for the month

S_{month} = the simulated kWh for the month

$$ERR_{year} = \sum_{year} ERR_{month}$$

Table 3.11. Acceptable Tolerances for Monthly Data Calibration

Source : Slade 2010

Calibration Type	Index	Acceptable Value
Monthly	ERR_{month}	± 25%
	ERR_{year}	± 15%

*Lower values indicate better calibration

To calibrate the base case model simulation results to the actual energy use, the simulation schedules of the lighting and equipment were adjusted to decrease the lighting and equipment operation hours at night and on weekends until the simulation results reasonably agreed with the actual energy use (utility bills). To improve the overall base case model calibration accuracy, Microsoft Excel graphical analysis software was used to monitor the effects of each alteration to the EnergyPlus base case computer model simulation results. This graphic software excellently presented the EnergyPlus 7.0 base case model simulation results in a graphical manner. Monthly energy consumption data from EnergyPlus 7.0 were imported into Microsoft Excel to understand the exact trend of energy consumption at the monthly level. The comparison and modification procedures were repeated several times until acceptable minimal errors were achieved for the base case calibrated model. Figure 3.25 shows the procedure for calibrating the base case model in EnergyPlus 7.0 simulation software.

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3.6.3 Adjustments for Calibrating the Base Case to Billing History

There are many reasons why the energy predicted in the base case model may not match the billing history (utility bills). After establishing the initial base case model and running the software, we had to calibrate the model to mirror the existing utility bills. For the UKM base case model, it was found that there are some differences between monthly electricity energy use and the simulation results. For each month, some adjustements are made to better calibrate the base case model. The comparison and adjustment process was repeated several times until an acceptable calibrated simulation model with minimal amount of errors was established. The case study model calibration involved the following main steps:

- Initial simulation run with one Single Zone system without any heating system
- Initial simulation run with 2 systems (2 Packaged Single Zone).
- Modified Single Zone (SZS) system using defaults from the EnergyPlus manual
- Modified cooling set-point temperatures for the systems
- Modified occupancy, lighting, equipment schedules using weekday and weekend profiles based on actual schedules and monthly electricity consumption.
- If the electricity consumption predicted by the EnergyPlus simulation is high relative to the utility bills in some months, modified EnergyPlus simulation schedules to increase lighting and equipment hours at nights and weekends within that months.
- In case of the electricity consumption predicted by the EnergyPlus simulation is low relative to the utility bills in any month, modified EnergyPlus simulation schedules to reduce lighting and equipment hours at nights and weekends within that month.

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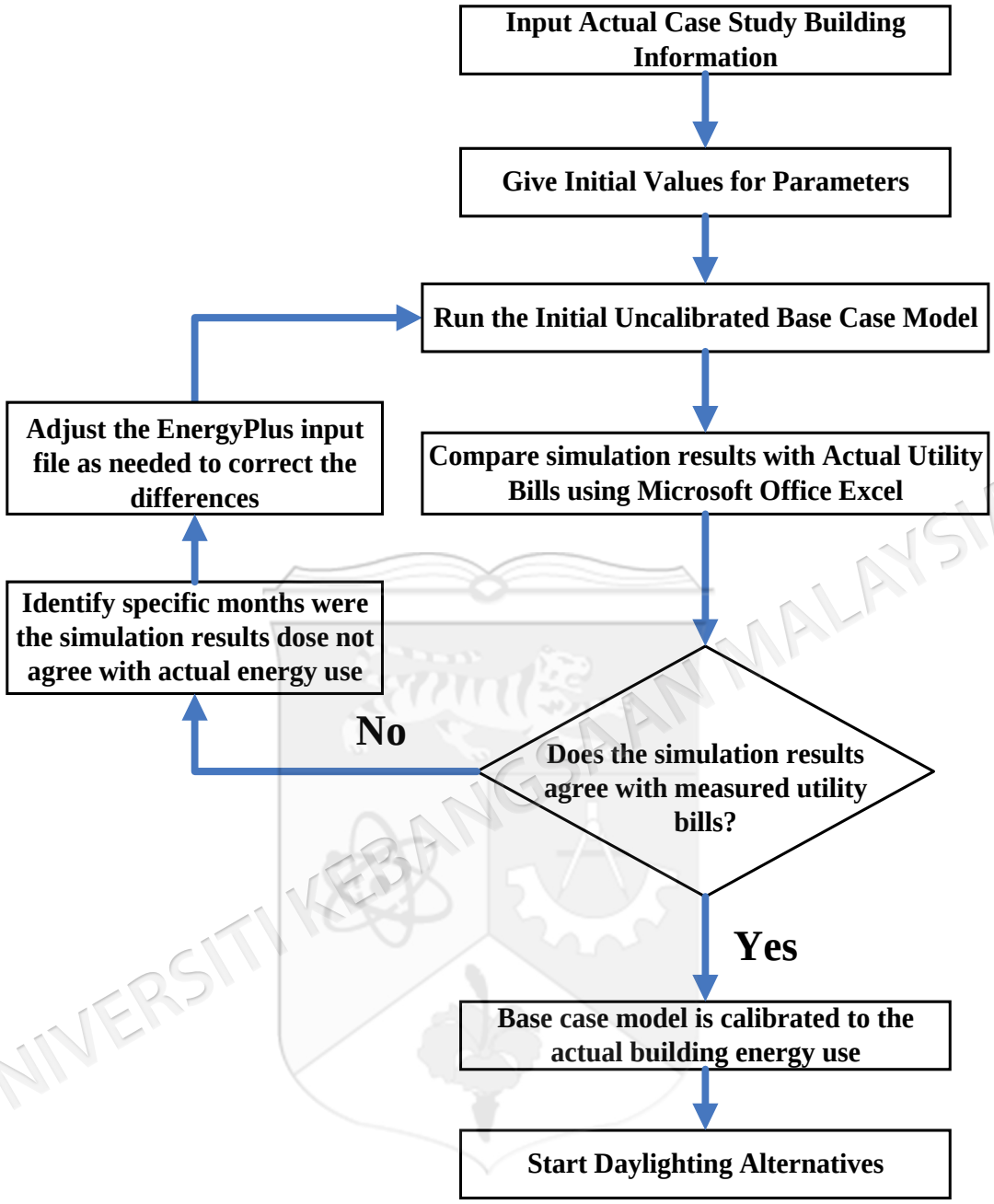

Figure 3.25 EnergyPlus procedure for calibrating base case computer model

The information regarding to the operation time of the case study building was used to provide the schedules for occupancy, lighting, and equipment in the EnergyPlus with OpenStudio simulations. Table 3.3 shows the case study occupancy and operation schedules used in the EnergyPlus simulation. Although the schedules did not perfectly match with existing conditions, they represented a typical weekday

and weekend operation hours for the case study building that achieve the level of calibration for this study.

To achieve calibration at the monthly level for the case study building electricity consumption, monthly plot was developed for the twelve months of the year (January to December) for the simulated case study building using the weekday and weekend schedule. This plot was then compared with the monthly electricity consumption profile for the twelve months for the existing case study building using utility bills.

With the base case model calibrated to the building energy use and the simulation model showing reliable output results, the simulated energy consumption and measured energy use were compared. Table 3.19 presents the actual versus simulated energy use of the UKM case study building from January 2010 to December 2010 according to EnergyPlus 7.0. This table reports the differences (%) between the simulated and actual energy consumption. The highest discrepancies between the simulated and actual energy consumption occurred in June 2010, with a difference of 22.7%, and in August 2010, with a discrepancy of −16.0%. These discrepancies between the simulated and actual monthly energy consumption are considered within the acceptable error range defined by the ASHRAE handbook (Handbook 1987) and Zmeureanu et al. (1995). Figure 3.26 presents the simulated versus actual monthly energy consumption of the UKM hall case study building, where the error bars of ±22.7% on the simulated and actual energy use are shown.

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Table 3.19 Monthly simulated energy consumption versus actual

Month/year	Energy consumption (kWh)		Difference (%)	**Acceptable Range**
	Actual	Simulated		
January 2010	36731	36876	0.4	± 25%
February 2010	33006	32556	-1.4	± 25%
March 2010	40958	48952	19.5	± 25%
April 2010	34175	41010	20.0	± 25%
May 2010	34307	41259	20.3	± 25%
Jun 2010	37423	45902	22.7	± 25%
July 2010	35148	33233	-5.4	± 25%
August 2010	34252	28760	-16.0	± 25%
September 2010	31435	37528	19.4	± 25%
October 2010	35959	39024	8.5	± 25%
November 2010	32754	35900	9.6	± 25%
December 2010	31968	35873	12.2	± 25%
Annual Total	418116	456873	**9.3**	**± 15%**

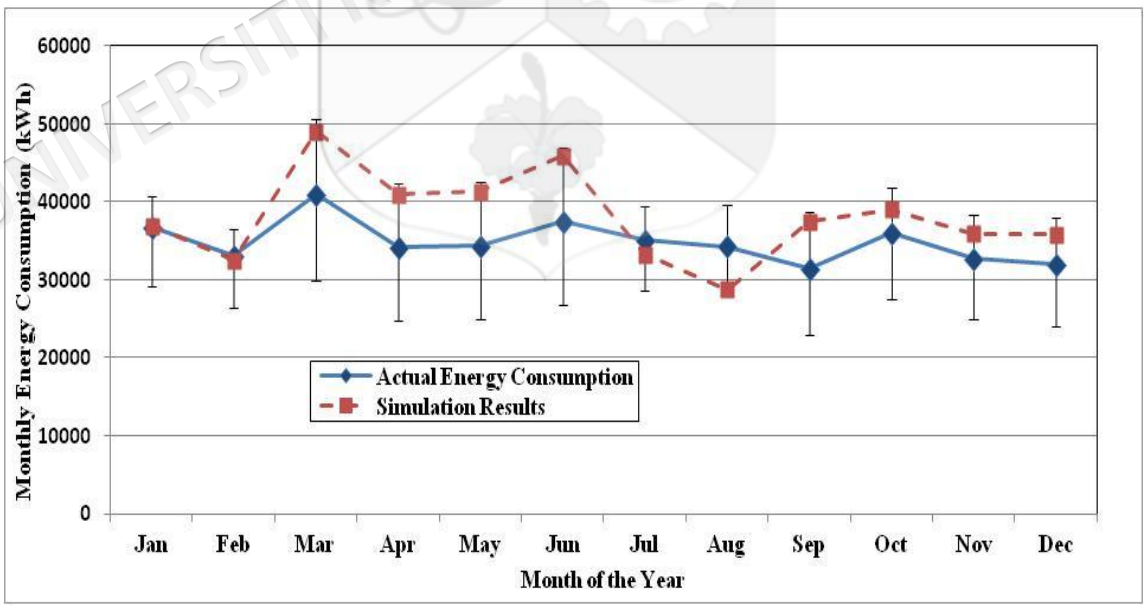

Figure 3.26 Comparison of simulated versus actual building energy consumption

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3.6.4 Calibrating to Actual On Site Measured Weather Data

The study conducted by (Haberl & Bou-Saada 1998) indicated that there is a relation between on-site measured weather data and that weather file used in EnergyPlus 7.0 simulation program to their impact on the energy consumptions. The Kuala Lumpur IWEC weather file was used for the EnergyPlus 7.0 simulation in this study. As the study was carried out for the Universiti Kebangsaan Malaysia, Kuala Lumpur, it was found that it is very important to make a comparison between the temperature profiles for the on-site measured weather data for UKM and the typical weather data from EnergyPlus weather file (EPW) that will be used in the EnergyPlus7.0 simulation software. A comparison between the on-site measured daily outdoor dry bulb temperatures obtained from the university campus and that ones from Kuala Lumpur EnergyPlus (EPW) weather file.

The UKM on-site measured daily outdoor dry bulb temperature for the years 2010 and 2011 were obtained from department of Faculty of Social Sciences and Humanities and the weather station located inside UKM campus. The UKM weather data includes daily minimum and maximum dry bulb temperature and wet bulb temperature, daily dew point temperature, daily relative humidity (RH), daily evaporation, and daily wind speed. It was found that the temperature profiles of both weather file fall in the similar range of maximum and minimum values, but when evaluated at daily level it showed a lot of dissimilarities. The daily level dissimilarties range from 0.0 % to 19.5% and the annual average dissimilarities between both weather file range 8%. Figure 3.27 shows a comparison between the measured outdoor daily dry temperatures for the case study building and the Kuala Lumpur EPW weather file.

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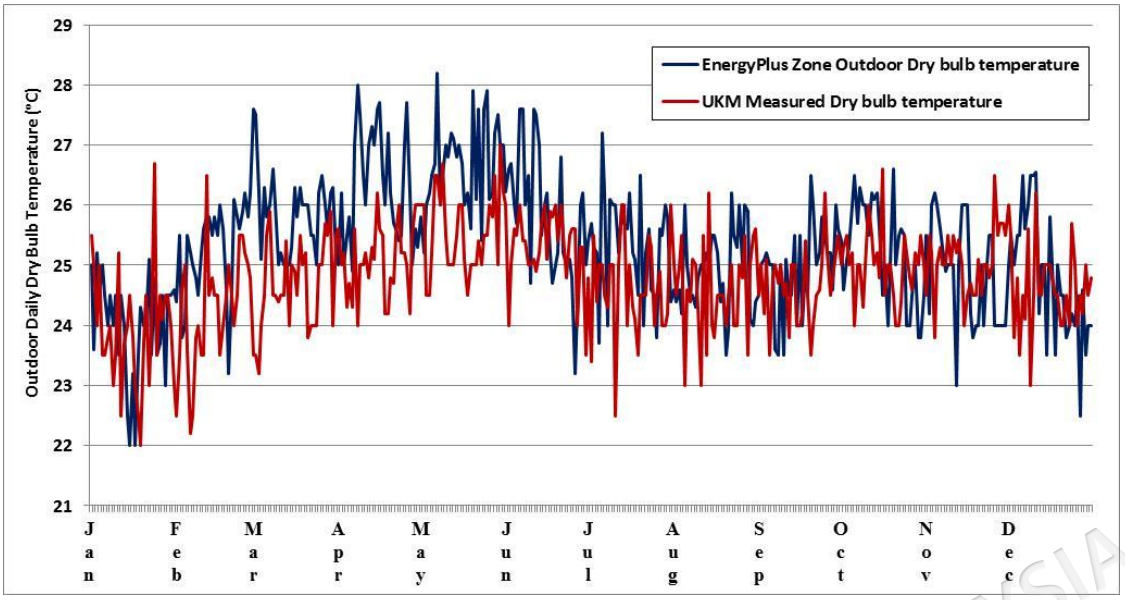

Figure 3.27 Comparison between UKM measured outdoor dry bulb temperatures for case study building and EnergyPlus zone outdoor dry bulb temperatures

To calibrate the base case model at the monthly level, the actual monthly energy consumption for the entire building was compared with the measured average monthly dry bulb temperatures, and the simulated monthly energy consumption for the entire building was compared with the average monthly dry bulb temperature from the EnergyPlus (EPW) weather file.

After the base case model was calibrated, the base case model was considered as a reference base case for all simulations to study the effects of toplighting design alternatives on energy performance.

3.6.5 Design Limitation of Toplighting System

The limitation of the topighting system design in this study is limited to the study of three types of toplighting systems namely skylight, sawtooth, and roof monitor with four types of glazing, main cardinal orientations, and two spacing-to-height ratio which we will refer to as “toplighting”. This study is limited to 5% to 60% TFR. Toplighting system is a form of daylighting strategy as can be seen from the figures discussed in Chapter 3 page 101 and 102. The functions of the design of toplighting systems are for only daylighting. The ventilation and thermal comfort aspects were

not considered in this study. The daylighting evaluation is limited to determining the work plane illuminance level at 0.76 meter from the floor level. The energy evaluation is limited to determining the potential of energy savings (lighting and total) that can be obtained in the case study building from the above toplighting strategies when illuminance level target at the work plane is 500 lux.

3.7 SUMMARY

The methodology chapter provides the information and the procedures involved in creating a base case EnergyPlus energy simulation model for the UKM case study building. The hall area inside the UKM case study building was analyzed using waik-through, daylight factor, and illuminance level measurements to understand existing lighting conditions and the potential for toplighting daylighting systems. The case study building charactarastsies, measured data, and as-built drawings were used to create the base case input file for the simulation, and this file was then modified through a number of adjusments of different input parameters in order to match the simulated results to the actual monthly electricity use. Then, computer simulation models were created for the base case and the three suggested toplighting strategies for building lighting and energy performance evaluations using EnergyPlus with OpenStudio building energy simulation program. Daylight factor and illuminance level from the actual case study space and computer simulation outputs were studied for trends in interior daylight illuminance levels.

Consistent calibration was achieved between the billing history of the UKM case study building and the simulation results at the monthly level. Lighting and cooling energy consumption data for the UKM case study building were unobtainable for the calibration. Therefore, the simulated lighting, cooling, and equipment energy consumption profiles were created for the case study model with EnergyPlus 7.0 (Appendix A). Lighting, equipment, and occupancy schedules were considered crucial in calibrating the case study model. To achieve the monthly and annual energy use calibration for the case study model, a common method was followed. Actual monthly electric energy consumption data (utility bills) for the UKM case study building was compared with the EnergyPlus simulation results to reveal the differences. The

modification procedures for the occupancy schedules were repeated several times until acceptable minimal errors were achieved for the base case model. After every change in operating occupancy schedules, Microsoft Excel was used to understand the exact trend of the monthly electric energy use data from the EnergyPlus output file. Another major factor that can improve the accuracy of the calibration process is the availability of the UKM on-site measured weather data. The calibration process for the base case computer model required a considerable amount of time in this study. Calibration was considered a highly important part in validating the simulation results for future research.

This chapter also describes the methodology used in current study, including the development of the three toplighting alternaitevs, daylighting performance methodology, and energy performance methodology. The daylighting pereformnace were done using OpenStudio with EnergyPlus simulation program to compare the results with actual measured from the case study building. The toplighting alternatives were simulated by OpenStudio and EnergyPlus simulation program with 1 to 1 and 1 to 1.5 spacing-to-height ratio of: skylight, sawtooth, and roof monitor. The toplighting alternatives simulated were 9 units and 6 units of skylight, sawtooth, and roof monitor with double Low-e clear glazing.

The energy performance methodologies of three toplighting alternatives were simulated using OpenStudio and EnergyPlus simulation program. The evaluations of the energy performance are based on the results of OpenStudio and EnergyPlus simulations with 1 to 1 and 1 to 1.5 spacing-to-height ratio of: skylight, sawtooth, and roof monitor with single clear, double clear, double reflect clear, and double Low-e clear glazing and then compare with the actual monthly electricity consumption. The three toplighting alternatives used the same materials and asimilar constraction style, so the only difference was in the design of the toplighting alternatives.

The simulation results for the EnergyPlus7.0 calibration model and the building energy use and energy and cost savings analysis are presented in the next chapter.

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CHAPTER IV

RESULTS AND DISCUSSIONS

4.1 DAYLIGHTING ANALYSIS

4.1.1 Introduction

This chapter presents the different shapes and geometries of toplighting strategies and their effect on the daylighting quality of the case study building space. The toplighting alternatives in this chapter were designed and modeled using OpenStudio SketchUp Plug-in support whole building energy modeling with EnergyPlus simulation software to allow daylight to penetrate the building space and provide the acceptable amount of daylight illuminance level, daylight factor, daylight illuminance uniformity and distribution, and daylight glare. The daylighting quality is evaluated for each toplighting option using different parameters described in Chapter III: daylight factor, illuminance level, and daylight illuminance uniformity and distribution. This chapter also presents a comparison of the skylight, sawtooth, and roof monitor cases. The objective is to formulate a recommendation for the most appropriate toplighting system design that can provide acceptable daylight quality and simultaneously maximize the energy savings of the building.

4.1.2 Comparison of Daylight Measurement of Case study Building and EnergyPlus with OpenStudio Simulation results

The daylight illuminance level of the case study building was measured and compared with the OpenStudio simulation results to formulate a context for any problems or discrepancies that might arise. The daylight measurements were taken underactual clear and overcast sky conditions at UKM, Kuala Lumpur. The methodology of

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measuring daylight illuminance is described in Chapter III. For the clear sky condition, a comparison of the daylight illuminance levels was conducted. For the overcast sky condition, a daylight factor comparison was conducted. The UKM case study building represented the base case for the simulation of the daylight parametric analysis conducted to evaluate the effect of different shapes of toplighting options on daylighting quality. A comparison of the daylight illuminance level of the base case and the OpenStudio simulation results was then conducted for each toplighting option: skylight, sawtooth, and roof monitor, with 1-to-1 and 1-to-1.5 spacing-to-height ratios, and with a double low-e clear glazing type available in EnergyPlus.

As part of the daylighting analysis for the case study academic hall, actual daylight factors were measured at two points inside the hall space and compared with daylight factors calculated by the EnergyPlus simulation program for base case model with sidelighting system. Daylight factor (%) was determined for each point as the ratio of the 'interior illuminance at a point inside the case study space due to daylight' with the 'simultaneous exterior illuminance outside the case study space on a horizontal plane from an unobstructed hemisphere of overcast sky'. The daylight factors at 22 points along the central axis of the base case space were then compared with daylight factors resulting from applying toplighting alternatives using the analysis illuminance grid provided by EnergyPlus program.

4.1.2.1 Locations of measurement points for case study building and EneryPlus model

Locations of measurement points for the different analysis are given in Figures 4.1, 4.2, and 4.3. For the daylight factor analysis, two points between the actual case study space with only sidelighting and the EnergyPlus base case model were compared. For the daylight factor and illuminance level analysis in EnergyPlus when applying toplighting alternatives, 22 points along the central axis of the base case space are used. For the EnergyPlus illuminance level uniformity analysis when applying toplighting alternatives, 330 square reference points (2.45m x 2.35m) using the analysis illuminance grid provided by EnergyPlus are used.

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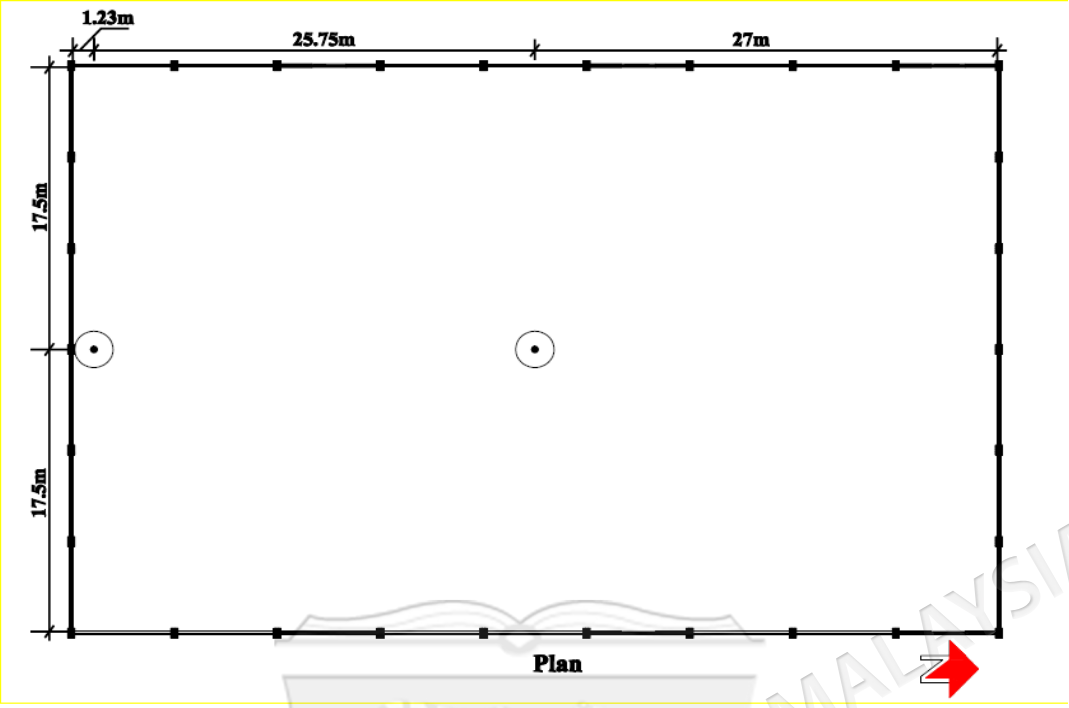

Figure 4.1 Measurement points locations for comparison daylight factor of the actual case study space and EnergyPlus base case model

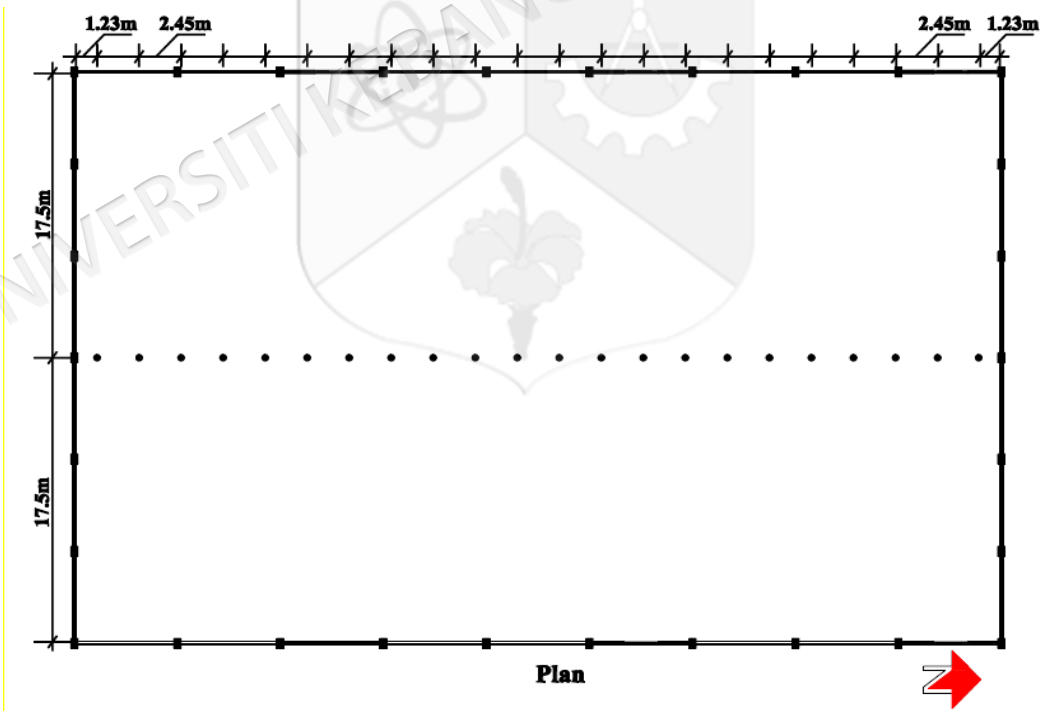

Figure 4.2 Measurement points locations for EnergyPlus base case model: daylight factor and illuminance level analysis

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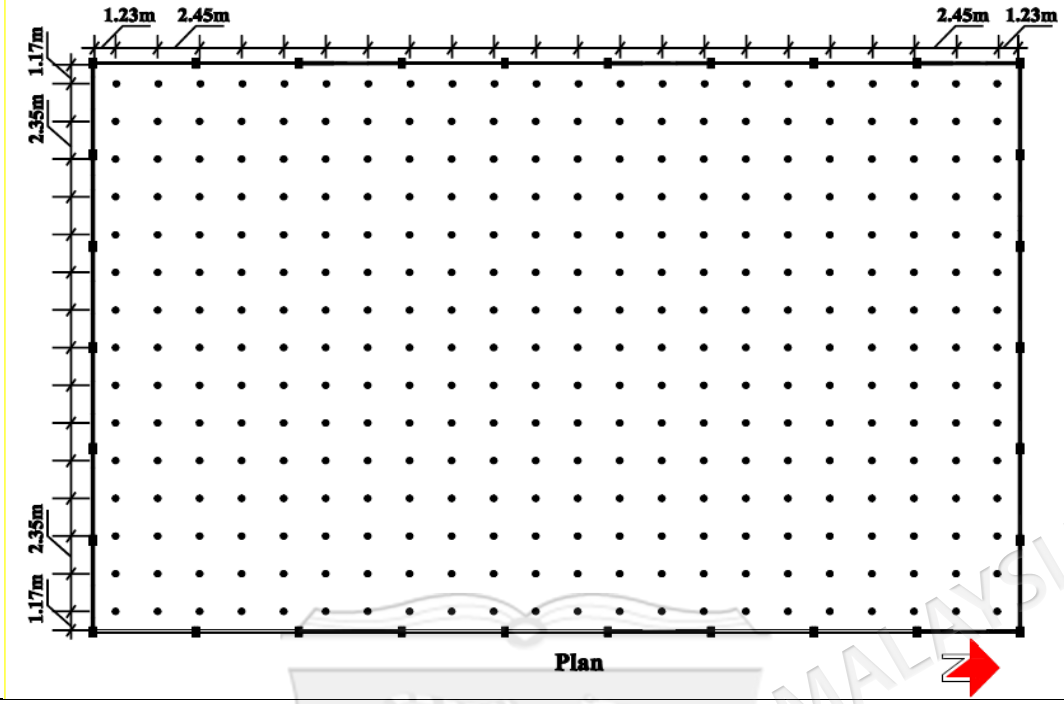

Figure 4.3 Measurement points locations for EnergyPlus base case model: daylight uniformity analysis

4.1.2.2 Analysis of the Overcast Sky Daylight Measurements

In EnergyPlus, the daylight factor reports contain the pre-calculated hourly daylight factors for the four CIE sky types (clear, turbid clear, intermediate, and overcast sky) at 12:00 noon and two daylight reference points for every exterior window of the daylight zone. The file is CSV-formatted and ready for spreadsheet viewing (Doe 2010).

The daylight measurements demonstrate that, under overcast sky conditions, the daylight factor obtained from the case study building and that obtained from EnergyPlus are quite different. The daylight factor generated from EnergyPlus is slightly higher than that from the case study building measurements. The overall difference is approximately 9.2%. In EnergyPlus, the measurement was located at the latitude of 3.12°N. EnergyPlus might have overestimated the daylight factor value. The actual overcast sky in Kuala Lumpur might have actually generated 9.2% less of the daylight factor value. This difference may be a result of the measurement procedure. Overcast sky measurement was conducted under the actual sky and not

under the CIE overcast sky condition as in the base case computer model simulated in EnergyPlus with OpenStudio Plug-in calculations. Furthermore, the daylight measurements were conducted outside the UKM building, parts of which were surrounded by obstructions, such as corridors columns, trees and neighboring constructions. By contrast, the base case model conditions in EnergyPlus with OpenStudio included no obstructions from trees or buildings as seen on Figure 4.4. Table 4.1 shows the daylight factor simulation result generated from the EIO file type in EnergyPlus versus that from the case study building measurements.

Figure 4.4 Outside views for the UKM case study academic hall surrounded by obstructions, such as corridors columns, trees, and constructions

Table 4.1 Daylight factor simulation result from EnergyPlus versus actual case study measurements

	Simulation Results		On-site measurements	
	Reference Point #1	Reference Point #2	Reference Point #1	Reference Point #2
Overcast sky Daylight Factor	1.95	2.82	0.18	0.22

4.1.2.3 Analysis of Intermediate Sky Daylight Measurements

The measurements show that under intermediate sky conditions, the daylight illuminance levels from the case study building and those from the EnergyPlus are also considerably different. The daylight illuminance level from the actual case study building measurement is slightly smaller than the average daylight illuminance level generated from EnergyPlus, with a total difference of approximately 19%. In EnergyPlus, the daylight illuminance was measured at the latitude of 3.12°N. The interior daylight illuminance value might have been overestimated by approximately 19% in December. This value increases to 36% in March. Furthermore, the actual intermediate sky condition in Kuala Lumpur might have generated less daylight illuminance than that in EnergyPlus.

For the intermediate sky analysis, the actual interior daylight illuminance level was measured and compared with the simulation results. The interior daylight illuminance levels for the case study model produced from the CSV file in EnergyPlus is calculated and reported in Table 4.9. Figures 4.5-4.7 present the illuminance map of the case study model generated from EnergyPlus.

Table 4.9 Case study computer model interior illuminance levels generated from CSV file in EnergyPlus with OpenStudio.

Date/Time	21 Mar 9:00 am	21 Mar 12:00 pm	21 Mar 15:00 pm
Average	212	390	387

Continued

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Continued

Maximum	1915	2738	2325
Minimum	66	195	211
	21 Jun 9:00 am	21 Jun 12:00 pm	21 Jun 15:00 pm
Average	282	387	338
Maximum	2170	2455	2099
Minimum	96	191	168
	21 Dec 9:00 am	21 Dec 12:00 pm	21 Dec 15:00 pm
Average	145	361	366
Maximum	1396	3451	3451
Minimum	55	170	174

The results show that, in the intermediate sky condition, the illuminance levels results from the case study space and from the EnergyPlus base case model are different. The case study measurements are somewhat lower than the illuminance levels generated from EnergyPlus base case model, with an overall discrepancy of about 27%. It seems that EnergyPlus, for the measurement location of latitude 3.12°N under intermediate sky, might overestimate the illuminance level value and that the real intermediate sky in Kuala Lumpur might generate illuminance level value 27% lower.

Some possible causes of the discrepancy in intermediate sky condition could be as the following:

- The intermediate sky measured is real Kuala Lumpur sky and not CIE intermediate sky as in the sky model used in the EnergyPlus calculations.
- The real intermediate sky measured is in Universiti Kebangsaan Malaysia, Bangi which might have different characteristics as compared with the intermediate sky in Kuala Lumpur.
- The measurements were conducted inside the case study academic space where there are obstructions of light reflectance from more than 800 chairs and tables. This is different from the conditions modeled in EnergyPlus where there are no interior obstructions such as chairs and tables.

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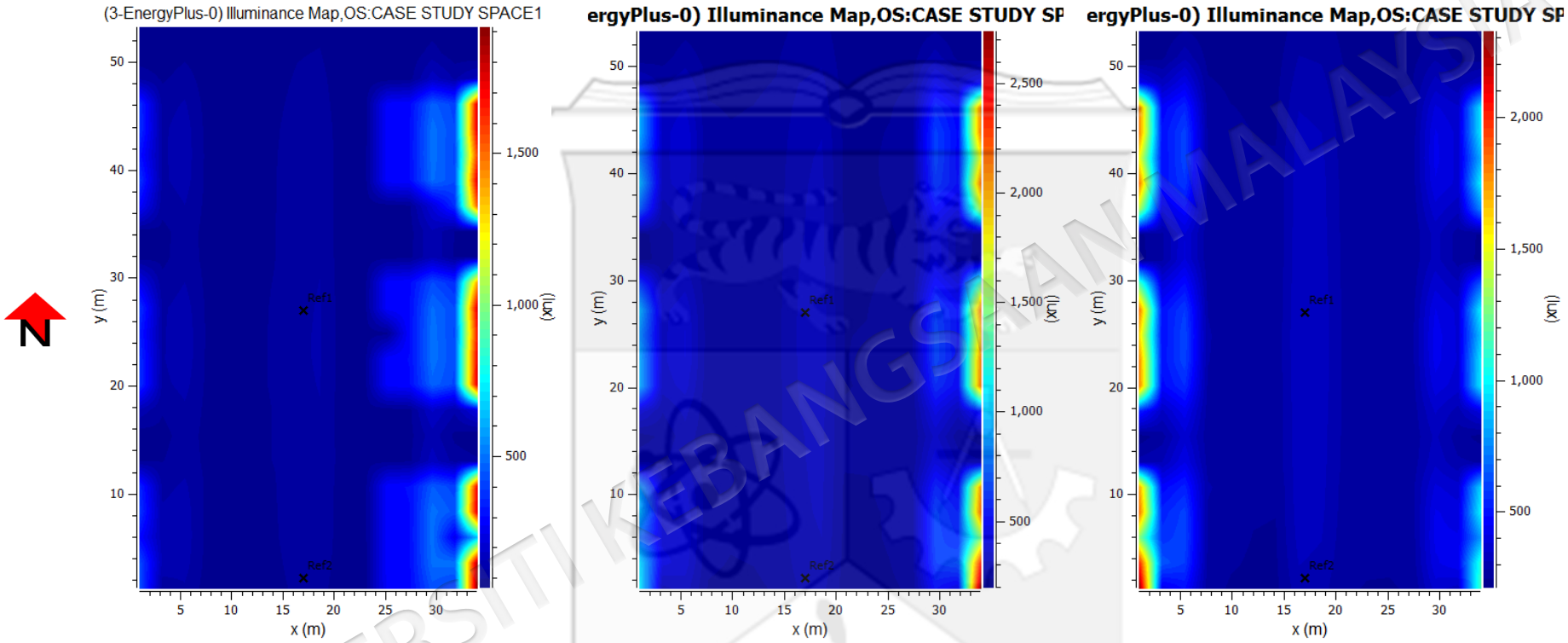
Date	21 March 9:00 am	21 March 12:00 pm	21 March 9:00 pm
			
Average	212	390	387

Figure 4.5 EnergyPlus average daylight illuminance level map of case study model. 21 March

Note: The two reference points in the diagrams are the locations of the lighting control systems in the EnergyPlus case study space

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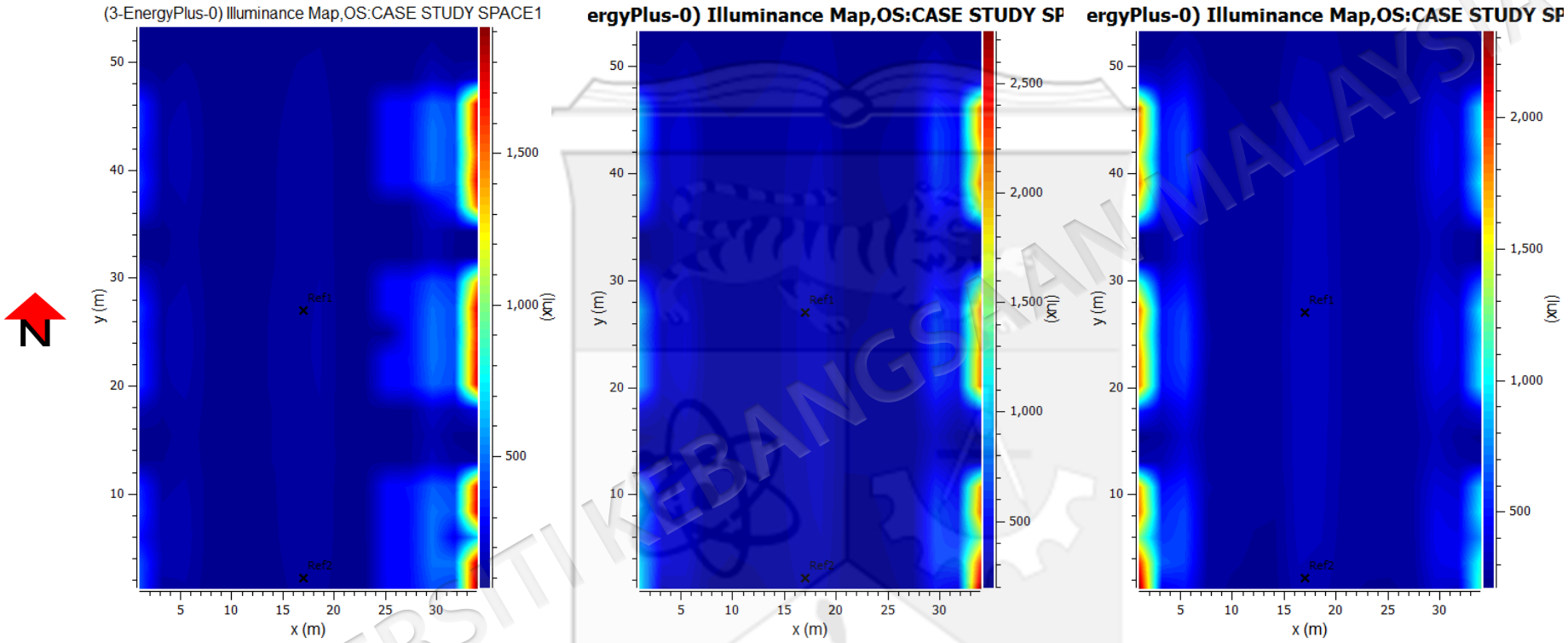
Date	21 Jun 9:00 am	21 Jun 12:00 pm	21 Jun 15:00 pm
			
Average	282	387	338

Figure 4.6 EnergyPlus average daylight illuminance level map of case study model. 21 Jun

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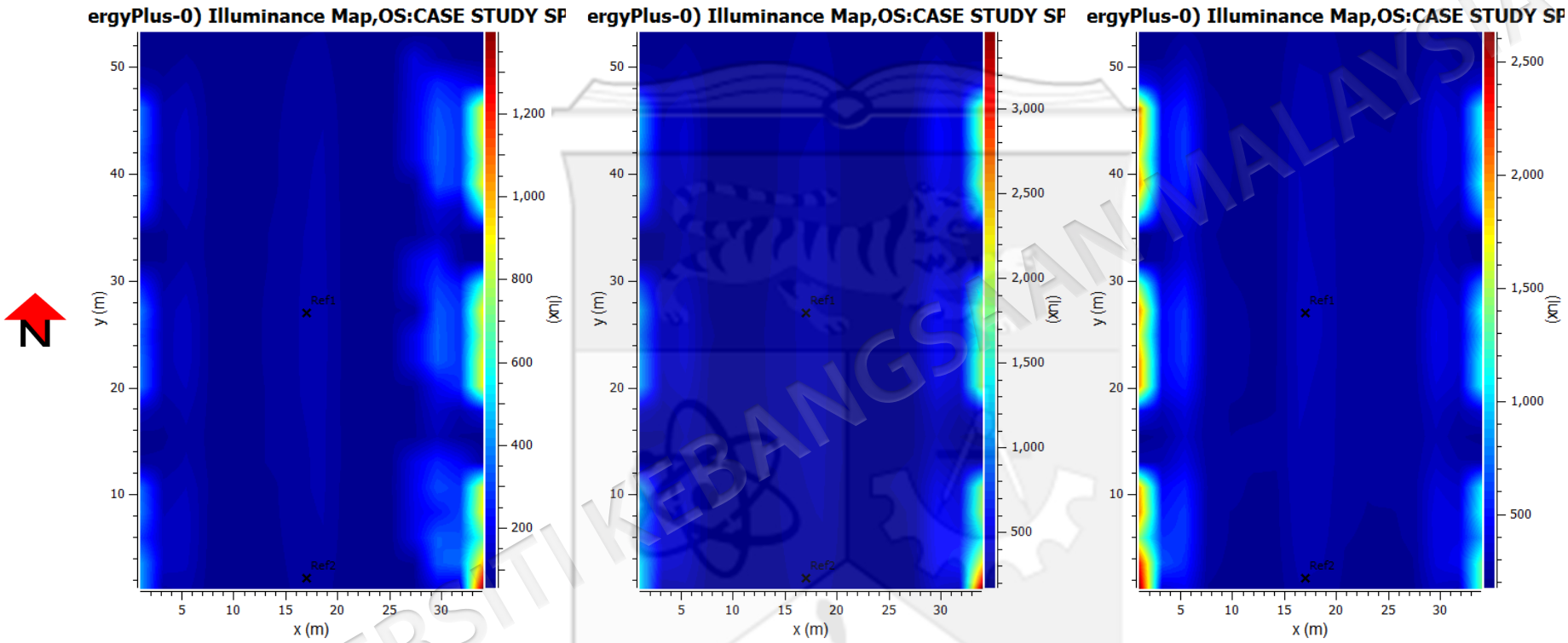
Date	21 December 9:00 am	21 December 12:00 pm	21 December 15:00 pm
			
Average	145	361	366

Figure 4.7 EnergyPlus average daylight illuminance level map of case study model. 21 December

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4.1.3 Toplighting Alternatives Analysis: 1-to-1 Spacing-to-Ceiling Height Ratio

For the overcast sky conditions, daylight factors comparisons between the toplighting alternatives were made, while for the intermediate sky conditions, illuminance levels comparisons between the toplighting alternatives were made. These daylight parameters were analyzed for daylight level and daylight uniformity. These daylight values were obtained from the calculations of the EnergyPlus output files described in Chapter 3. OpenStudio SketchUp Plug-in with EnergyPlus was used for daylighting calculations and illuminance map rendering. The toplighting alternatives modeled were the 1-to-1 and the 1-to-1.5 spacing-to-height ratios of skylight, sawtooth, and roof monitor cases with a double low-e clear 6 mm to 13 mm air glazing type.

A double low-e clear type was used instead of a single clear or double clear glazing type because the former yields the best energy performance among the four glazing types, as presented in Chapter 4. The optical and thermal attributes of the glazing types are listed in Table 3.7 in Chapter 3. For the analysis of the illuminance level and daylight distribution, the simulation date and time are June 21 (summer solstice), March 21/September 21 (equinoxes), and December 21 (winter solstice), at 9:00 am, 12:00 pm, and 3:00 pm based on the LBNL reference on toplighting system designs.

4.1.3.1 Daylight Factor Analysis

The calibrated EnergyPlus base case model and the Kuala Lumpur IWEC weather file were used for the simulations. The base case model was then modified to include the toplighting alternatives to determine the effect of daylighting on the daylight quality. The daylight factors from the base case model were then compared with those obtained from the EnergyPlus simulation for the toplighting alternatives. A comparative graph of the daylight factors of toplighting alternatives with 1-to-1 spacing-to-height ratio versus those of the base case is presented in Figure 4.8. The toplighting alternatives analyzed are the skylight, sawtooth, and roof monitor cases.

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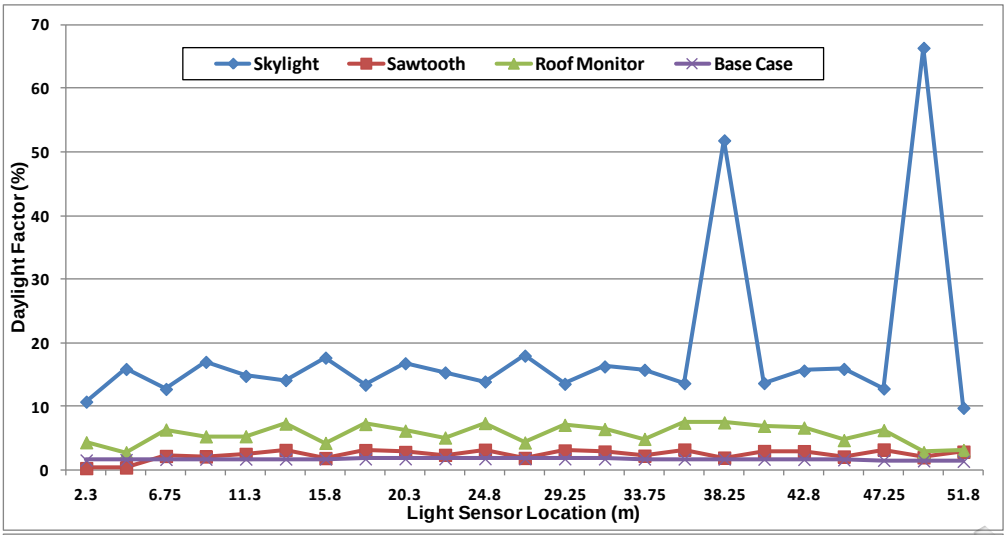
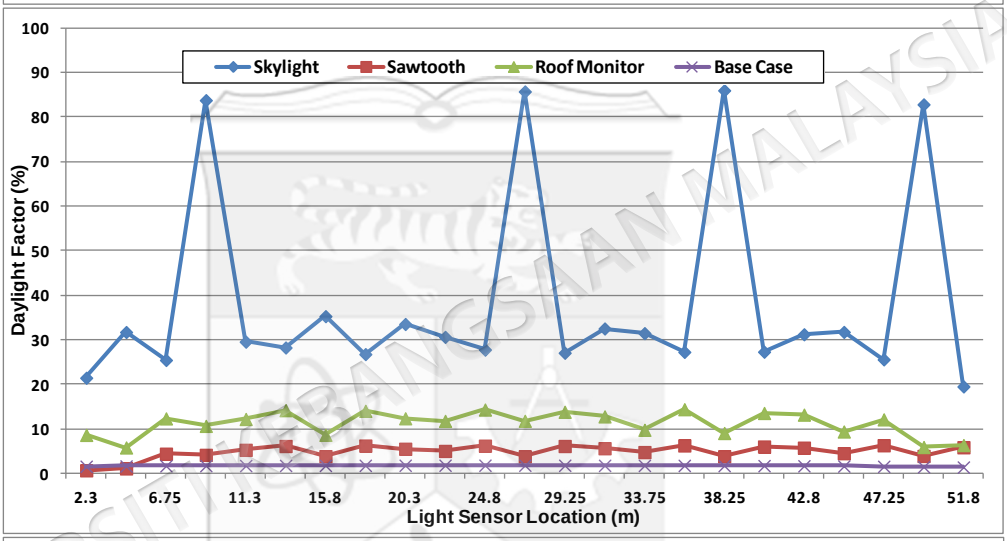
a)
5%



b)
10%



c)
15%

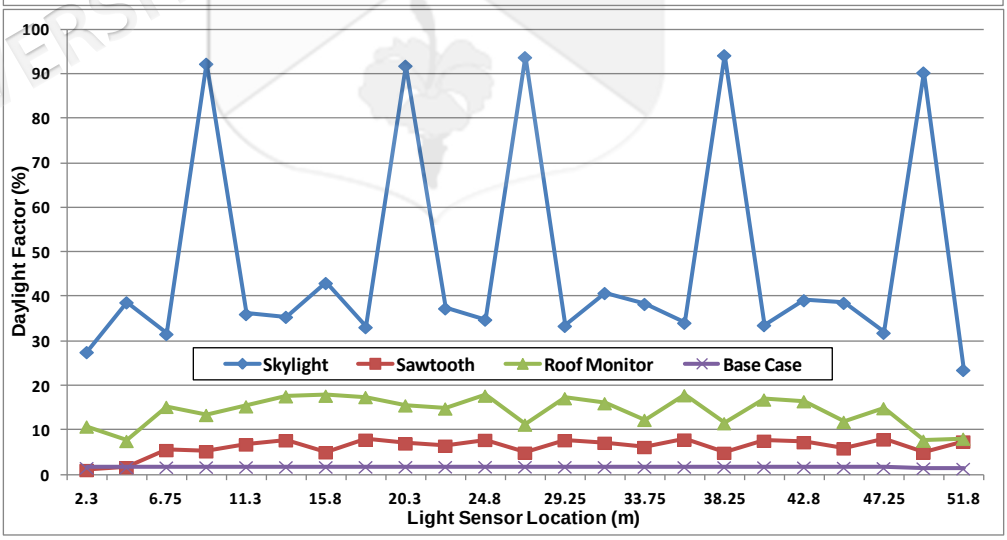


Figure 4.8 Comparison of daylight factors of 1-to-1 toplighting alternatives and base case with a TFR: a) 5%, b)10%, and c) 15% under overcast sky conditions

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As Figure 4.8 shows, the daylight factors from the calibrated base case model (case study building) were consistently lower than those from the toplighting alternatives. This difference may be a result of the various factors of the case study space, the main factor being the presence of a large corridor near the windows in the eastern and western elevations of the case study, which reduces the daylight penetrating the interior space. Other factors include the actual glazing light transmittance, reduction of internal light reflections by furniture, and reduction of daylight illuminance entering the building space as a result of trees and neighboring buildings outside.

For the daylight factor analysis under an overcast sky condition, the skylight alternative yields the highest daylight factor value among all toplighting alternatives. The sawtooth and roof monitor cases produce a lower maximum daylight factor value. The sawtooth alternative produces the lowest minimum values.

The toplighting alternatives evaluated include the skylight, sawtooth, and roof monitor cases. The 15% TFR skylight alternative yields the maximum daylight factor value of approximately 43%, whereas the sawtooth alternative yields a maximum daylight factor value of approximately 7.9%. The skylight and sawtooth alternatives yield a maximum difference of daylight factor of approximately 35.1%. The roof monitor alternative also yields a maximum daylight factor of approximately 9.9% more than the sawtooth alternative. . However, with the skylight alternative cases 5%, 10% and 15%, the maximum daylight factor occurs under the opening and is much higher here than at other points. The skylight cases with double low-E clear glazed are used in the lighting analysis, thus direct sunlight penetrates into the space directly causing the peak illuminance levels under the opening to be much higher than in the other toplighting alternatives and hence become incomparable with other toplighting alternative. Therefore, a double low-E clear glazed should not be used with skylight cases analysis and a diffuse glazing should be used instead of double low-E clear glazing, because, with double low-E clear glazed skylights, direct sunlight can penetrate the base case interior space directly. Diffuse glazing in the skylight alternative assists diffuse the direct sunlight that penetrates the base case interior space

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and make the skylight cases more comparable in terms of their daylighting performance with other sawtooth and roof monitor cases.

The sawtooth and roof monitor areas between 5% and 15% of the floor area generate average daylight factors between 3.2% to 7.8%, and these values were recommended as ideal for the hall spaces in the academic building.

4.1.3.2 Illuminance level Analysis

For the analysis of the illuminance level and daylight distribution, the simulation date and time are June 21 (summer solstice), March 21/September 21 (equinoxes), and December 21 (winter solstice), at 9:00 am, 12:00 pm, and 3:00 pm based on the LBNL reference on toplighting system designs.

The illuminance level comparison is used for intermadiate sky conditions. The illuminance level comparisons graphs for the toplighting alternatives with 1 to 1 spacing-to-height ratio with TFR 5% to 15% and base case are presented in Figures 4.9- 4.17.

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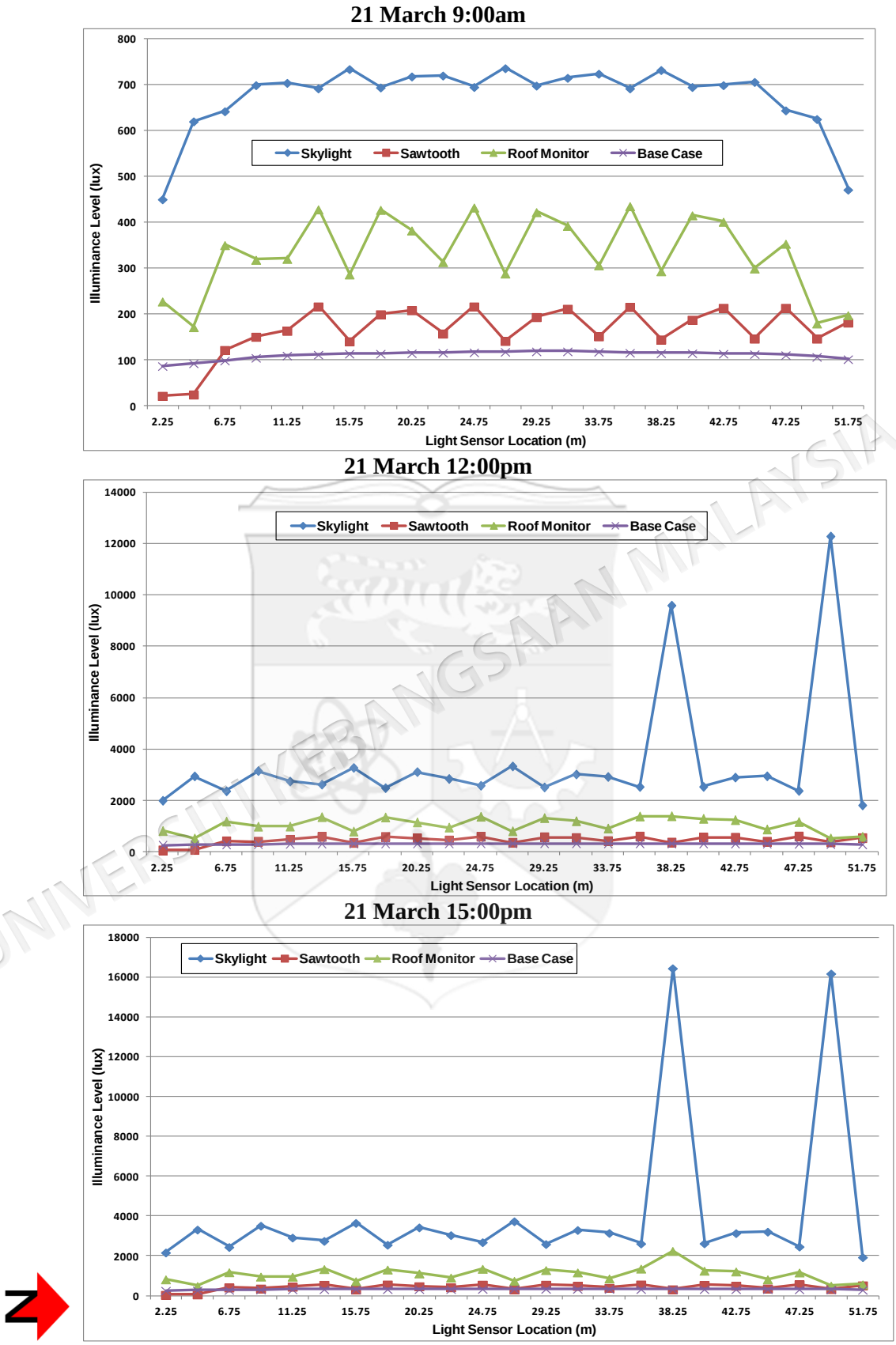

Figure 4.9 Illuminance level comparison: 1-to-1 spacing-to-ceiling height ratio, 5% TFR, double low-e clear, 21 of March

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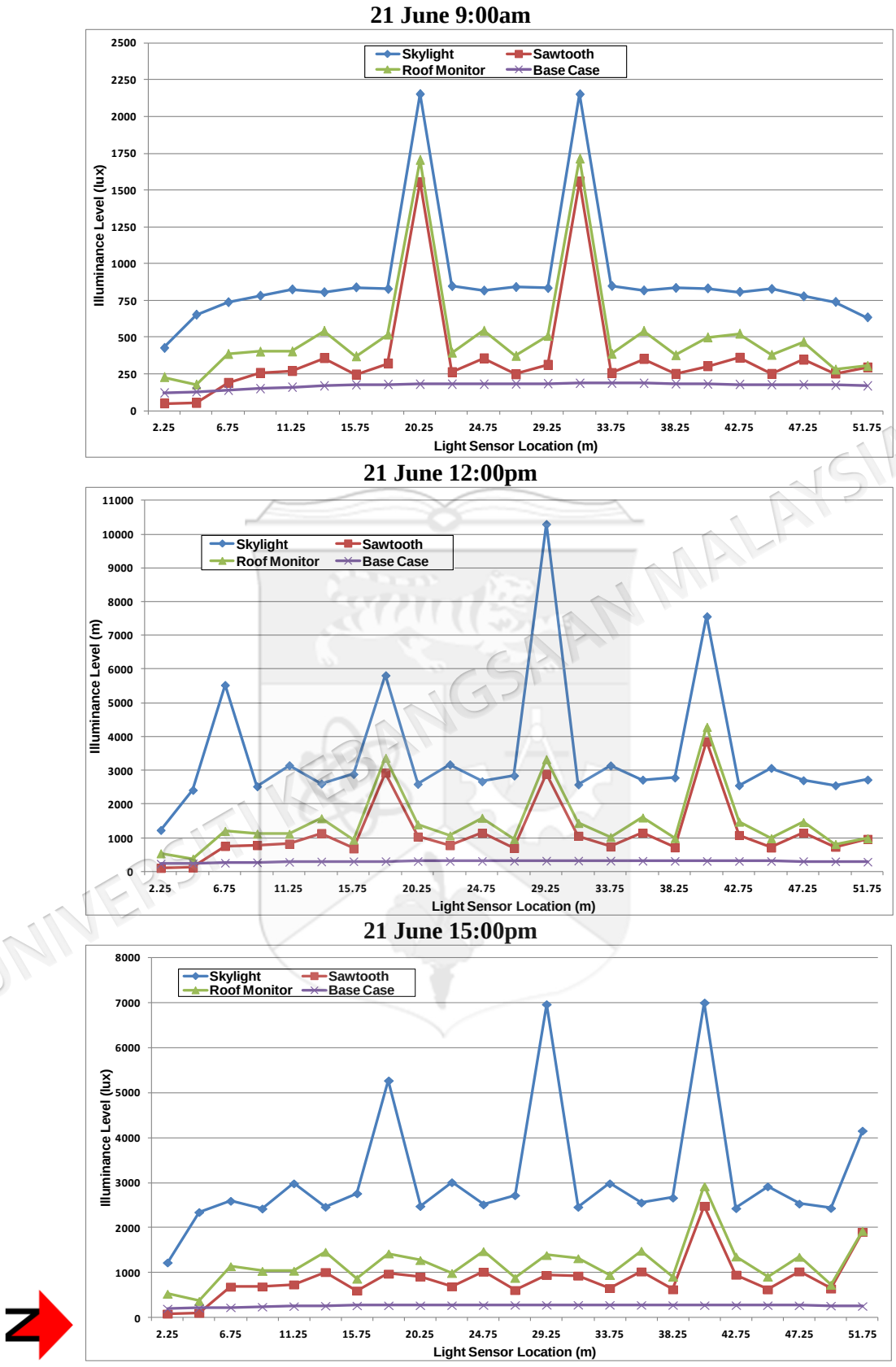

Figure 4.10 Illuminance level comparison: 1-to-1 spacing-to-ceiling height ratio, 5% TFR, double low-e clear, 21 of June

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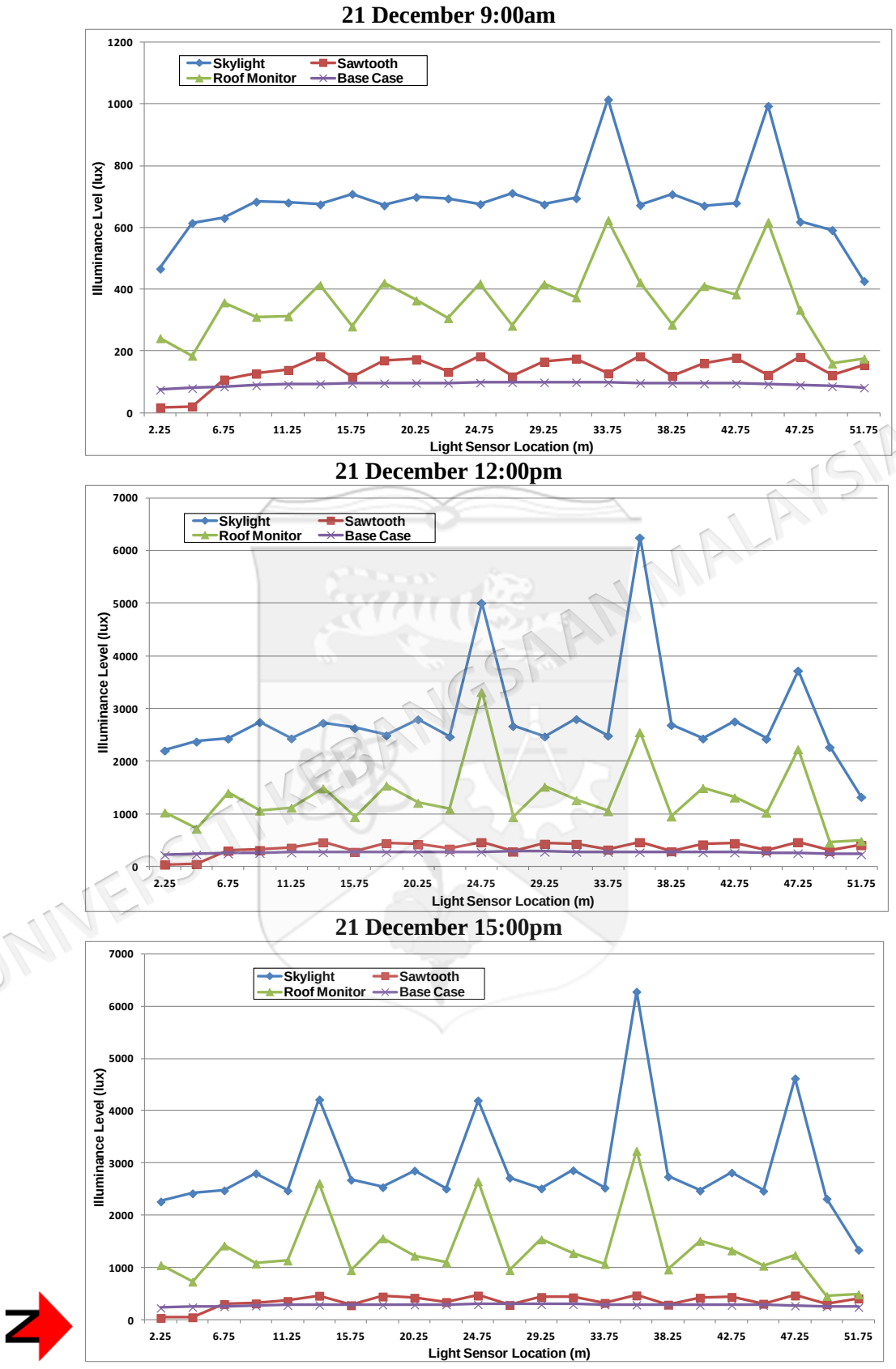

Figure 4.11 Illuminance level comparison: 1-to-1 spacing-to-ceiling height ratio, 5% TFR, double low-e clear, 21 of December

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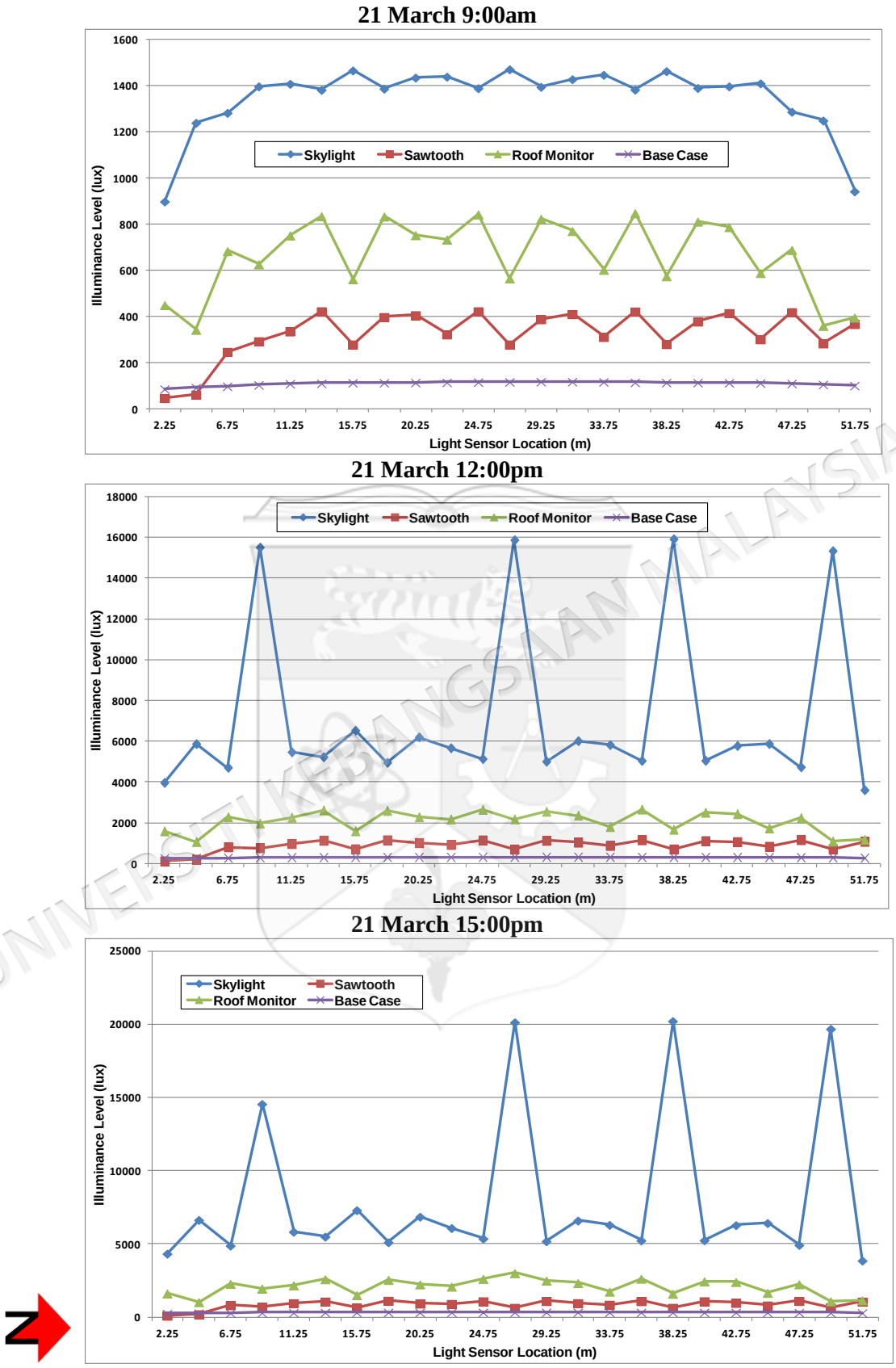

Figure 4.12 Illuminance level comparison: 1-to-1spacing-to-ceiling height ratio, 10% TFR, double low-e clear, 21 of March

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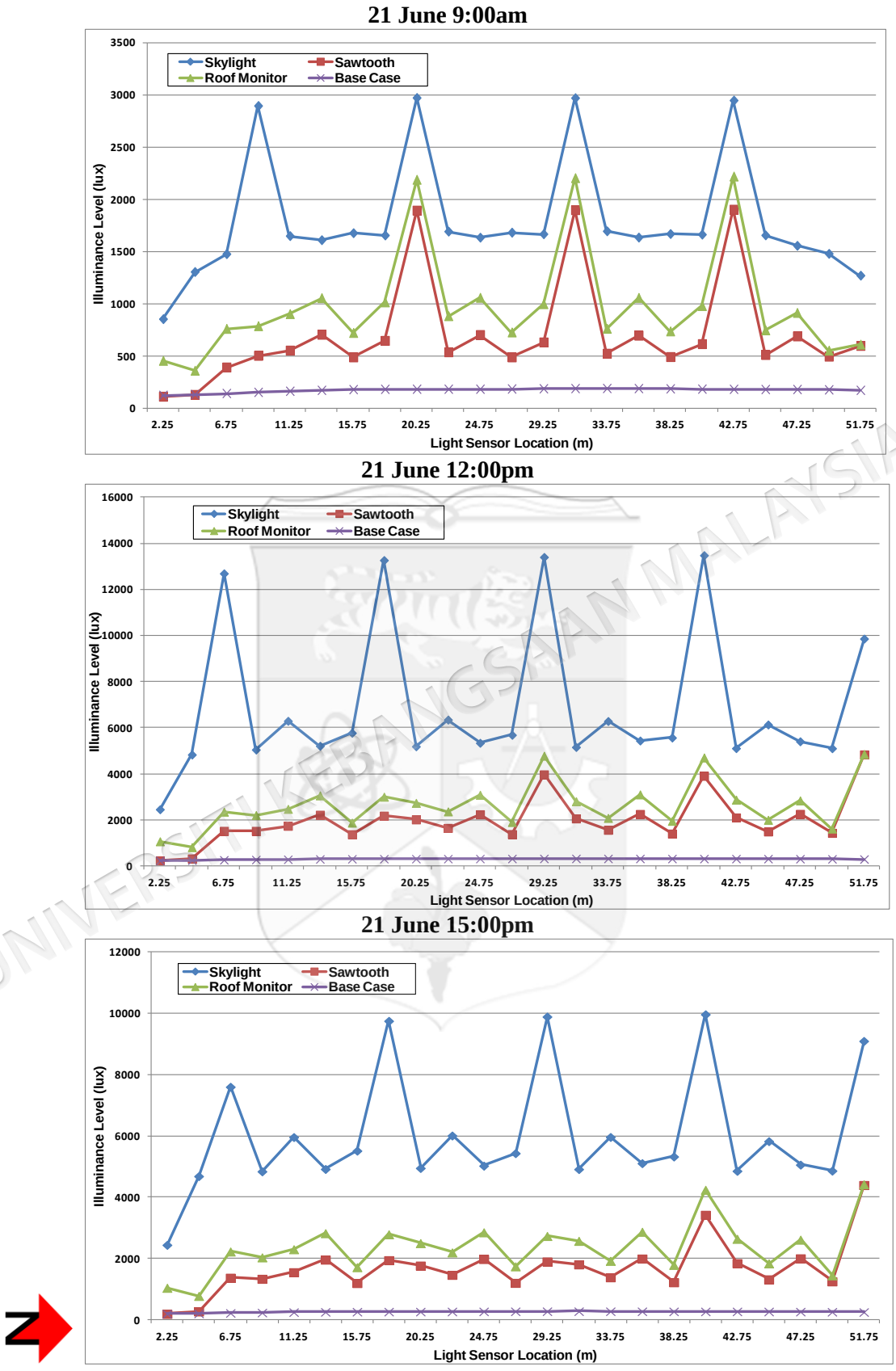

Figure 4.13 Illuminance level comparison: 1-to-1 spacing-to-ceiling height ratio, 10% TFR, double low-e clear, 21 of June

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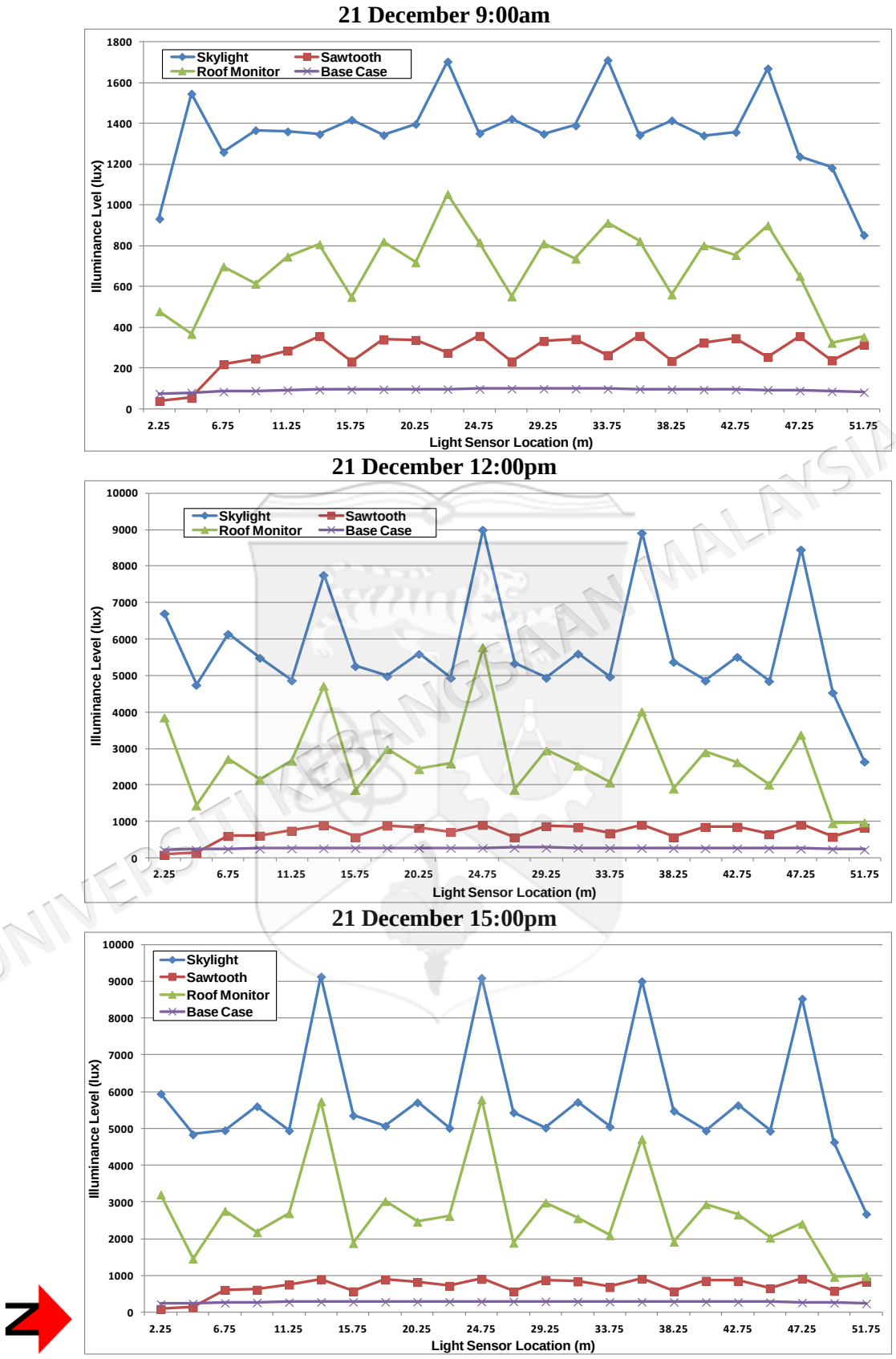

Figure 4.14 Illuminance level comparison: 1-to-1 spacing-to-ceiling height ratio, 10% TFR, double low-e clear, 21 of December

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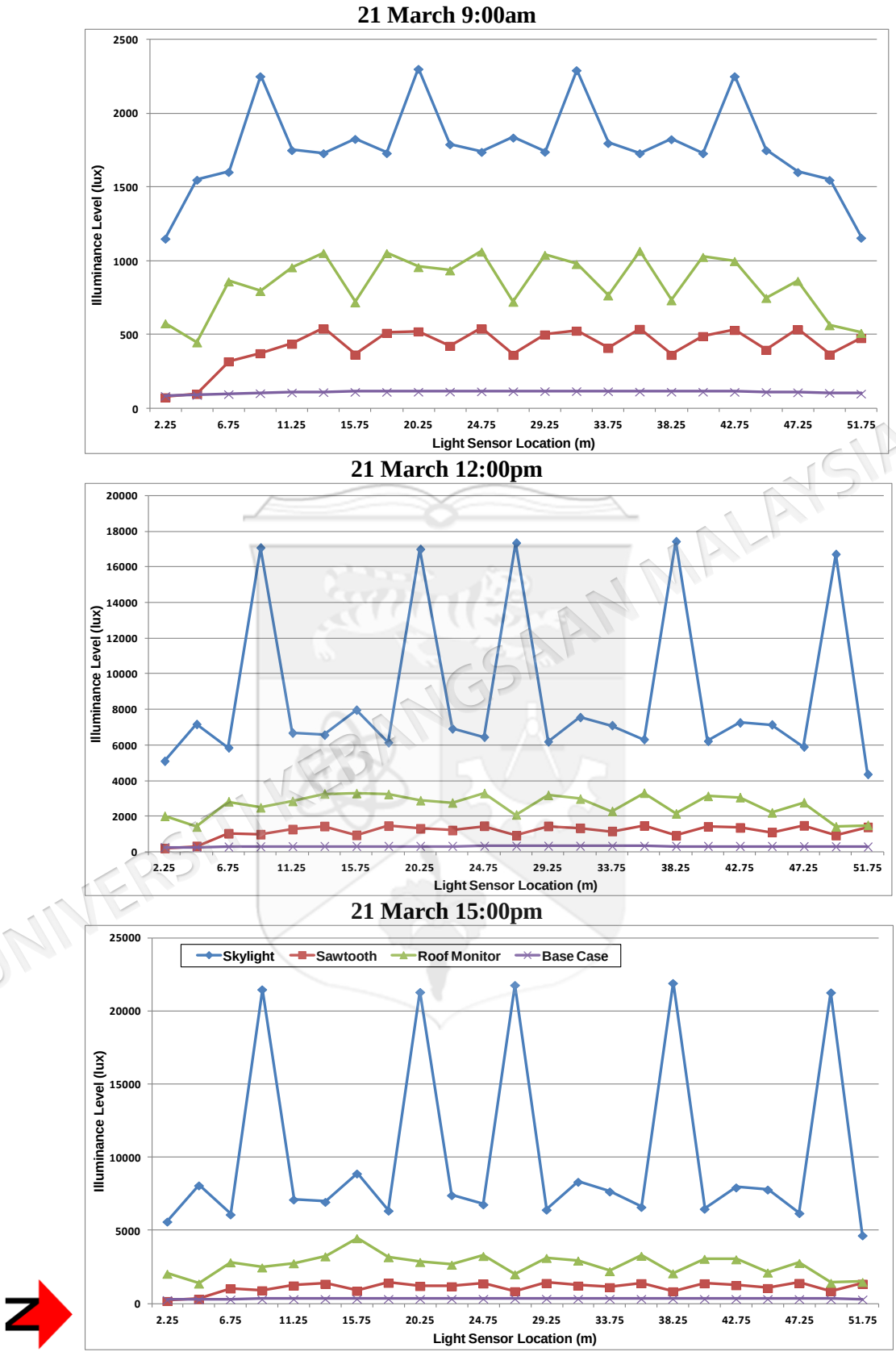

Figure 4.15 Illuminance level comparison: 1-to-1 spacing-to-ceiling height ratio, 15% TFR, double low-e clear, 21 of March

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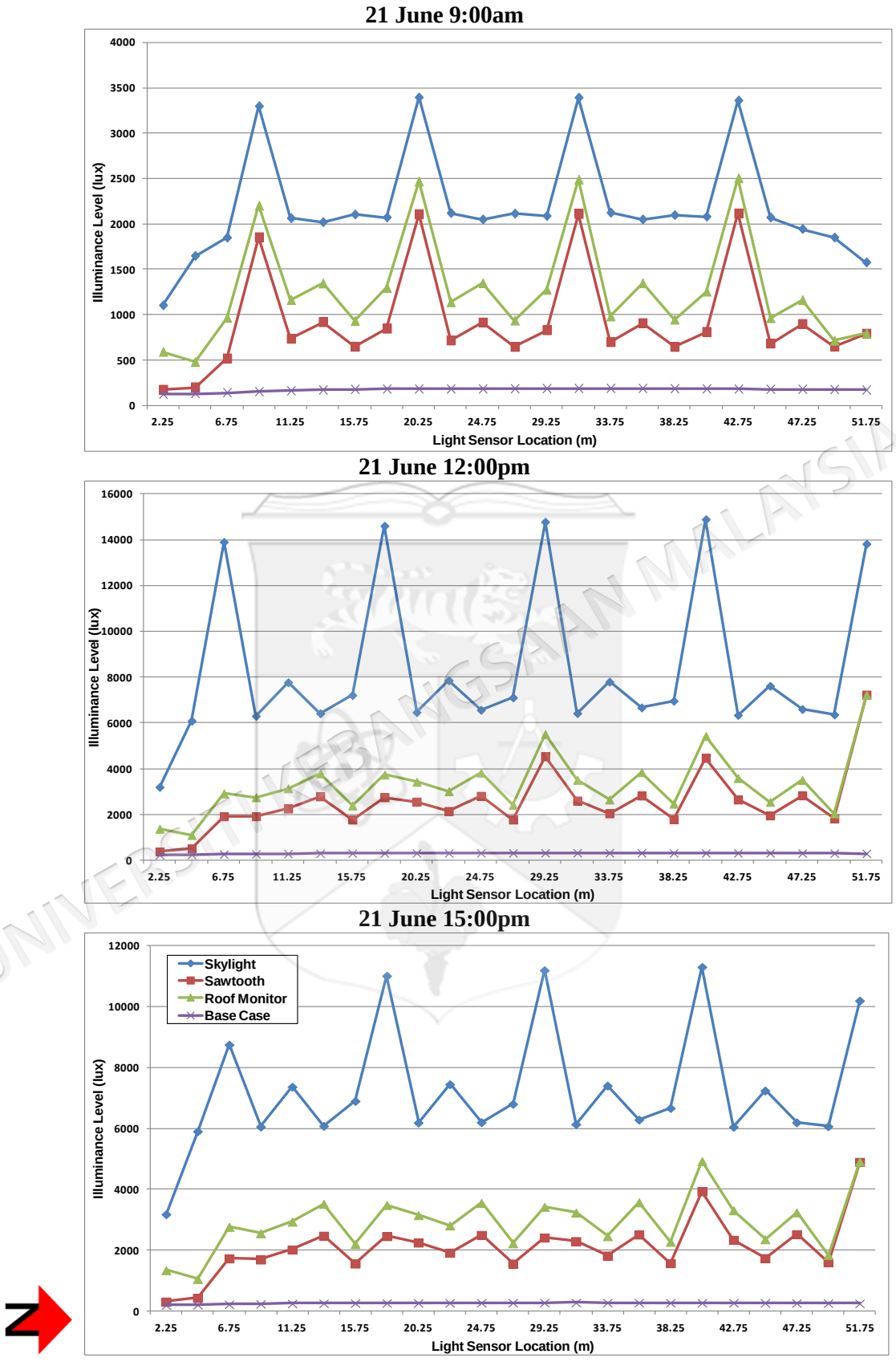

Figure 4.16 Illuminance level comparison: 1-to-1 spacing-to-ceiling height ratio, 15% TFR, double low-e clear, 21 of June

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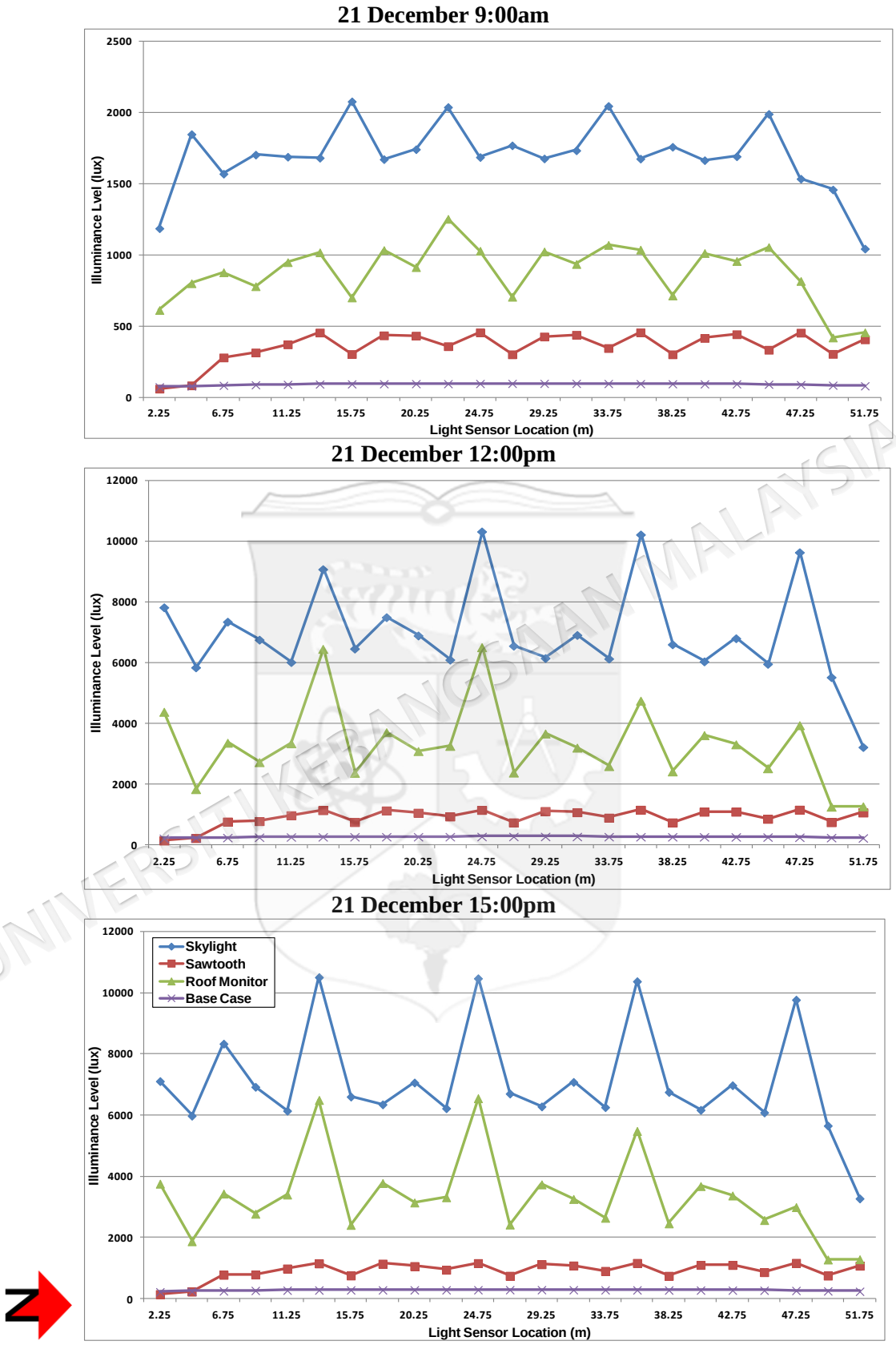

Figure 4.17 Illuminance level comparison: 1-to-1 spacing-to-ceiling height ratio, 15% TFR, double low-e clear, 21 of December

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For the illuminance level analysis under Intermediate sky conditions, the skylight alternative yields the highest illuminance level among all alternatives in most simulation dates and times, except in March and Jun in the entire TFR range from 5% to 25%. The sawtooth alternative yields the lowest illuminance level among all of the alternatives. This result may have been caused by the horizontal glazing of the skylight alternative as opposed to the vertical glazing of the sawtooth and roof monitor alternatives.

Under intermediate sky conditions, the skylight option allows sunlight to enter the interior space directly, which result in an extremely high interior illuminance level value occurs under the opening and is much higher than at other points. This is due to the use of double low-E clear glazed with skylight cases, thus direct sunlight penetrates into the space directly causing the peak illuminance levels to be much higher than in the other toplighting alternatives and hence become incomparable with other toplighting alternative. Therefore, a double low-E clear glazed should not be used with skylight cases and a diffuse glazing should be used instead of double low-E clear glazing, because, with double low-E clear glazed skylights, direct sunlight can entering the interior space directly. This, in turn, cause the interior illuminance level for skylight alternative under the openng to be very high, and hence the lighting performance could not be compared to the sawtooth and roof monitor, which have vertical glazing. Diffuse glazing in the skylight alternative cases helps diffuse the direct sunlight that enters the base case space and make the cases more comparable in terms of their lighting performance.

The skylight alternative illuminance levels vary seasonally by having higher illuminance level value in March and lower illuminance level values in June and December. The skylight alternative illuminance levels do not change significantly seasonally but vary in the course of a day more than sawtooth and roof monitor alternatives. For example, the maximum illuminance level of the skylight option with a 5% TFR, at 12:00 pm on June 21, ranges from 3,000 lux to 5,800 lux. The illuminance level also varies in the course of a day more than the sawtooth and roof monitor options and cases.

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For the roof monitor alternative, the illuminance level reaches a maximum of approximately 4200 lux at 12:00 pm on June 21. For the sawtooth alternative, the illuminance level is higher in June and lower in March. The illuminance levels range from 250 lux in March up to 1100 lux in June. The overall variation in the course of a day is approximately 600 lux. However, the roof monitor alternative yields higher illuminance levels than does of the sawtooth alternative throughout the year. This could be because it has a glazing for both north and south orientation. Even though the roof monitors alternative yields generally higher illuminance levels than the sawtooth, in winter, the illuminance levels of the roof monitor alternative are close to the sawtooth alternative.

The sawtooth alternative, in general, yields a lower illuminance level than other toplighting alternatives. Nevertheless, its illuminance level does not change considerably throughout the year as opposed to that of the skylight and roof monitor alternatives. This could be because it has a glazing for only north orientation. The illuminance level value reaches its maximum in June at 12:00pm at about 2,000 lux. For sawtooth, the illuminance level is higher in summer and is lower in winter. The illuminance levels range from 500 lux in winter and up to 2,000 in summer. The overall daily range is at about 750 lux. Even though the sawtooth alternative yields generally lower illuminance levels than the roof monitor, in winter, the illuminance levels of the sawtooth alternative are close to the roof monitor alternative.

The maximum illuminance level could also occur under the opening even with vertical glazing of toplighting alternatives like the sawtooth or roof monitor. This could be because roof monitor and sawtooth have vertical glazing which, in intermediate sky condition, some sunlight could enter directly through vertical glazing into the space, if these toplighting alternatives with vertical glazing do not have shading devices. The penetration of direct sunlight through the vertical glazing depends on sun angle and sun-path throughout the year for Kuala Lumpur location as presented in sun-path diagram for Kuala Lumpur in Chapter III Section 2.3.3 Figure 18. Differing sun paths in each season make different lighting level in the interior space of the base case. To control this direct sunlight penetration, the vertical glazing of the sawtooth and roof monitor cases needs to have external shading devises.

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However, no conclusions can be derived at this stage, since the illuminance sensor locations are located in a single row along the center of the base case model and better conclusion can be drawn through the illuminance distribution and uniformiy analysis, which will be analyzed later in this chapter.

For daylight distribution, as the figures and 2D graphs show, the sawtooth and roof monitor alternatives appear to perform in the same way and have more daylight distribution than the skylight alternative across all TFRs throughout the year. A more detailed analysis of the daylight distribution and uniformity of these three toplighting alternatives is presented in the subsequent section. The skylight alternative has a larger range of illuminance level, which may cause daylight distribution worse than that of the roof monitor and sawtooth cases. A detailed comparison of the illuminance levels of the skylight, sawtooth, and roof monitor cases with a TFR of 20% to 60% and a northward orientation versus those of the base case is presented in Figures A-12 to B-1 of Appendix B.

The daylighting performance of each of the three toplighting systems was examined. The daylighting performance parameters examined were illuminance level, daylight factor and light distribution, uniformity. The IESNA standards and CIBSE guidelines daylighting credit and recommendations were used as the minimum recommended level for all daylighting analyzed variables.

For skylight alternative 10% TFR performance in terms of illuminance level, the values change also dramatically in the course of the day and throughout the year. The maximum illuminance value was 3000 Lux, which occurred at 12:00 pm on March 21, June 21 and September 21. This value is also much higher than the recommended task illumination provided by CIBSE within the range of 300 to 500.

For sawtooth and roof monitor 10% TFR performance in terms of illuminance level, the values change dramatically in the course of the day and throughout the year. The maximum illuminance level values were range of 300 to 1500 Lux for sawtooth and of 500 to 2000 lux for roof monitor, which occurred at 12:00 pm on March 21,

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June 21 and September 21. These values are within and slightly higher than the recommended task illumination provided by CIBSE.

Even though skylight alternative yields a higher illuminance level than the two other toplighting alternatives during most of the year, the skylight alternative has poor lighting performance in terms of illuminance level, daylight factor, and light distribution and uniformity. This can be reduced by using diffuse film or glazing on the skylight opening.

4.1.3.3 Daylight Distribution and Uniformity Analysis

The parameters for analyzing the illuminance uniformity are illuminance gradient (or diversity of illuminance in CIBSE code) and uniformity of illuminance. For the illuminance gradient (the ratio of maximum to minimum illuminance), a lower value indicates better uniformity, while for uniformity of illuminance (the ratio of minimum to average illuminance), a higher value indicates better uniformity. The illuminance gradient is the primary parameter in the daylight quality analysis, since it is the more relaxed parameter. Therefore, it is suitable for a space without any furniture, as in the EnergyPlus base case model in this research.

Figures 4.18 to 4.35 present a comparative illuminance level map (contour) of the three toplighting alternatives with a 1-to-1 spacing-to-ceiling height ratio and a TFR ranging from 5% to 10% under intermediate sky condition and at different dates and times.

Tables 4.3 to 4.5 present the illuminance uniformity values of the skylight, sawtooth, and roof monitor alternatives with a 5% to 15% TFR. Tables 4.6 to 4.8 illustrate the gradient of the illuminance values. As explained in Chapter III, the most important parameter in evaluating the uniformity of daylight illuminance is the illuminance diversity or illuminance gradient described by CIBSE. An analysis and evaluation of the daylight distribution and daylight uniformity of each of the toplighting alternatives under clear sky conditions are provided later in this section.

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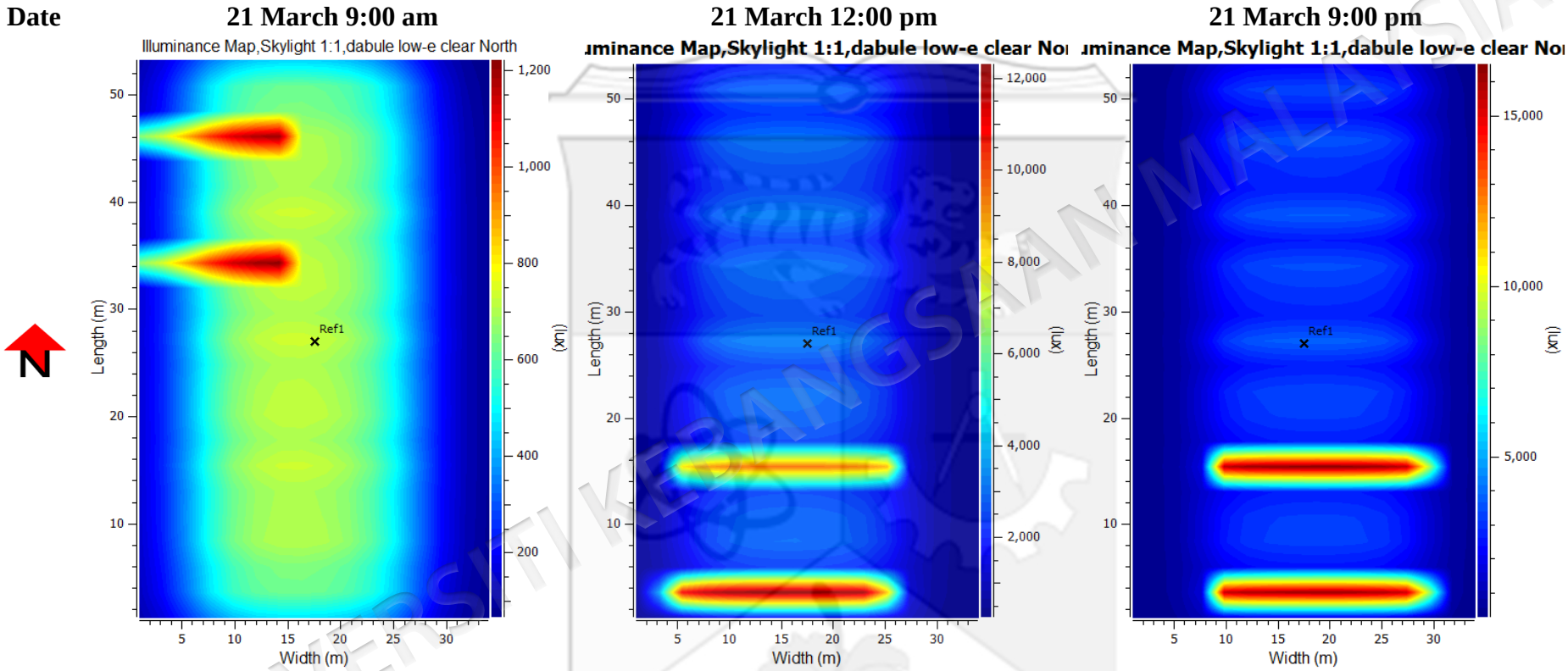

Figure 4.18 EnergyPlus **Skylight** Illuminance level maps: 1 to 1 spacing-to-height ratio, **5% TFR**, double low-e clear. **21 March**

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Date	21 Jun 9:00 am	21 Jun 12:00 pm	21 Jun 9:00 pm

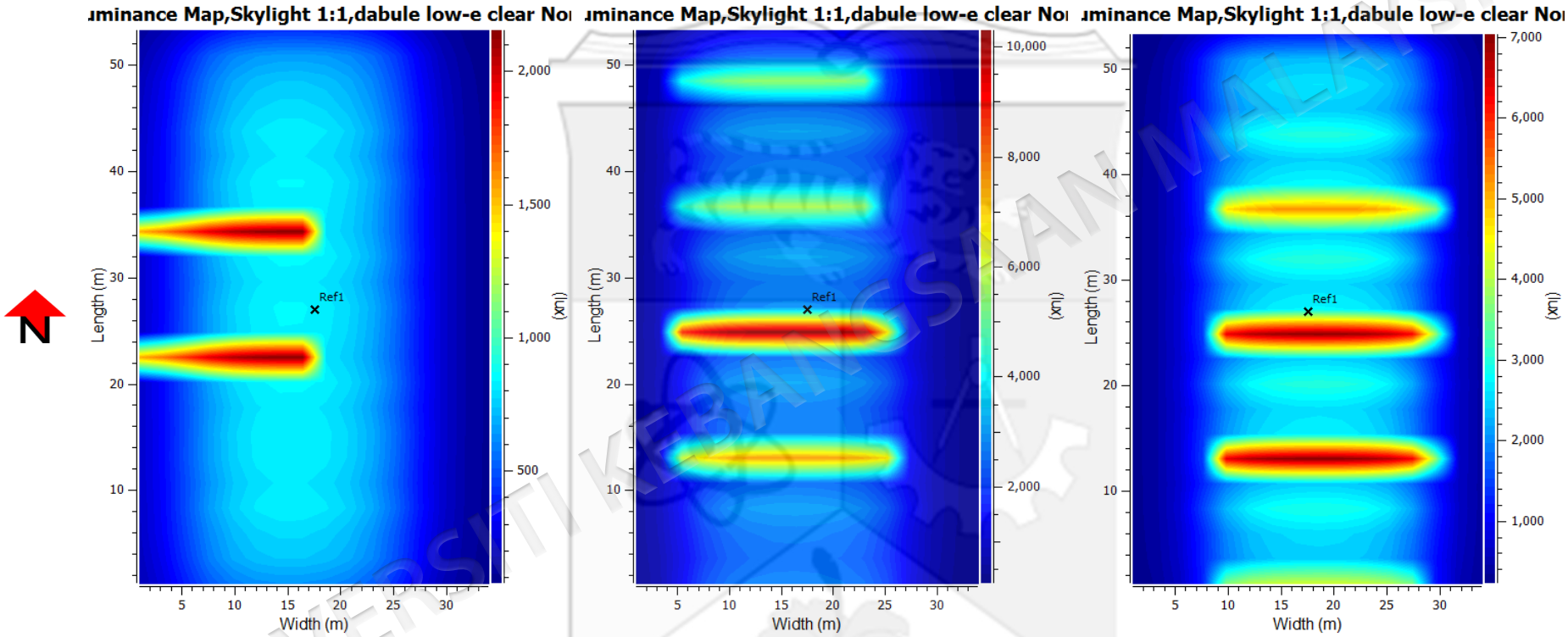

Figure 4.19 EnergyPlus **Skylight** Illuminance level maps: 1 to 1 spacing-to-height ratio, **5% TFR**, double low-e clear. **21 Jun**

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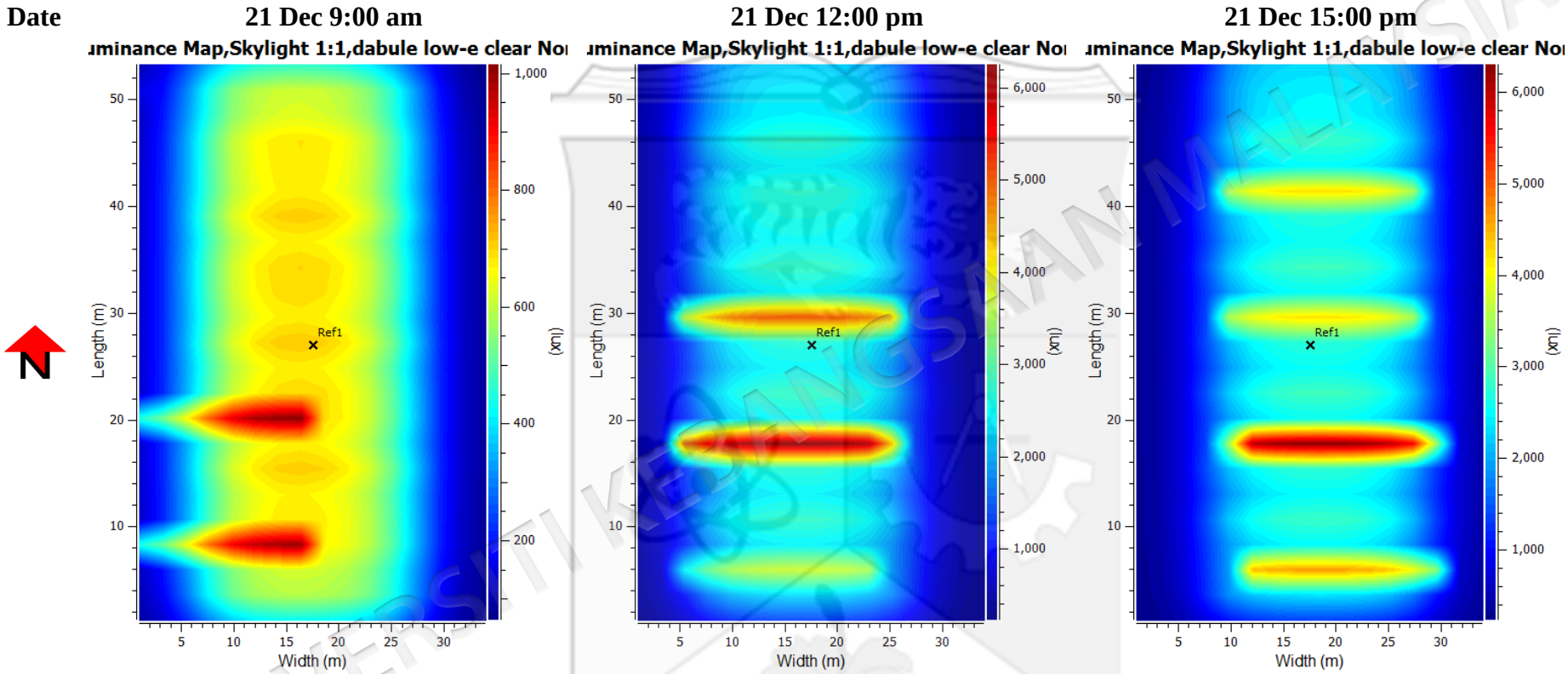

Figure 4.20 EnergyPlus **Skylight** Illuminance level maps: 1 to 1 spacing-to-height ratio, **5% TFR**, double low-e clear. **21 December**

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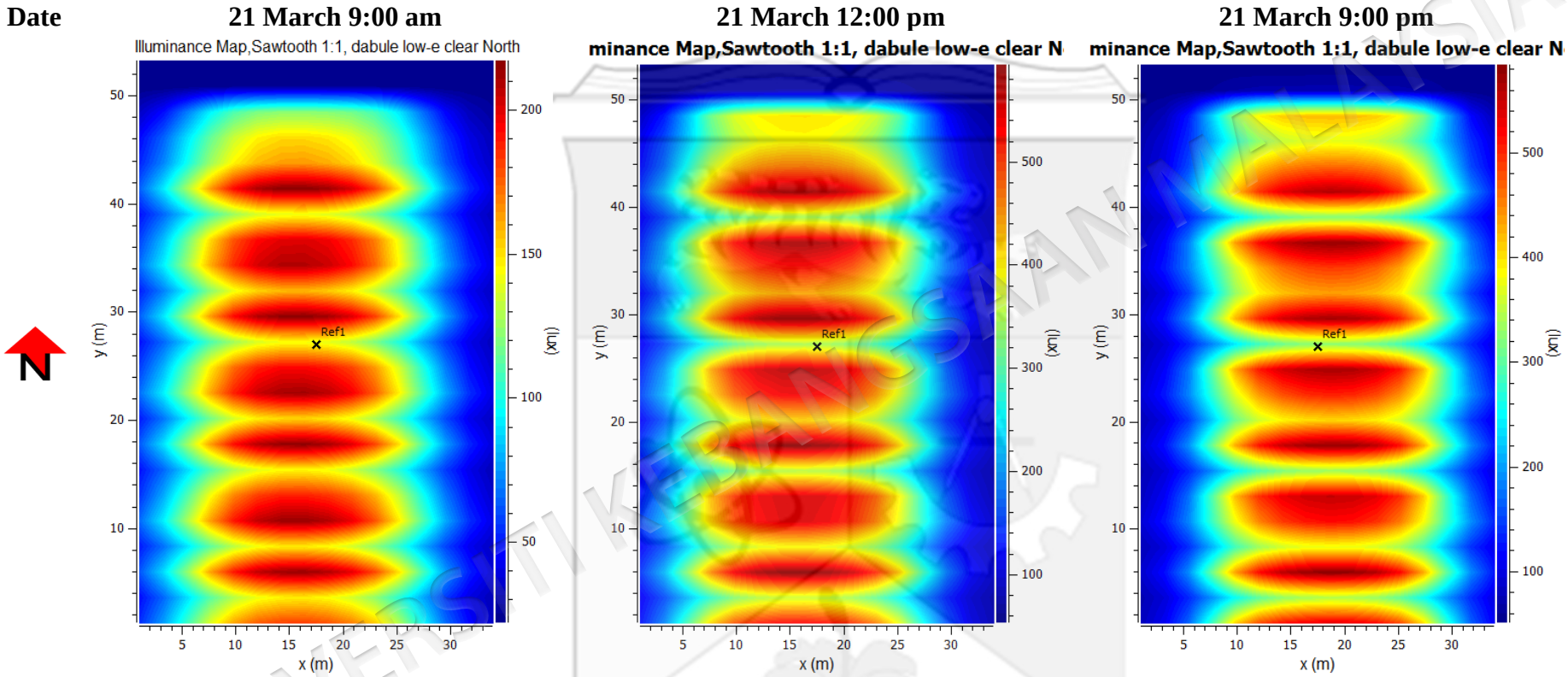

Figure 4.21 EnergyPlus **Sawtooth** Illuminance level maps: 1 to 1 spacing-to-height ratio, **5% TFR**, double low-e clear. **21 March**

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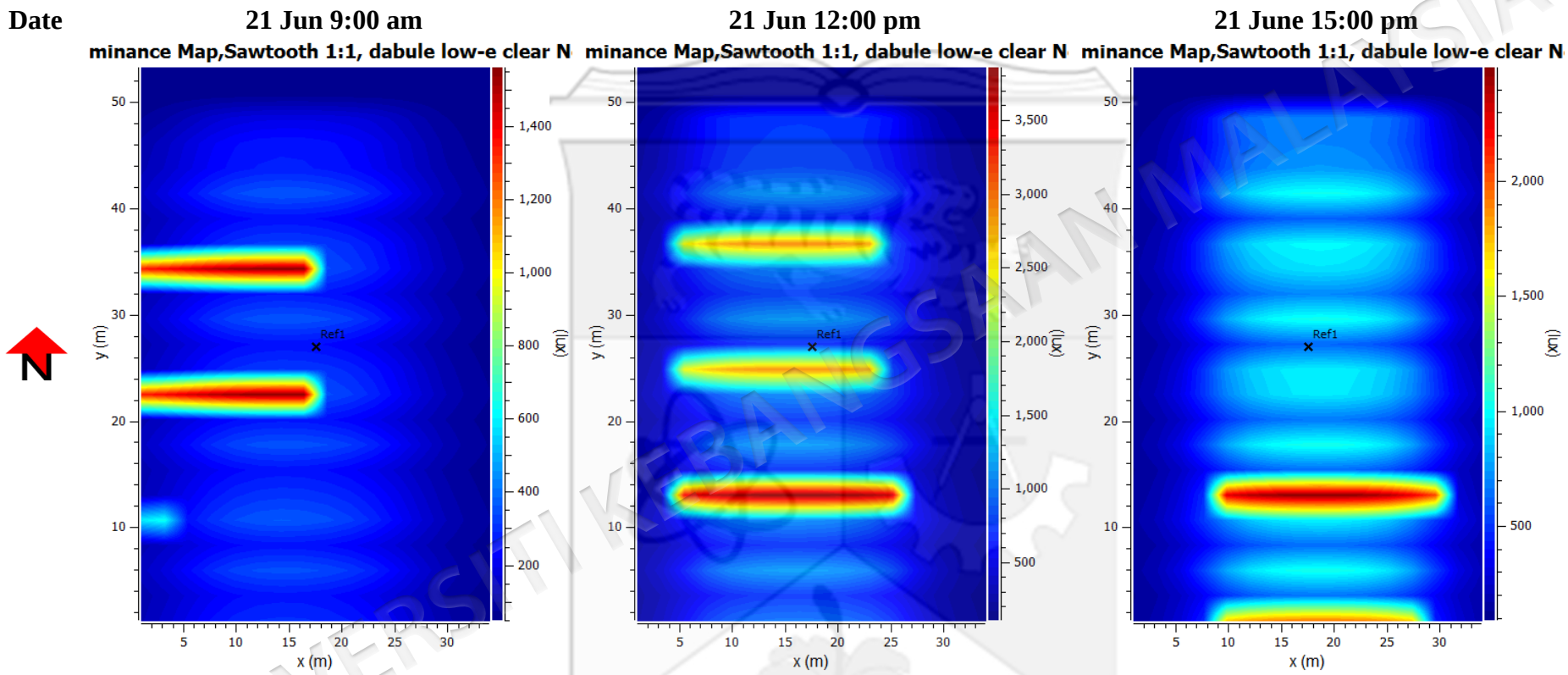

Figure 4.22 EnergyPlus **Sawtooth** Illuminance level maps: 1 to 1 spacing-to-height ratio, **5% TFR**, double low-e clear. **21 Jun**

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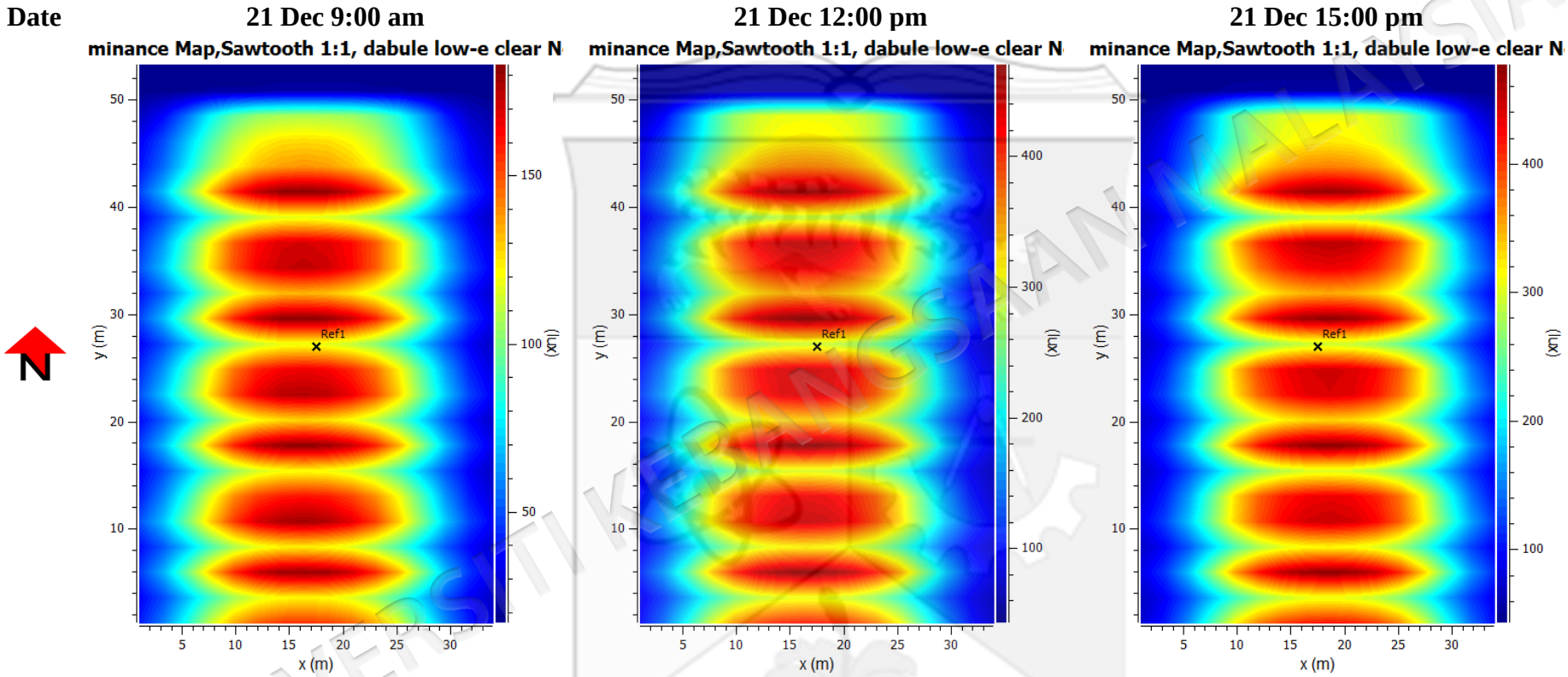

Figure 4.23 EnergyPlus **Sawtooth** Illuminance level maps: 1 to 1 spacing-to-height ratio, **5% TFR**, double low-e clear.**21 December**

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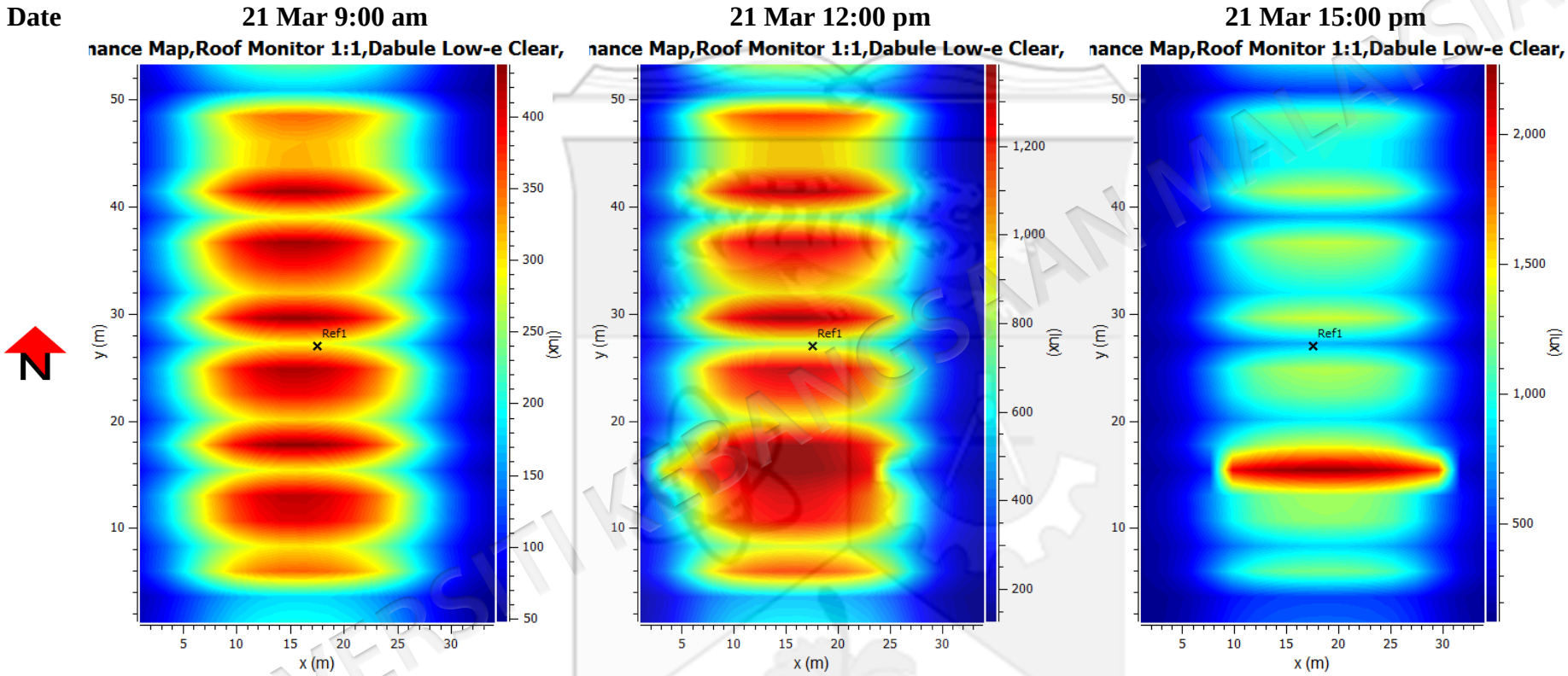

Figure 4.24 EnergyPlus **Roof Monitor** Illuminance level maps: 1 to 1 spacing-to-height ratio, **5% TFR**, double low-e clear. **21 March**

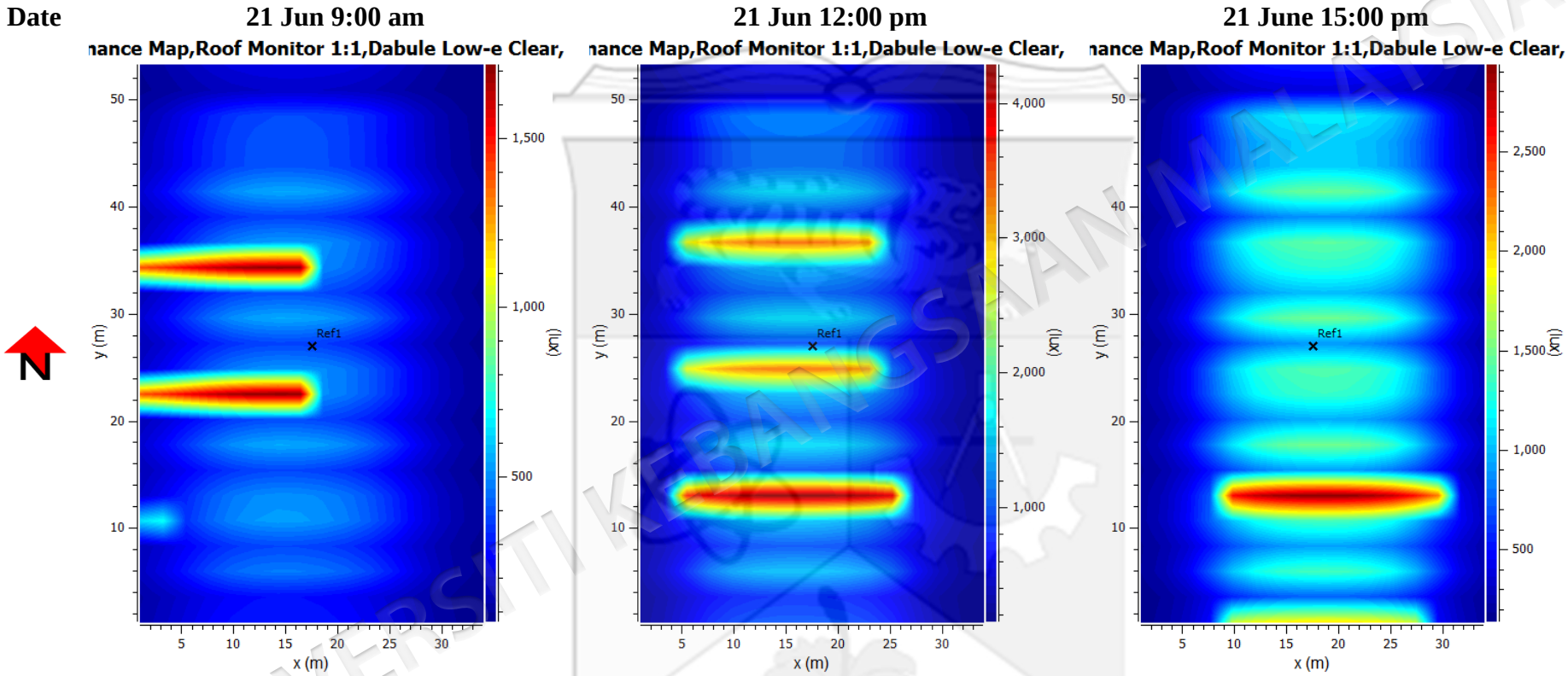

Figure 4.25 EnergyPlus **Roof Monitor** Illuminance level maps: 1 to 1 spacing-to-height ratio, **5% TFR**, double low-e clear. **21 Jun**

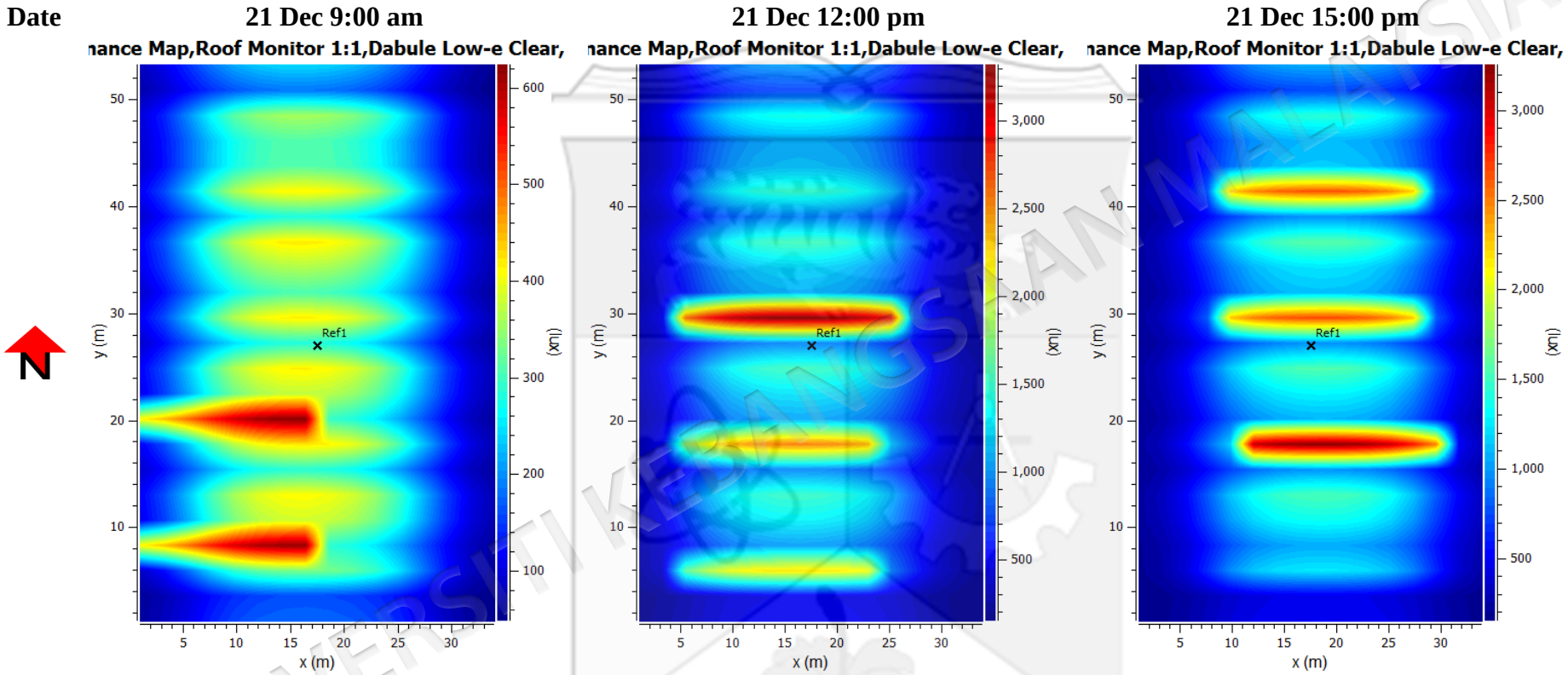

Figure 4.26 EnergyPlus **Roof monitor** Illuminance level maps: 1 to 1 spacing-to-height ratio, **5% TFR**, double low-e clear. **21 December**

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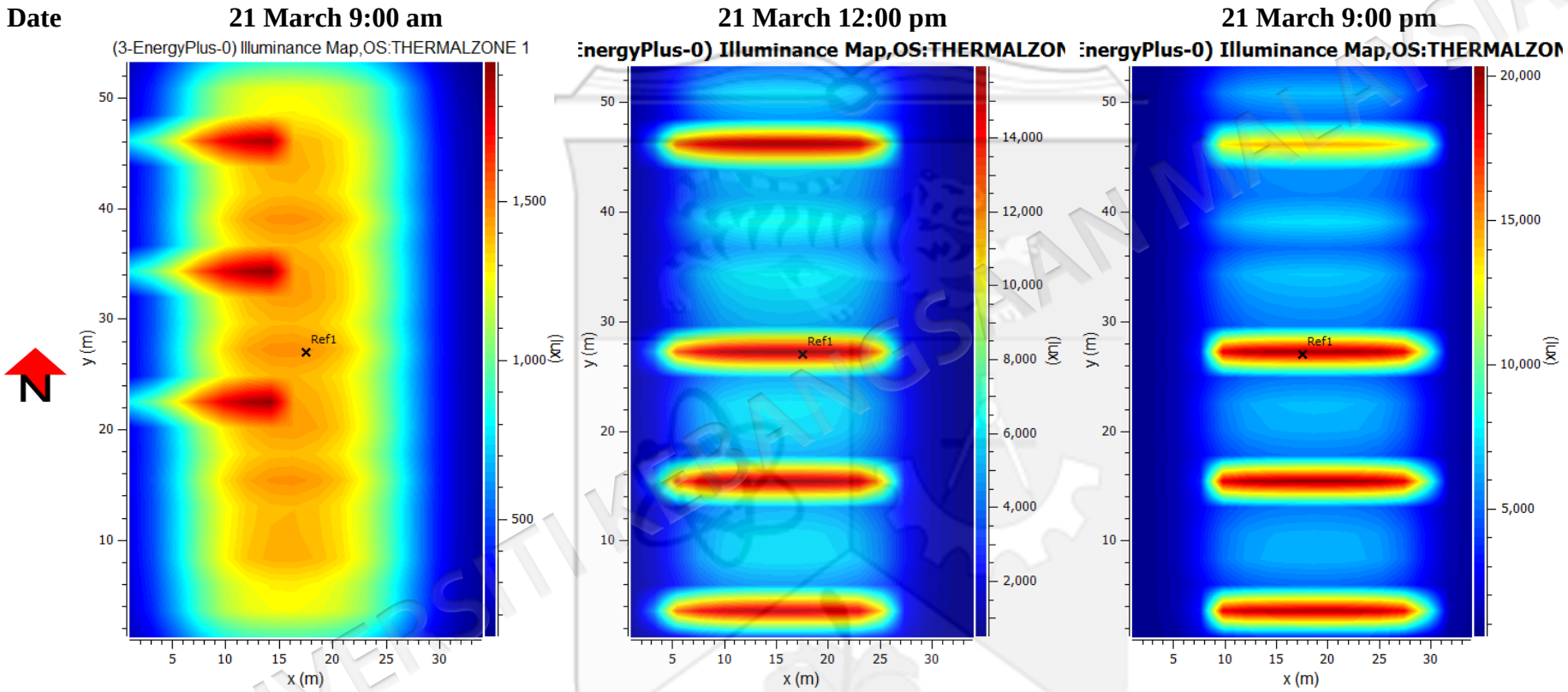

Figure 4.27 EnergyPlus **Skylight** Illuminance level maps: 1 to 1 spacing-to-height ratio, **10% TFR**, double low-e clear. **21 March**

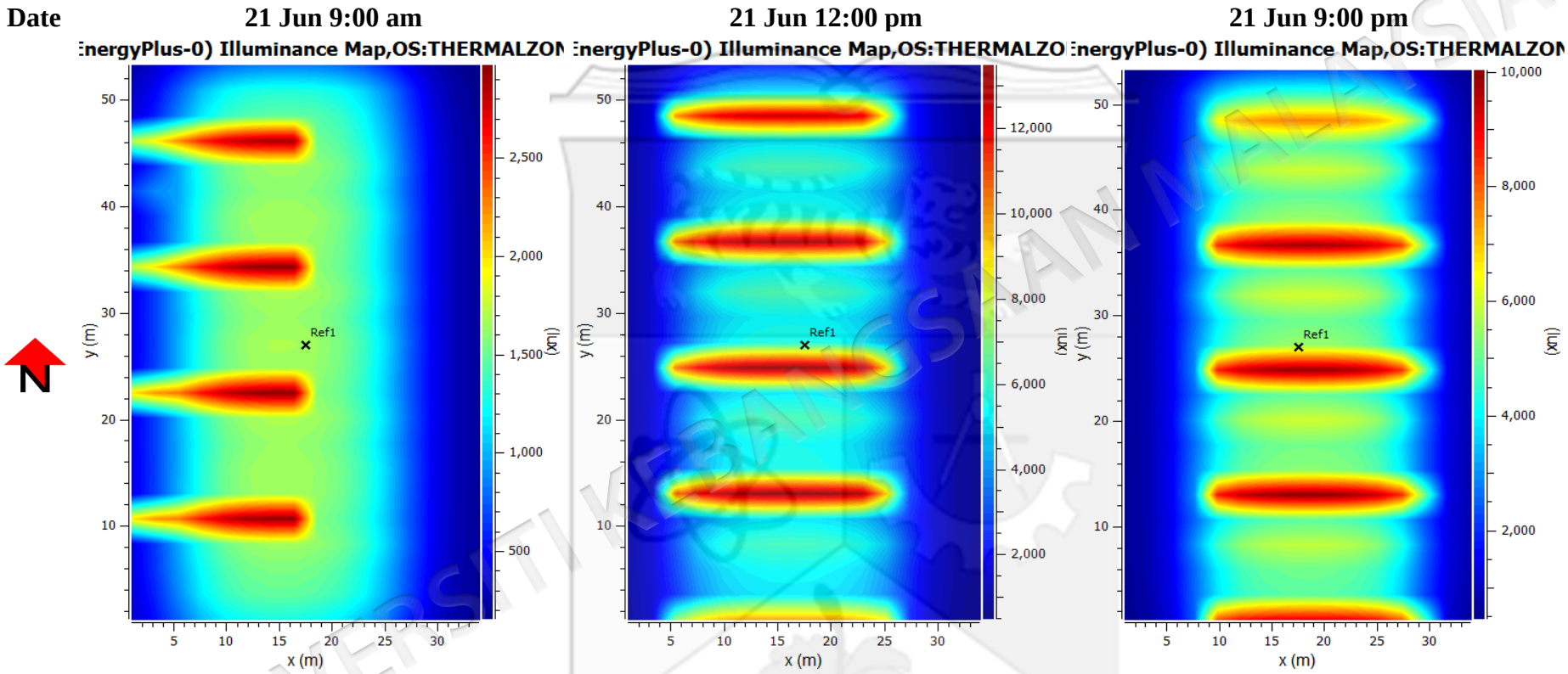

Figure 4.28 EnergyPlus **Skylight** Illuminance level maps: 1 to 1 spacing-to-height ratio, **10% TFR**, double low-e clear. **21 Jun**

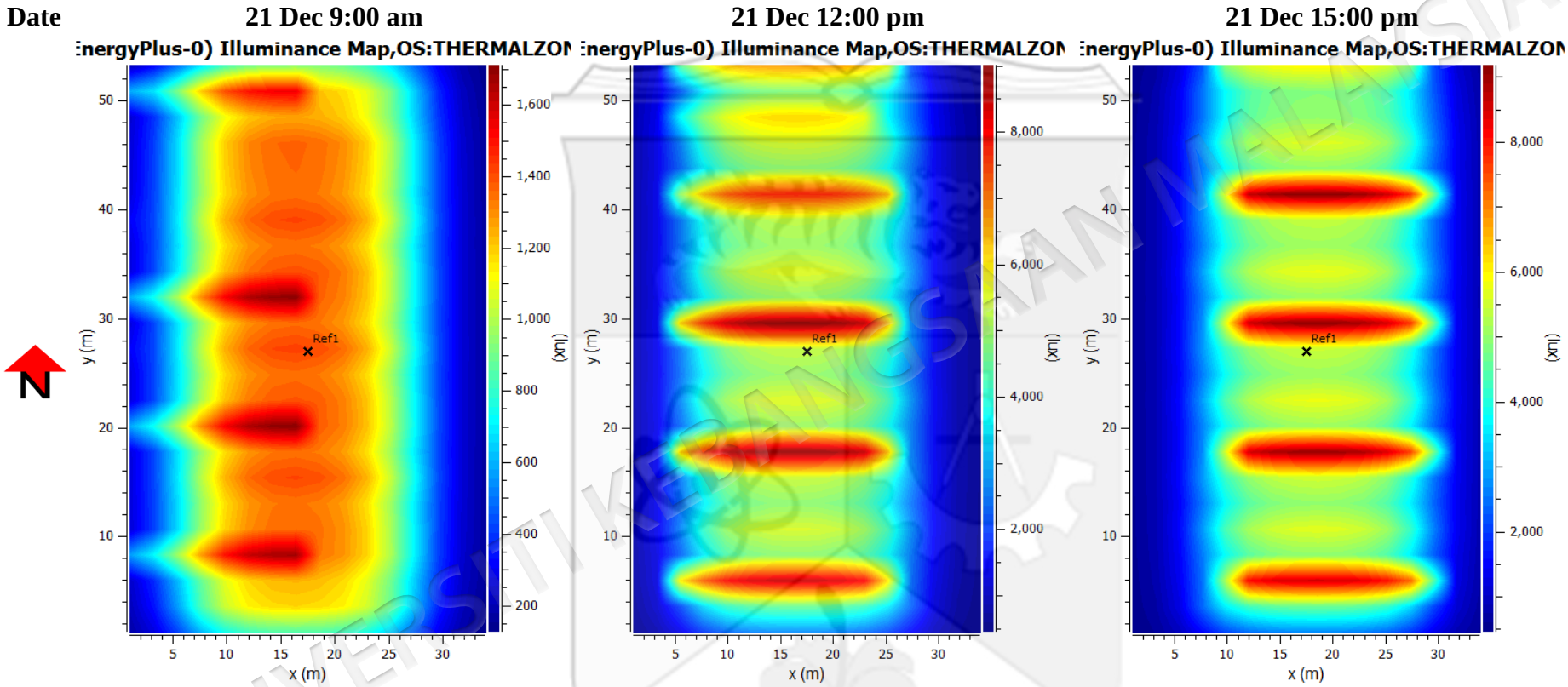

Figure 4.29 EnergyPlus **Skylight** Illuminance level maps: 1 to 1 spacing-to-height ratio, **10% TFR**, double low-e clear. **21 December**

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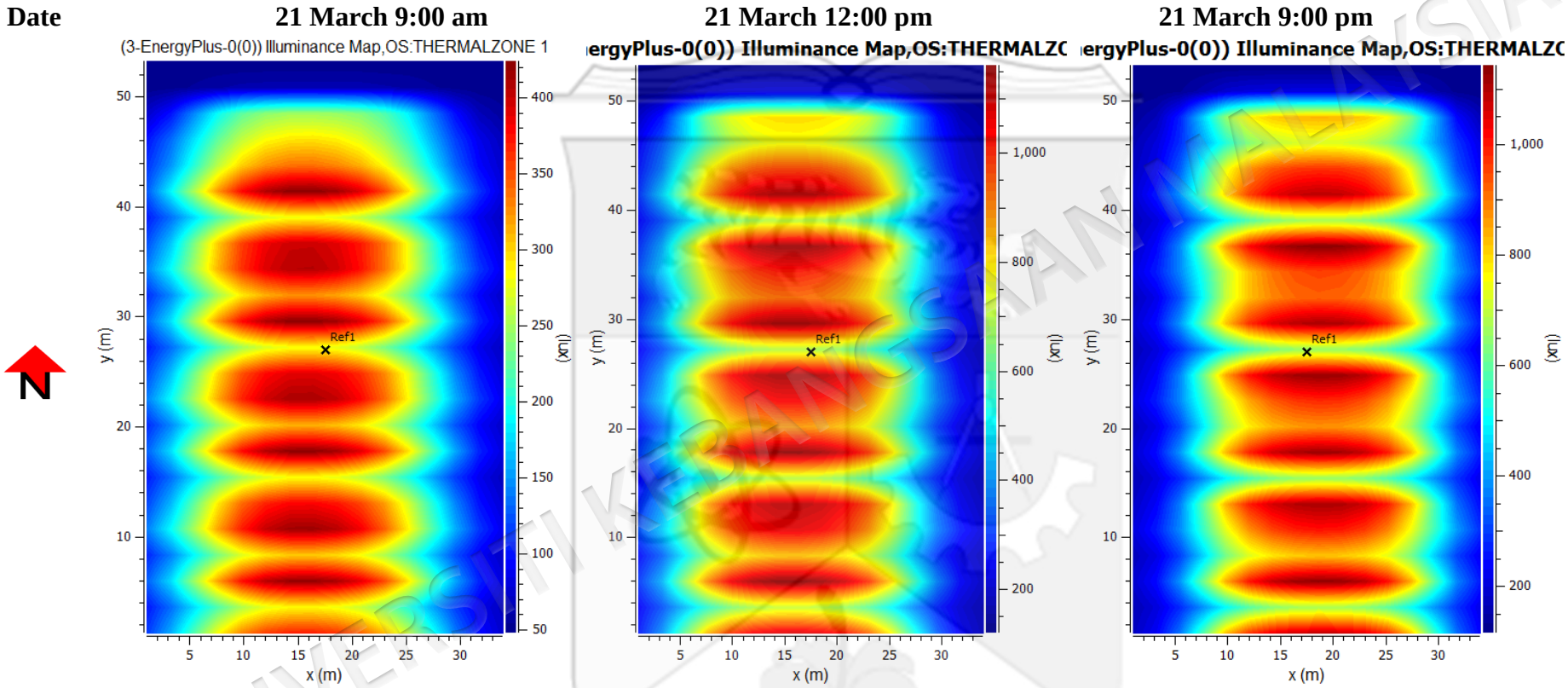

Figure 4.30 EnergyPlus **Sawtooth** Illuminance level maps: 1 to 1 spacing-to-height ratio, **10% TFR**, double low-e clear. **21 March**

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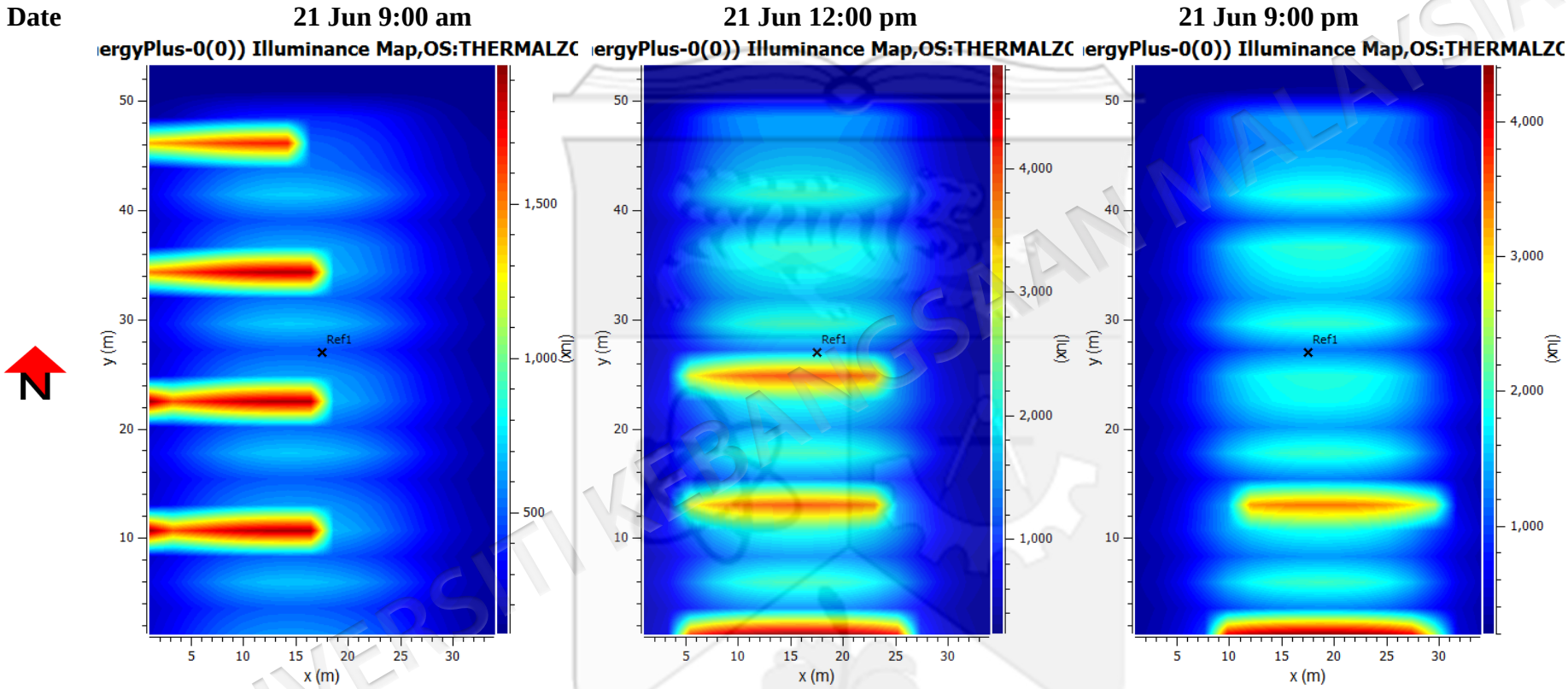

Figure 4.31 EnergyPlus **Sawtooth** Illuminance level maps: 1 to 1 spacing-to-height ratio, **10% TFR**, double low-e clear. **21 Jun**

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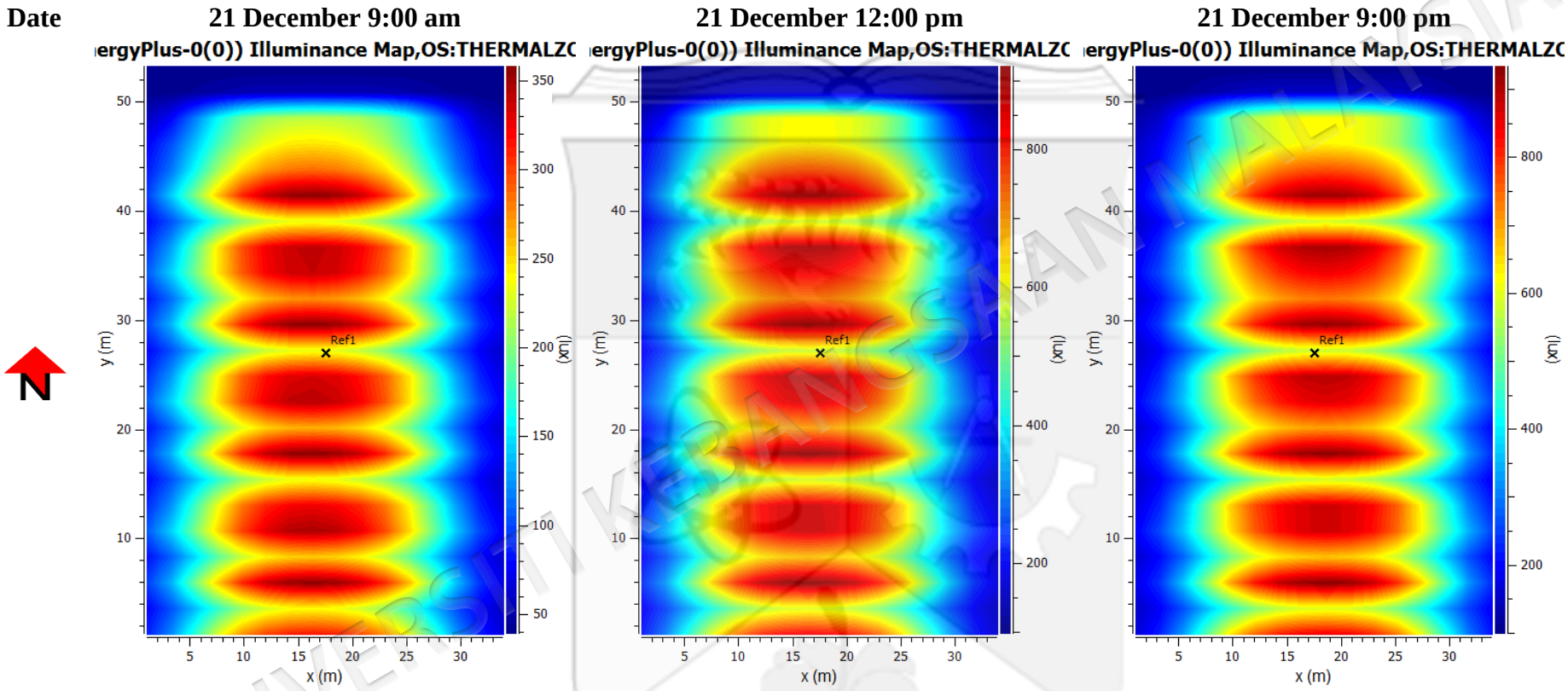

Figure 4.32 EnergyPlus **Sawtooth** Illuminance level maps: 1 to 1 spacing-to-height ratio, **10% TFR**, double low-e clear. **21 December**

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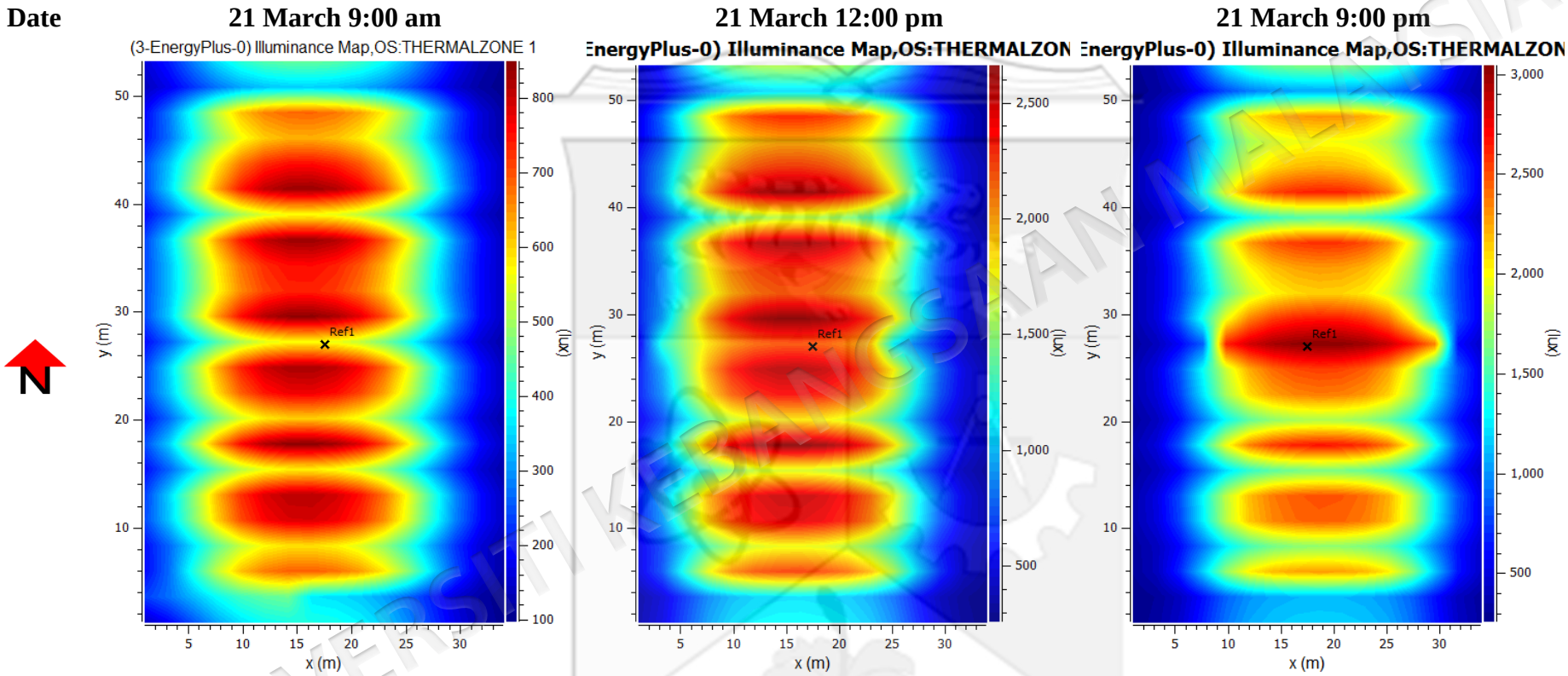

Figure 4.33 EnergyPlus **Roof Monitor** Illuminance level maps: 1 to 1 spacing-to-height ratio, **10% TFR**, double low-e clear. **21 March**

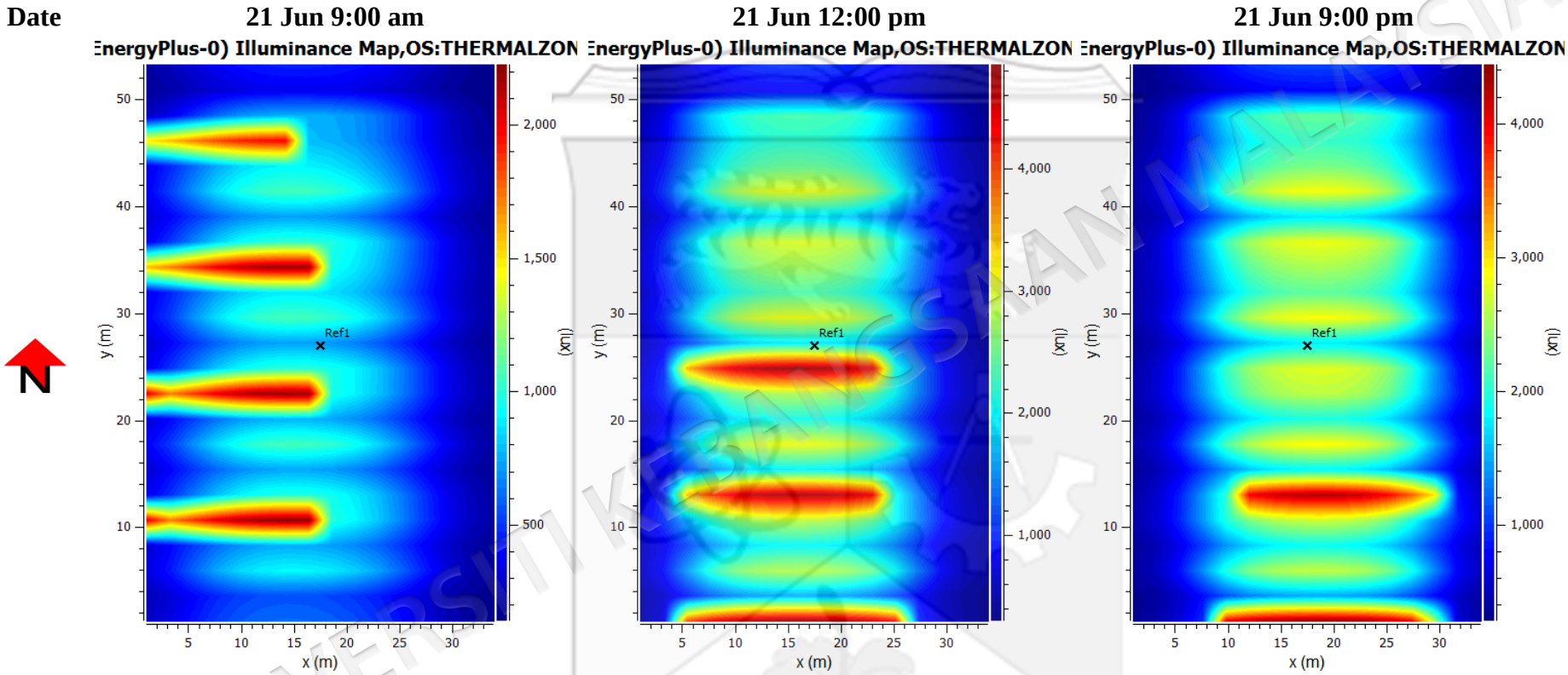

Figure 4.34 EnergyPlus **Roof Monitor** Illuminance level maps: 1 to 1 spacing-to-height ratio, **10% TFR**, double low-e clear. **21 Jun**

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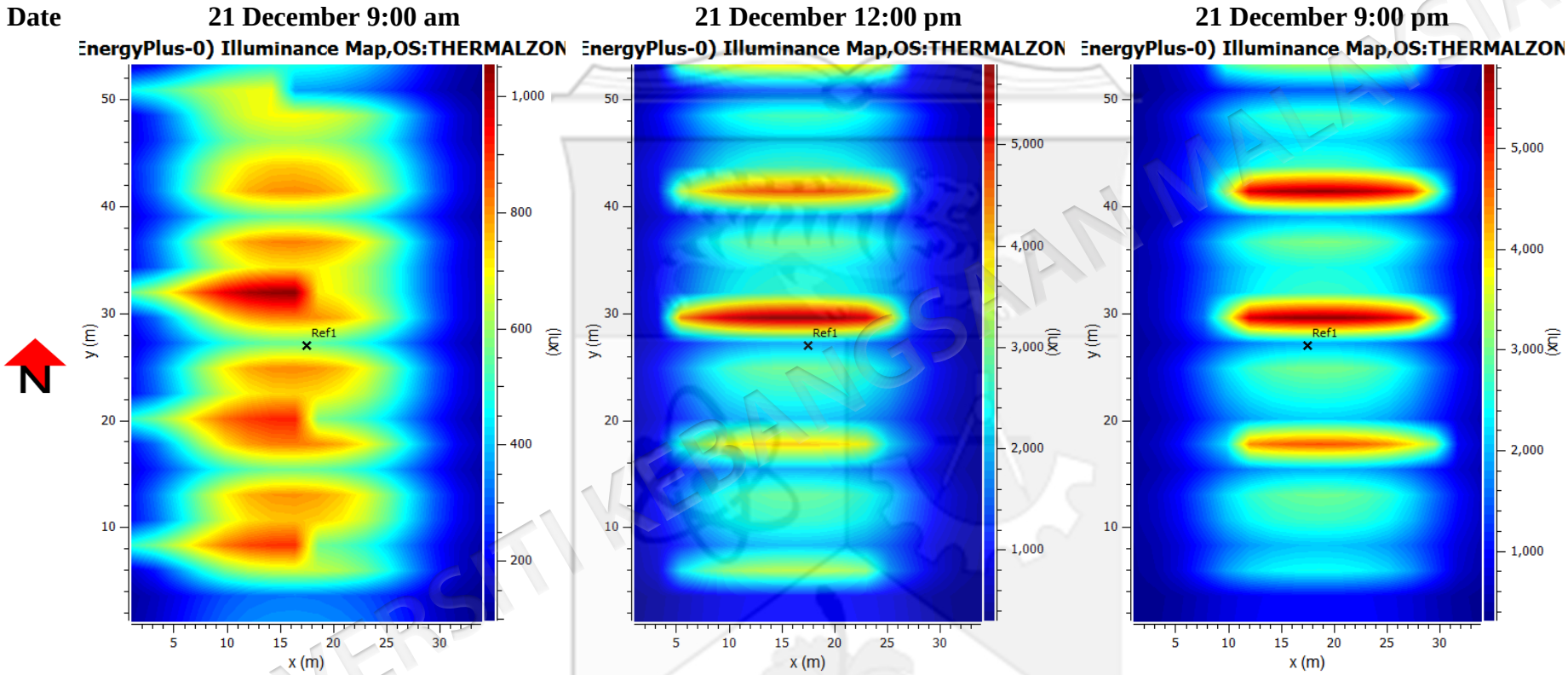

Figure 4.35 EnergyPlus **Roof Monitor** Illuminance level maps: 1 to 1 spacing-to-height ratio, **10% TFR**, double low-e clear. **21 December**

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Table 4.3 Comparison of daylight illuminance uniformity: 1 to 1 spacing-to- ceiling height ratio, 5% TFR

	Base case	**Skylight**	**Sawtooth**	**Roof Monitor**
21 Mar 9:00 am	0.31	0.15	0.20	0.22
21 Mar 12:00 pm	0.50	0.12	0.18	0.18
21 Mar 15:00 pm	0.54	0.11	0.18	0.18
21 Jun 9:00 am	0.34	0.14	0.20	0.21
21 Jun 12:00 pm	0.49	0.11	0.15	0.16
21 Jun 15:00 pm	0.50	0.12	0.16	0.17
21 Dec 9:00 am	0.38	0.15	0.18	0.21
21 Dec 12:00 pm	0.471	0.13	0.18	0.17
21 Dec 15:00pm	0.475	0.13	0.18	0.17

Table 4.4 Comparison of daylight illuminance uniformity: 1 to 1 spacing-to- ceiling height ratio, 10% TFR

	Base case	**Skylight**	**Sawtooth**	**Roof Monitor**
21 Mar 9:00 am	0.31	0.15	0.22	0.22
21 Mar 12:00 pm	0.50	0.11	0.20	0.19
21 Mar 15:00 pm	0.54	0.11	0.20	0.19
21 Jun 9:00 am	0.34	0.14	0.22	0.21
21 Jun 12:00 pm	0.49	0.11	0.18	0.18
21 Jun 15:00 pm	0.50	0.12	0.18	0.18
21 Dec 9:00 am	0.38	0.15	0.21	0.21
21 Dec 12:00 pm	0.471	0.12	0.20	0.17
21 Dec 15:00 pm	0.475	0.13	0.20	0.17

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Table 4.5 Comparison of daylight illuminance uniformity: 1 to 1 spacing-to- ceiling height ratio, 15% TFR

	Base case	Skylight	Sawtooth	Roof Monitor
21 Mar 9:00 am	0.31	0.20	0.23	0.26
21 Mar 12:00 pm	0.50	0.14	0.21	0.22
21 Mar 15:00 pm	0.54	0.13	0.21	0.22
21 Jun 9:00 am	0.34	0.18	0.24	0.24
21 Jun 12:00 pm	0.49	0.14	0.19	0.19
21 Jun 15:00 pm	0.50	0.16	0.19	0.21
21 Dec 9:00 am	0.38	0.20	0.22	0.25
21 Dec 12:00 pm	0.471	0.16	0.22	0.20
21 Dec 15:00 pm	0.475	0.16	0.22	0.20

* The daylight uniformity ratio is the ratio of lowest illuminance value to average illuminance of the space area for each case: A higher value indicates better uniformity

Table 4.6 Comparison of daylight illuminance gradient: 1 to 1 spacing-to-ceiling height ratio, 5% TFR

	Base case	Skylight	Sawtooth	Roof Monitor
21 Mar 9:00 am	29.0	18.5	9.9	9.1
21 Mar 12:00 pm	14.0	48.4	11.2	11.0
21 Mar 15:00 pm	11.0	57.9	11.5	18.3
21 Jun 9:00 am	22.6	27.6	31.8	24.5
21 Jun 12:00 pm	12.9	42.0	36.4	28.8
21 Jun 15:00 pm	12.5	30.9	27.7	21.4
21 Dec 9:00 am	25.4	15.9	10.8	13.0
21 Dec 12:00 pm	20.3	27.6	10.9	22.4
21 Dec 15:00 pm	19.8	27.1	10.9	22.0

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Table 4.7 Comparison of daylight illuminance gradient: 1 to 1 spacing-to-ceiling height ratio, 10% TFR

	Base case	Skylight	Sawtooth	Roof Monitor
21 Mar 9:00 am	29.0	14.9	8.8	8.8
21 Mar 12:00 pm	14.0	31.7	9.7	10.3
21 Mar 15:00 pm	11.0	36.0	9.9	11.8
21 Jun 9:00 am	22.6	19.3	18.2	15.9
21 Jun 12:00 pm	12.9	27.8	20.6	16.1
21 Jun 15:00 pm	12.5	22.2	22.1	16.0
21 Dec 9:00 am	25.4	13.6	9.2	10.9
21 Dec 12:00 pm	20.3	20.1	9.5	19.3
21 Dec 15:00 pm	19.8	19.7	9.4	18.9

Table 4.8 Comparison of daylight illuminance gradient: 1 to 1 spacing-to-ceiling height ratio, 15% TFR

	Base case	Skylight	Sawtooth	Roof Monitor
21 Mar 9:00 am	29.0	8.9	7.1	6.3
21 Mar 12:00 pm	14.0	19.0	7.6	7.5
21 Mar 15:00 pm	11.0	21.4	7.7	10.2
21 Jun 9:00 am	22.6	11.8	13.6	11.2
21 Jun 12:00 pm	12.9	16.9	19.2	14.7
21 Jun 15:00 pm	12.5	13.3	15.4	10.7
21 Dec 9:00 am	25.4	8.1	7.4	7.5
21 Dec 12:00 pm	20.3	12.1	7.6	12.9
21 Dec 15:00 pm	19.8	11.8	7.5	12.6

* The daylight gradient ratio can be found by calculating the ratio of maximum to minimum illuminance value of the space area of each case: lower value indicates better uniformity

After the UKM case study building with its sidelight system was modeled and successfully calibrated, it is considered as the reference base case model for all future simulations comparisons. The base case model was then modified to exclude its sidelight apertures and include only toplighting alternatives, namely, skylight,

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sawtooth, and roof monitor with daylighting control and was simulated again to determine the effect of daylighting through toplighting systems on the energy savings and daylight quality of the building and compare the simulation results of the toplighting alternatives cases with the reference base case model with only sidelight apertures.

As the graphs 4.18-4.35 indicate, the daylight distribution considerably improves in the toplighting alternatives with a 1-to-1 spacing-to-height ratio relative to the base case. This improvement is a result of more daylight apertures installed in the toplighting alternatives as opposed to the base case, which has only sidelighting daylight apertures. Based on the analysis of the illuminance distribution and uniformity, the sawtooth option with a 1-to-1 spacing-to-ceiling height ratio provides the most illuminance among the various alternatives in all of the simulated cases and days.

As the illuminance maps in Figures 5.19 to 5.26 show, the daylight distribution of the skylight alternative under the Kuala Lumpur sky condition focuses on the middle areas directly under the skylight apertures. Daylight is not distributed in the circumferential space as much as it is in the other toplighting alternatives. However, the skylight alternative provides a high daylight illuminance value. The daylight distribution method is similar throughout the year, but the daylight level increases in March in all skylight cases with a TFR ranging from 5% to 60%.

The daylight distribution patterns of the roof monitor alternative also do not change throughout the year in all cases. Better daylight uniformity is achieved in (June) and December because of the minimum daylight level during these months relative to that in March. The daylight distribution patterns of the roof monitor retain a small amount of daylight but are not as clear as in the skylight case because the daylight is distributed further near the circumference of the building space.

Throughout the year, the daylight distribution patterns of the sawtooth option with a 1-to-1 spacing-to-height ratio show a slight variation: more daylight is distributed across the building space in March and December and less daylight

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distribution in June. Daylight is spread better than in the roof monitor option because the illuminance maps (contours) are not farther apart as in the roof monitor option. However, the sawtooth case provides a lower daylight illuminance value. Generally, the daylight distribution achieved is again close to that in the roof monitor alternative with a 1-to-1 spacing-to-ceiling height ratio.

As the illuminance maps indicate, the alternative that achieves the best daylight illuminance distribution and daylight uniformity is the sawtooth alternative, followed by the roof monitor alternative.

As Tables 4.3 to 4.5 show, the sawtooth alternative with a TFR from 5% to 15% also provides the highest value of daylight illuminance uniformity among all toplighting alternatives. That is, the sawtooth alternative provides the highest daylight uniformity ratio at all simulated dates and times. The roof monitor case provides approximately 0.1 to 0.3 less than the sawtooth option. All of the daylight uniformity values do not meet the recommendation set by the CIBSE Code, which is more than 0.8. The CIBSE Code for interior lighting (CIBSE 1994) gives guidance on daylight uniformity. It recommends 'the uniformity of illuminance (minimum to overage illuminance) over any task area and immediate surrounded should not be less than 0.8. Where task area may be located anywhere over the area of a space then the recommendation applies to that area. However it recognizes that greater variations can occur if different tasks are carried out in different parts of an interior (Dewey & Littlefair 1998). However, the EnergyPlus base case simulated space does not contain any interior people or furniture, so that the daylight uniformity parameter is not evaluated as a major factor, as is the daylight illuminance gradient. Generally, the obtained and evaluated daylight illuminance uniformity is similar to the daylight illuminance gradient parameter.

As the comparison of the daylight illuminance gradient ratios in Tables 4.6 to 4.8 demonstrate, the sawtooth alternative with a TFR of 5% to 15% also yields the lowest illuminance gradient value at all simulated dates and times. However, in June, the roof monitor option provides the lowest illuminance gradient ranging from 6.1 to 31.8. The tables further indicate that the sawtooth alternative meets, and in certain

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dates exceeds, the criteria set by the CIBSE Code, the maximum of which is 5. Consequently, in the roof monitor case, the spacing-to-ceiling height ratio and TFR can be increased while retaining the illuminance gradient within the standard. The illuminance gradient values produced by EnergyPlus correspond to the analysis of the illuminance maps. For the sawtooth and roof monitor alternatives, the daylight illuminance gradient ratio increases in June and decreases in March and December. The illuminance gradient values do not differ considerably in the course of a day, except in June when the daylight illuminance gradient values differ significantly.

A detailed comparison of the daylight illuminance maps of the skylight, sawtooth, and roof monitor cases with a TFR ranging from 30% to 60% is presented in Figures B-13 to B-16 of Appendix B.

A detailed comparison of the daylight illuminance uniformity and gradient of the skylight, sawtooth, and roof monitor cases with a TFR ranging from 30% to 60% is presented in Tables B-1 to B-10 of Appendix B.

4.1.4 Toplighting Alternatives Analysis: 1 to 1.5 Spacing-to-Ceiling Height Ratio

4.1.4.1 Daylight Factor Analysis

The daylight factors of the toplighting alternatives were compared using an overcast sky condition. Figure 4.36 shows a comparative graph of the daylight factor of the toplighting alternatives with a 1-to-1.5 spacing-to-height ratio versus that of the base case. The toplighting alternatives analyzed include the skylight, sawtooth, and roof monitor cases.

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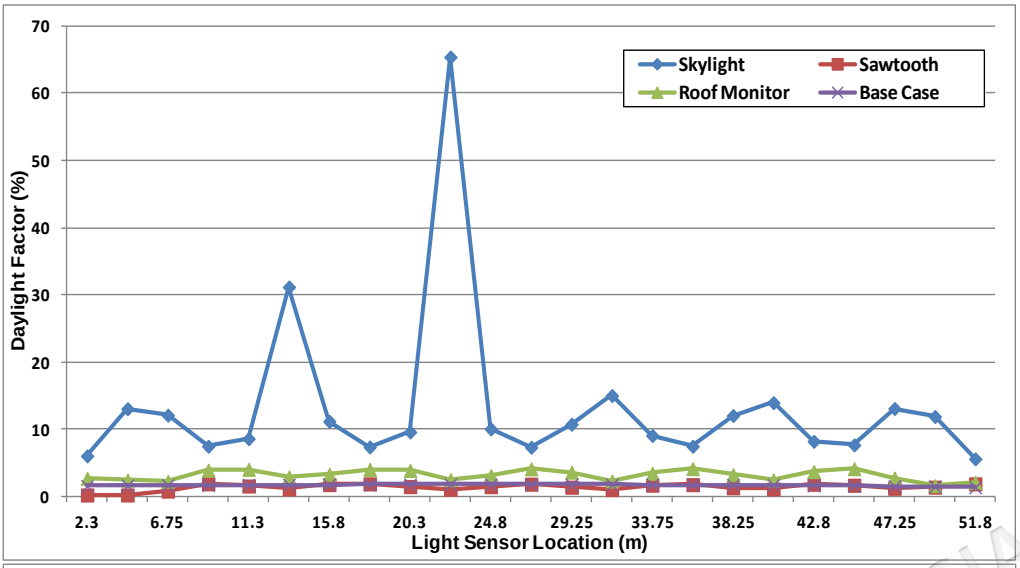
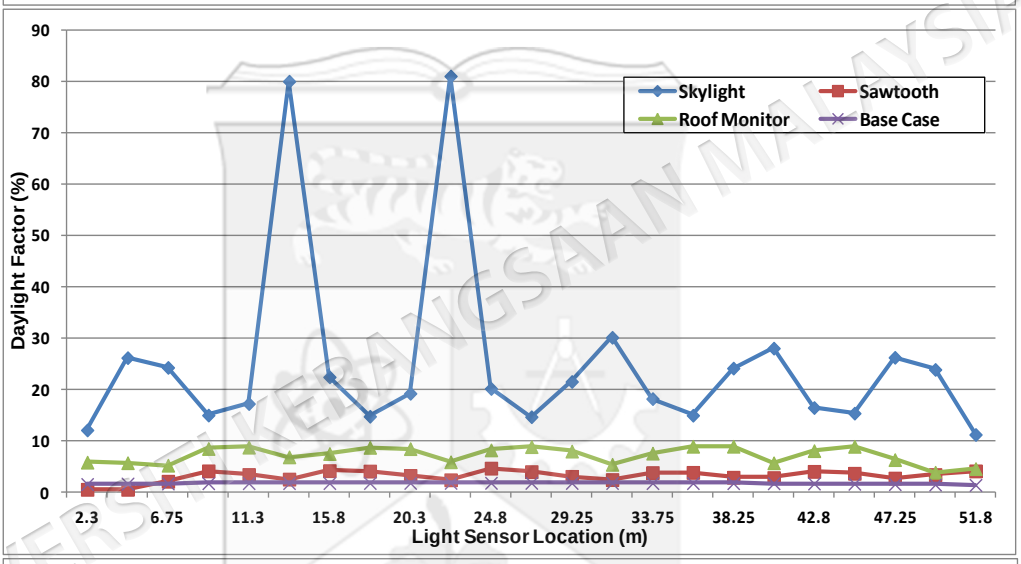
a)
5%



b)
10%



c)
15%

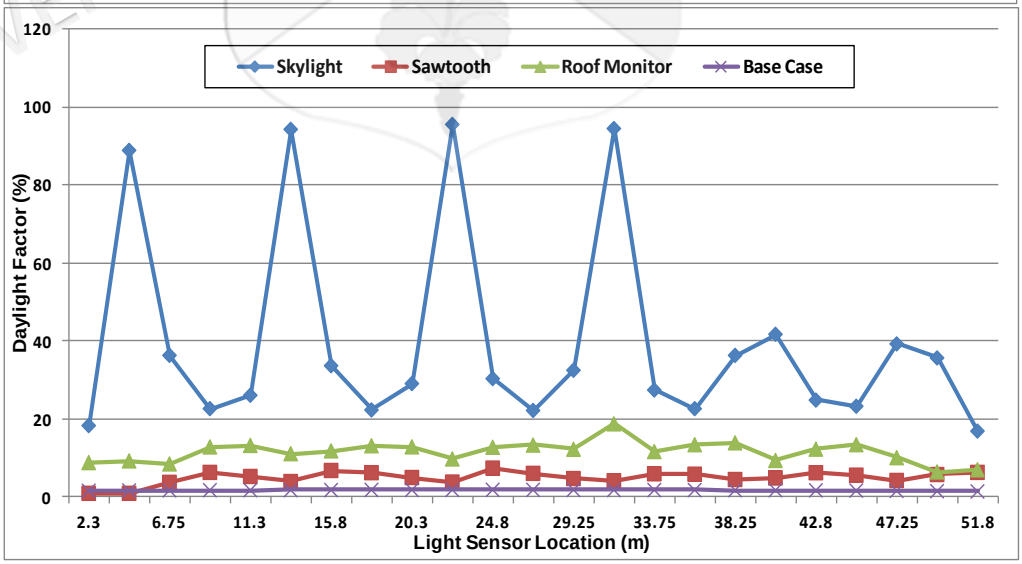


Figure 4.36 Comparison of daylight factor of 1 to 1.5 toplighting alternatives versus base case under overcast sky condition, a) 5%, b)10%, and c) 15% TFR

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As Figure 4.36 shows, the daylight factors from the calibrated base case model (case study building) were consistently lower than those from the toplighting alternatives. This difference may be due to various factors in the building space, the main factor being the presence of a large overhang near the windows in the eastern and western elevations of the case study building, which reduces the daylight penetrating the interior space. Other factors include the actual glazing light transmittance, reduction of internal light reflections by the space furniture, and reduction of daylight illuminance entering the building caused by trees and neighboring buildings outside.

For the daylight factor analysis under the overcast sky condition, the skylight alternative also yields the highest daylight factor value among all of the toplighting alternatives. The roof monitor and sawtooth cases produce a lower maximum daylight factor value. As the figure indicates, although the sawtooth option achieves a lower daylight factor than the roof monitor, the lines remain close to each other. The sawtooth alternative yields the lowest minimum daylight factor values.

For the skylight alternative with 5% TFR, the maximum daylight factor is 15% and the minimum is 8%. This toplighting alternative was much higher than the recommended daylight factor value of 5% provided by CIBSE. For the sawtooth alternative 5% TFR, the maximum daylight factor is 3% and the minimum is 1%. This alternative falls beyond the recommended daylight factor value of 5% of CIBSE. For the roof monitor alternative with 5% TFR, the maximum daylight factor is 5% and the minimum is 3%. This alternative was falls beyond the recommended daylight factor value of 5% provided by CIBSE. According to CIBSE the minimum recommended daylight factor should not fall below 5%.

For the skylight alternative with 10% TFR, the maximum daylight factor is 15% and the minimum is 25%. This toplighting alternative is much higher than the recommended daylight factor value of 5% provided by CIBSE. But for the sawtooth alternative 10% TFR, the maximum daylight factor is 5% and the minimum is 3%. This alternative was within the recommended daylight factor value of 5% of CIBSE, while in the roof monitor alternative with 10% TFR, the maximum daylight factor is

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8% and the minimum is 5%. This alternative was within the recommended daylight factor value of 5% provided by CIBSE. According to CIBSE the minimum recommended daylight factor should not fall below 5%.

The skylight alternative with a 1-to-1.5 spacing-to-height ratio yields the maximum daylight factor value of 41.7%, whereas the sawtooth alternative yields the lowest maximum daylight factor of 7.4%. The skylight and sawtooth alternatives have a maximum daylight factor level discrepancy of 34.3%. The maximum daylight factor value of the roof monitor alternative is also lower than that of the skylight alternative, the range of difference being 23%. Generally, the daylight factor level is less in the 1-to-1 spacing-to-height ratio alternatives at approximately 1.3%.

As figure 4.36 shows, a 1-to-1.5 spacing-to-height ratio improves the daylight distribution compare to the base case model with only sidelight. However, a 1-to-1.5 spacing-to-height ratio option does not result in the same improvement of 1-to-1 spacing-to-height ratio option because of less built-in daylight openings (only six units). Although only three units are removed from the base case model with 1-to-1 spacing-to-height ratio option, the daylight distribution is not better. The sawtooth and roof monitor alternatives have similar daylight distribution patterns relative to the skylight alternative in all of the TFR cases. From the figure also, it can be seen that, the skylight yields a higher daylight factor than the sawtooth or roof monitor alternatives and is not very good. There are peaks values under the opening of skylight units and minimum values at the points in between, resulting from uneven in the light distribution in the interior space, which may have an effect on the daylight quality and possible of eye fatigue.

4.1.4.2 Illuminance level Analysis

For the analysis of the illuminance level and daylight distribution, the simulation date and time are June 21 (summer solstice), March 21/September 21 (equinoxes), and December 21 (winter solstice), at 9:00 am, 12:00 pm, and 3:00 pm based on the LBNL reference on toplighting system designs.

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A comparison of the illuminance levels was conducted under intermadiate sky condition. Figures 4.37 to 4.45 present the comparative graphs of the illuminance levels of the toplighting alternatives with a 1-to-1.5 spacing-to-height ratio and a TFR ranging from 5% to 15% versus those of the base case. The toplighting alternatives investigated include six-unit skylight, sawtooth, and roof monitor cases.

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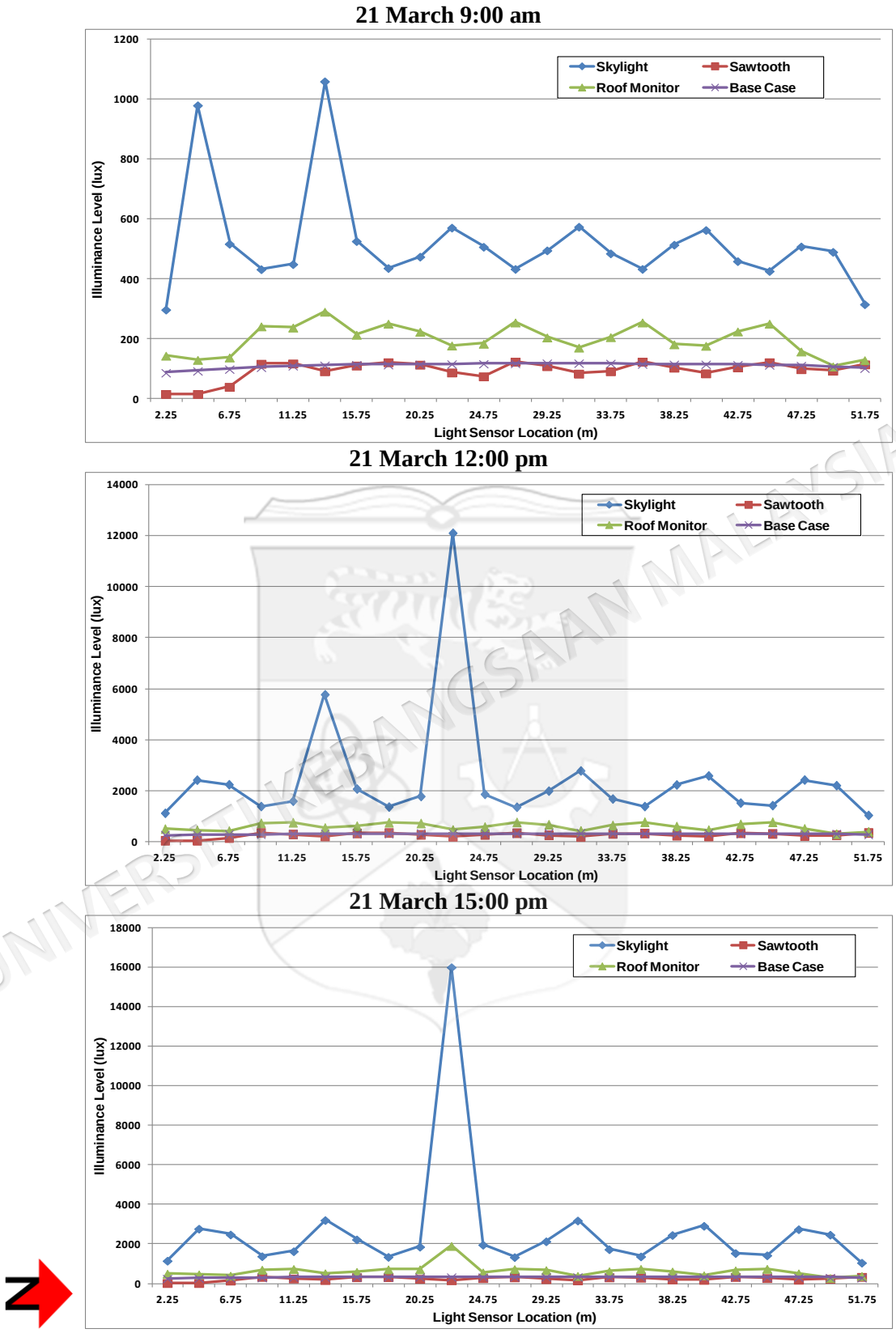

Figure 4.37 Illuminance level comparison: 1 to 1.5 spacing-to-ceiling height ratio, 5% TFR, double low-e clear, 21 of March

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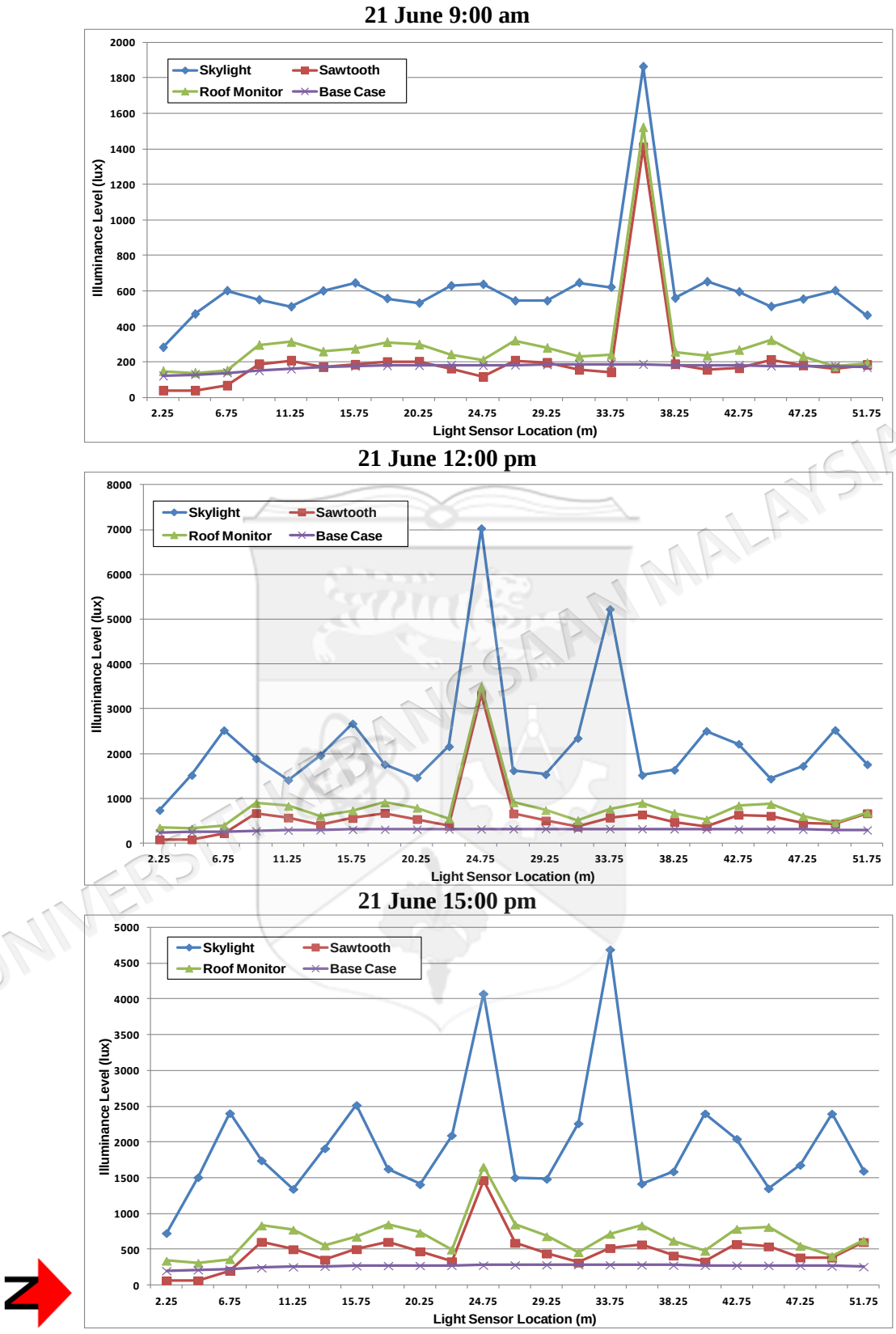

Figure 4.38 Illuminance level comparison: 1 to 1.5 spacing-to-ceiling height ratio, 5% TFR, double low-e clear, 21 of June

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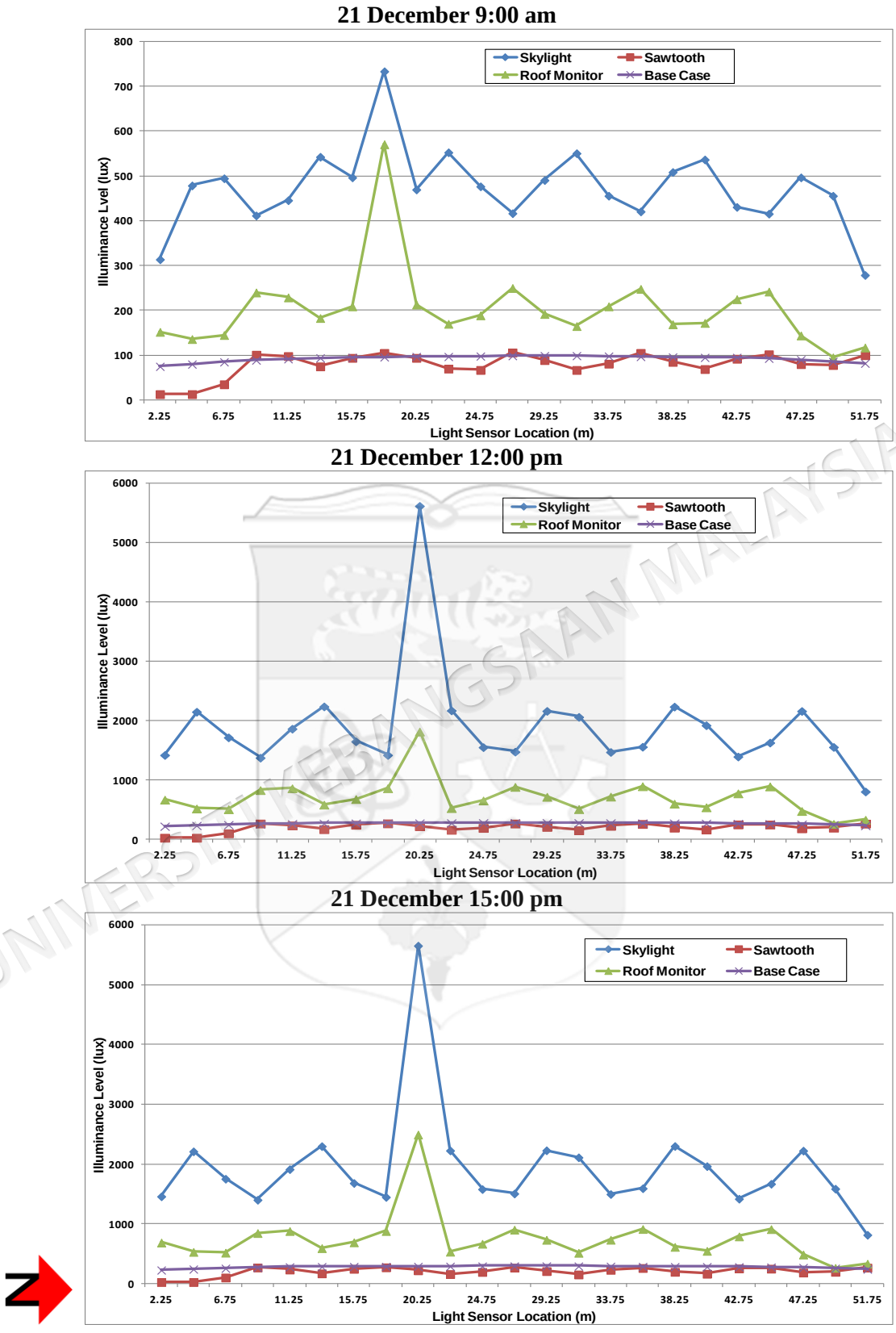

Figure 4.39 Illuminance level comparison: 1 to 1.5 spacing-to-ceiling height ratio, 5% TFR, double low-e clear, 21 of December

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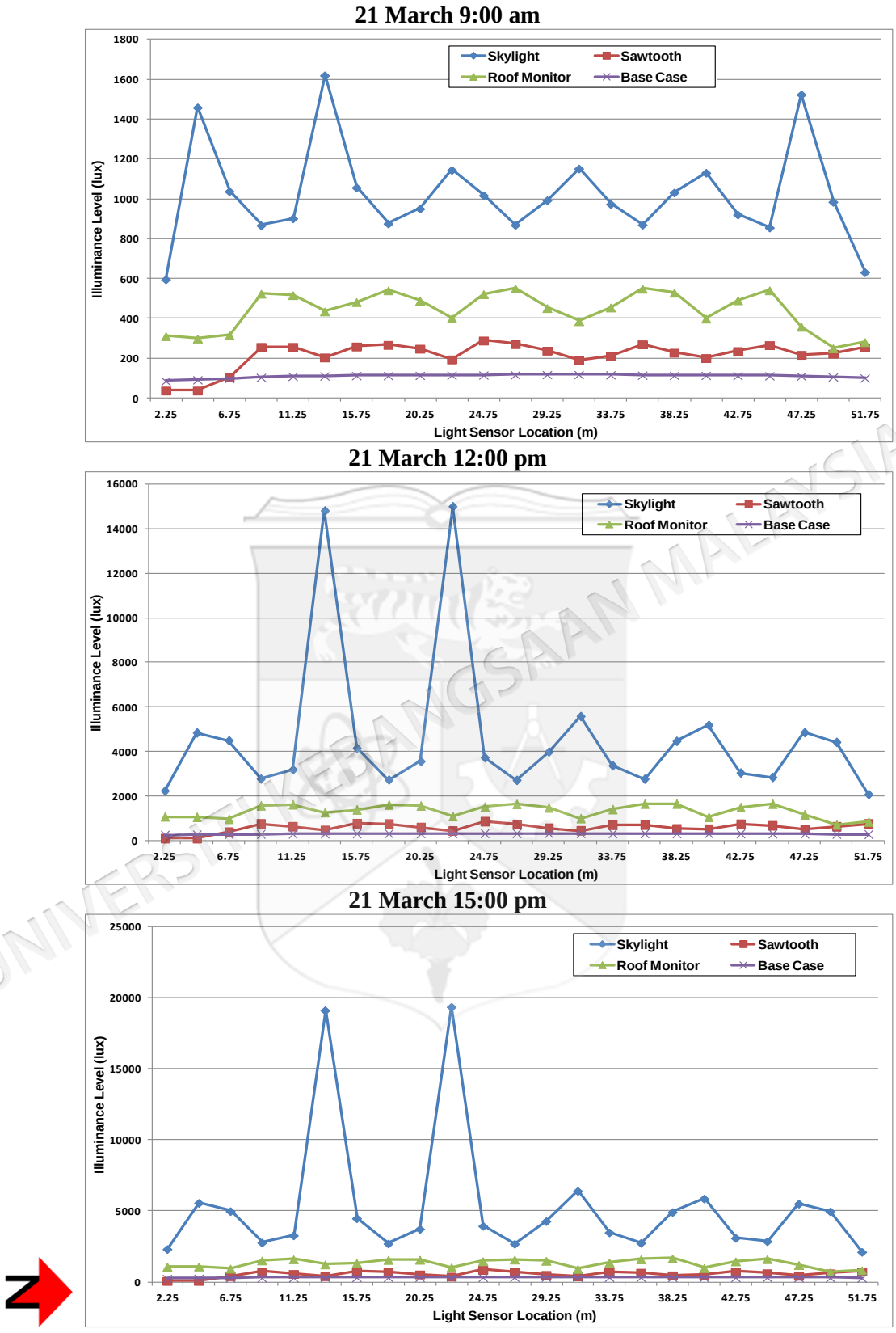

Figure 4.40 Illuminance level comparison: 1 to 1.5 spacing-to-ceiling height ratio, 10% TFR, double low-e clear, 21 of March

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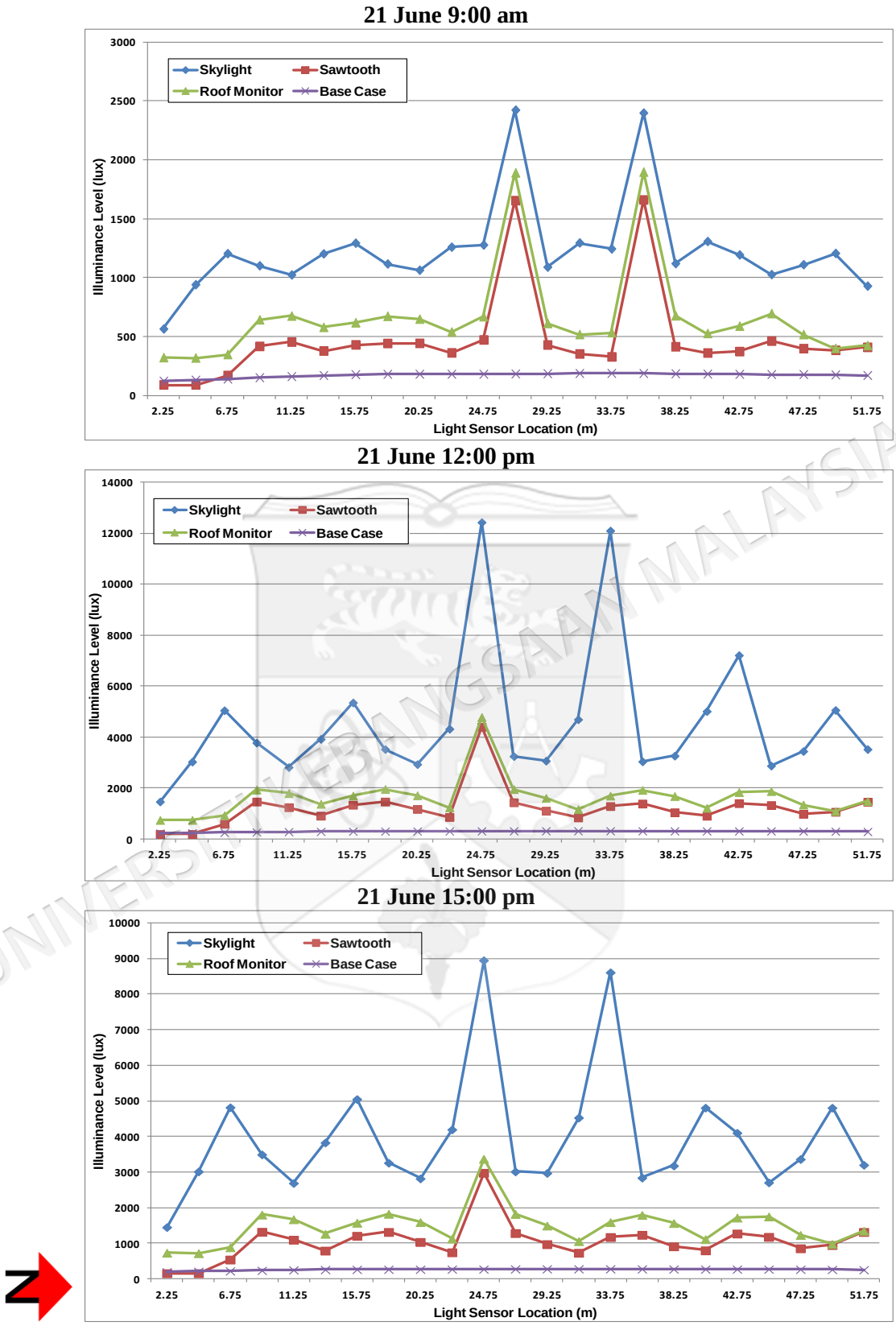

Figure 4.41 Illuminance level comparison: 1 to 1.5 spacing-to-ceiling height ratio, 10% TFR, double low-e clear, 21 of June

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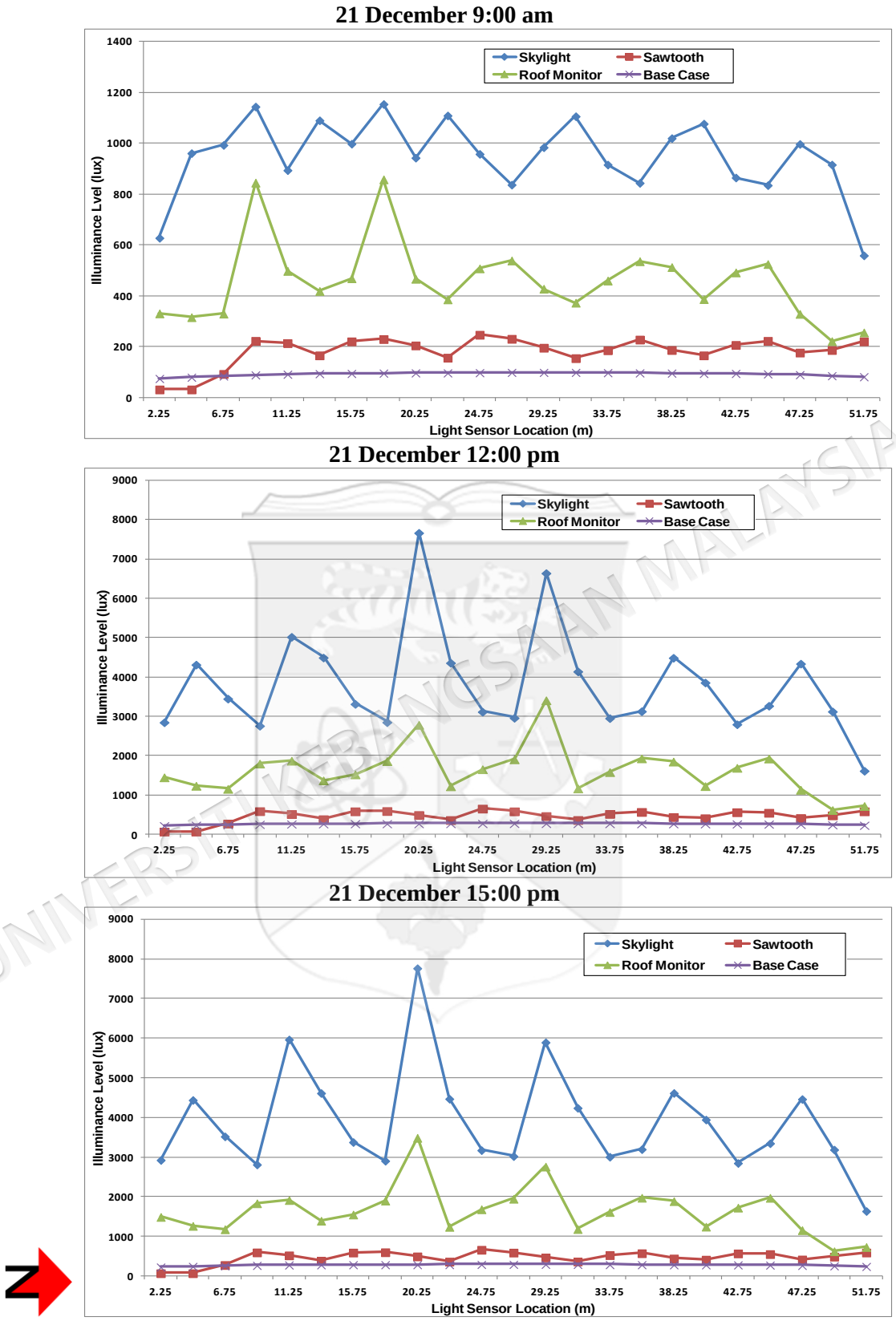

Figure 4.42 Illuminance level comparison: 1 to 1.5 spacing-to-ceiling height ratio, 10% TFR, double low-e clear, 21 of December

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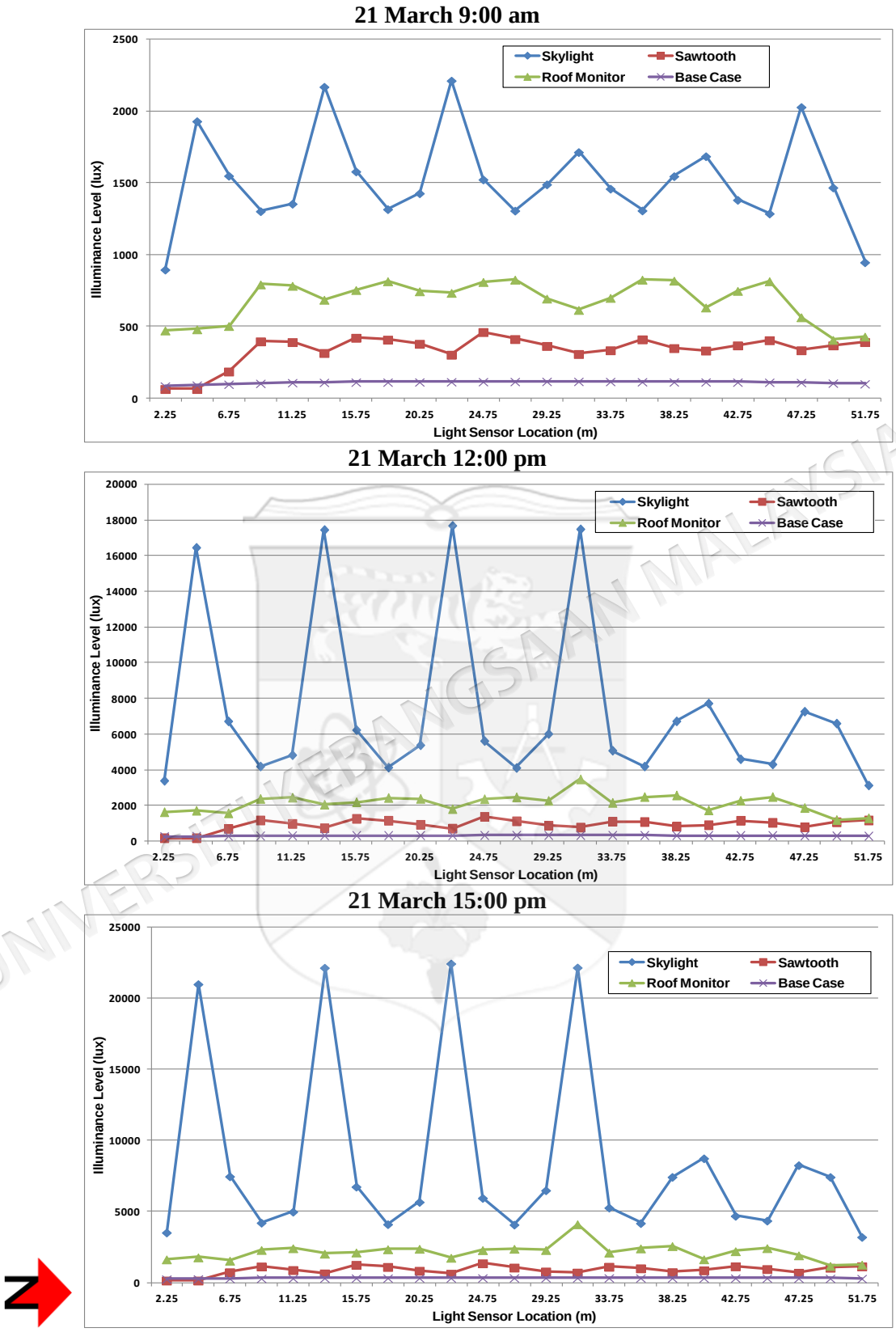

Figure 4.43 Illuminance level comparison: 1 to 1.5 spacing-to-ceiling height ratio, 15% TFR, double low-e clear, 21 of March

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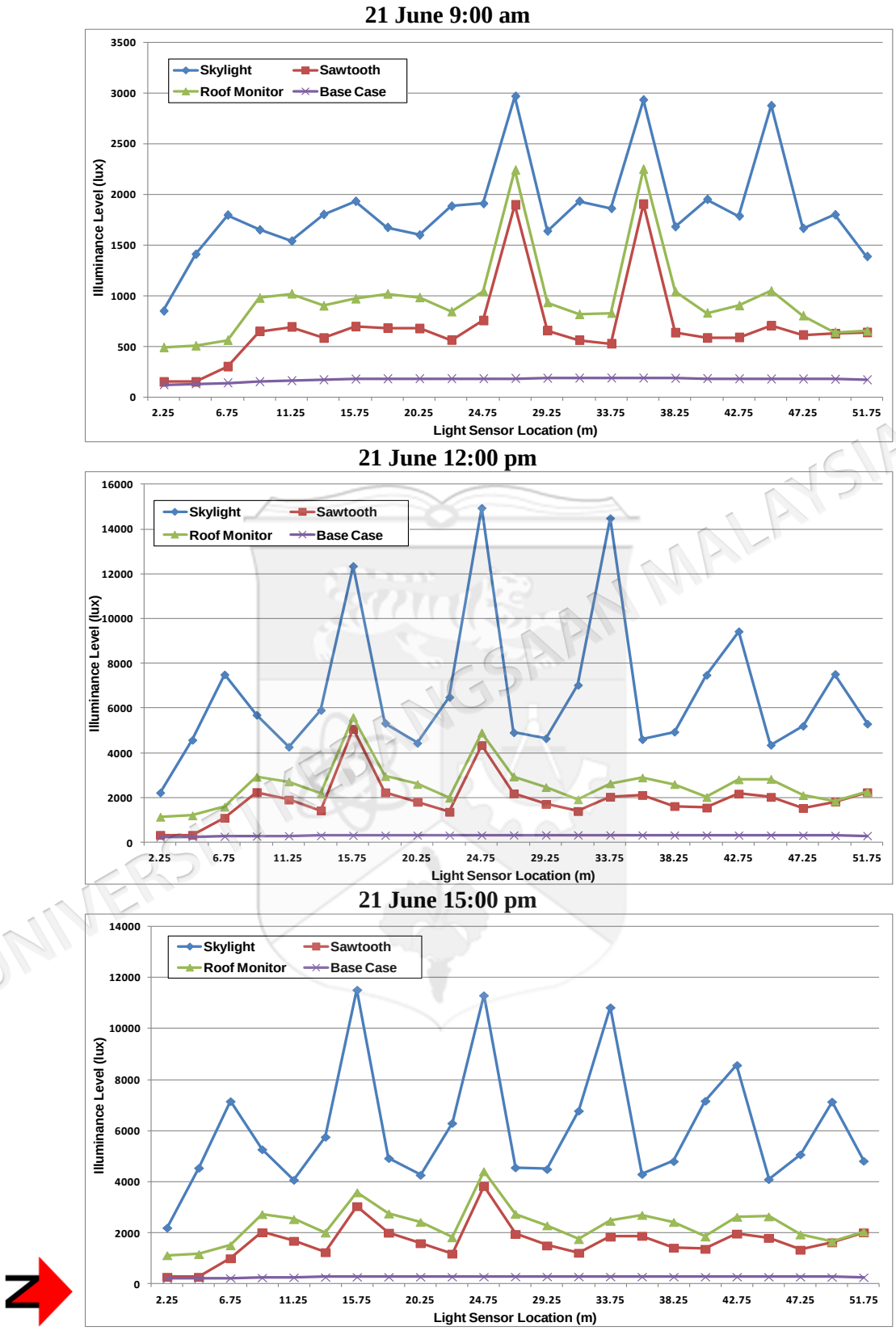

Figure 4.44 Illuminance level comparison: 1 to 1.5 spacing-to-ceiling height ratio, 15% TFR, double low-e clear, 21 of June

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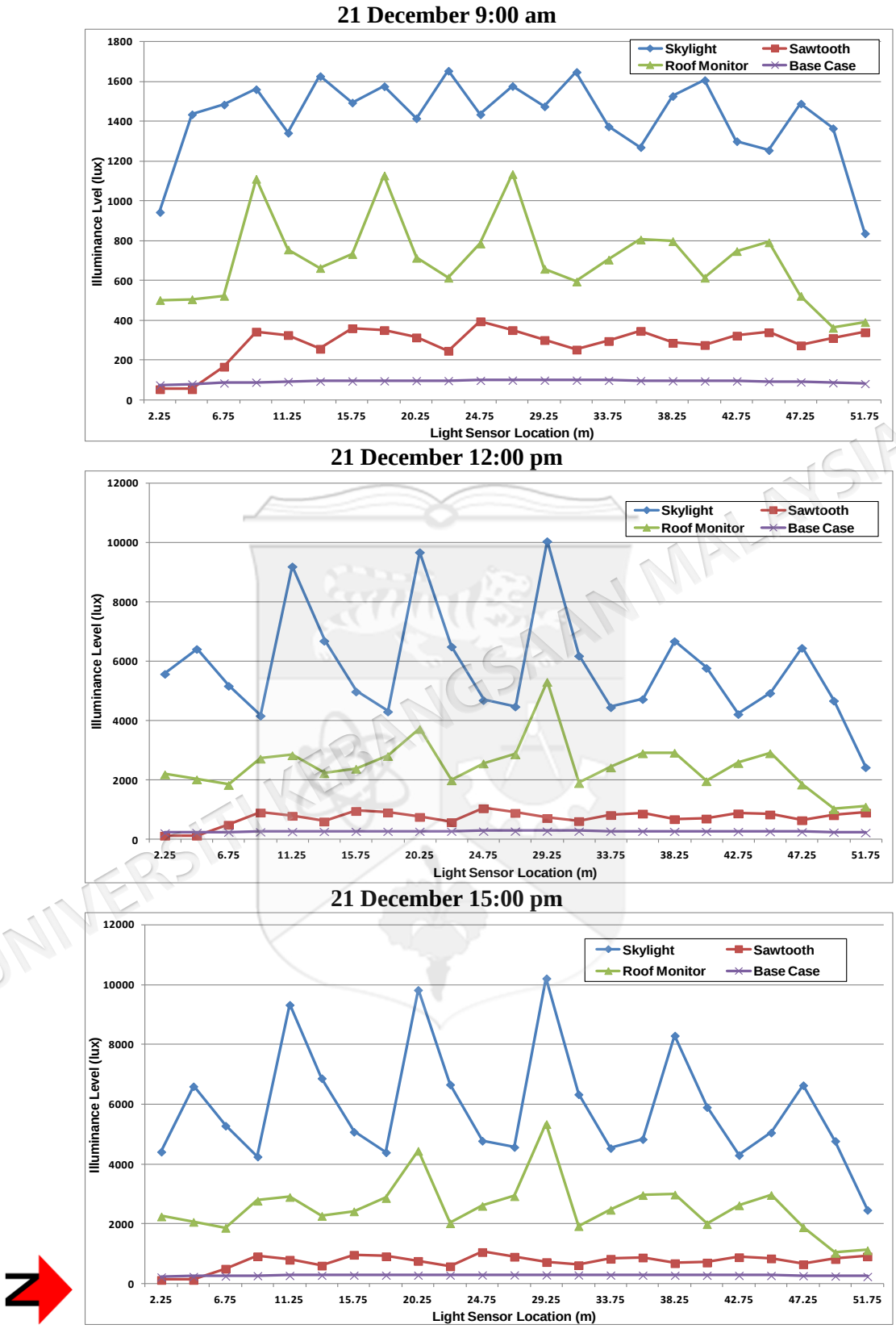

Figure 4.45 Illuminance level comparison: 1 to 1.5 spacing-to-ceiling height ratio, 15% TFR, double low-e clear, 21 of December

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Based on the analysis of the illuminance levels under intermadiate sky conditions, the skylight alternative yields the highest maximum illuminance level value in all cases with a TFR ranging from 5% to 15% and at all the simulated dates and times. This is due to the use of double low-E clear glazed with skylight cases, thus direct sunlight penetrates into the space directly causing the peak illuminance levels to be much higher than in the other toplighting alternatives and hence become incomparable with other toplighting alternative. Therefore, a double low-E clear glazed should not be used with skylight cases and a diffuse glazing should be used instead of double low-E clear glazing, because, with double low-E clear glazed skylights, direct sunlight can entering the interior space directly. This, in turn, cause the interior illuminance level for skylight alternative under the openng to be very high, and hence the lighting performance could not be compared to the sawtooth and roof monitor, which have vertical glazing. Diffuse glazing in the skylight alternative cases helps diffuse the direct sunlight that enters the base case space and make the cases more comparable in terms of their lighting performance. The illuminance level reaches more than 5,000 lux in December in the 15% TFR case. The roof monitor and sawtooth yield illuminance level values closer to each other than to the skylight alternative. However, in March, the skylight alternative yields an illuminance level closer to the other alternatives with a TFR of 5%.

The illuminance level values of the skylight alternative are generally higher than those of either sawtooth and roof monitor alternatives in all of the TFR cases. The daylight illuminance level shows a seasonal discrepancy. Higher illuminance level is observed in March and less in June and December. For the skylight alternative with a TFR of 10%, the maximum illuminance level value in March is approximately 5,800 lux; 5,000 lux in June; and approximately 4,500 lux in December. All measurements were taken at 12:00 pm.

The maximum illuminance level value of the roof monitor alternative is obtained in March at 12:00 pm at approximately 2,000 lux. The illuminance level value of the roof monitor alternative is higher in December and lower in March, with the discrepancy in the maximum illuminance level value of each month at approximately 1,300 lux. The roof monitor alternative generally yields a higher

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daylight illuminance level than the sawtooth alternative throughout the year. This could be because it has a glazing for both north and south orientation. However, in March and June at 12:00 pm and 15:00 pm, the illuminance level of the roof monitor alternative with a 10% TFR is closer to that of the sawtooth, as in the option with a 1-to-1 spacing-to-ceiling height ratio alternative.

In general, the sawtooth alternative yields a lower illuminance level than the roof monitor alternative in all of the TFR cases. However, the illuminance value does not differ significantly in June compared with that of the roof monitor alternative with a TFR of 15%. This could be because it has a glazing for only north orientation. . The illuminance level value reaches its maximum in June at 12:00pm at about 4,000 lux. For sawtooth, the illuminance level is higher in summer and is lower in winter. The illuminance levels range from 500 lux in winter and up to 4,000 in summer with a TFR of 15%. The illuminance values of the sawtooth alternative are higher than those of the base case and are lower than those of the other toplighting alternatives across all TFR cases throughout the year.

The maximum illuminance level again occurs under the aperture, just as in 1 to 1 spacing-to-ceiling height ratio condition, even with vertical glazing of toplighting alternatives like the sawtooth or roof monitor. This could be because roof monitor and sawtooth have vertical glazing which, in intermediate sky condition, some sunlight could enter directly through vertical glazing into the space, as the toplighting alternatives have no exterior shading device installed. The penetration of direct sunlight through the vertical glazing depends on position of the sun and sun-path on summer solstice (June 21), equinoxes (March 21/September 21), and winter solstice (December 21) at 9:00am, 12:00pm, and 15:00pm solar time. for Kuala Lumpur latitude as presented in sun-path diagram for Kuala Lumpur in Chapter III Section 2.3.3 Figure 18. Differing sun paths in each season make different lighting level in the interior space of the base case. To eliminate this direct sunlight penetration, the vertical glazing of the sawtooth and roof monitor cases needs to have external shading devises.

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As the figures indicate, the sawtooth and roof monitor alternatives yield the same daylight distribution under intermediate sky condition. The daylight distribution of these alternatives is less than that of the skylight alternative across all TFR cases throughout the year. The skylight alternative has a larger range of illuminance level, which results in poorer daylight distribution relative to that of the roof monitor and sawtooth alternatives. However, no conclusions can be drawn from these charts alone, since the illuminance sensor locations are located in a single row along the center of the base case model and better conclusion can be derived through the illuminance distribution and uniformiy analysis, which will be analyzed in the next section.

Overall, the roof monitor alternative yields a higher illuminance value under a intermediate sky condition and a higher daylight factor under an overcast sky condition than do the sawtooth and base cases under the same conditions. The sawtooth alternative yields a lower illuminance level in all cases and a visually better daylight distribution because the curves are flatter and more constant.

For skylight alternative 5% TFR performance in terms of illuminance level, the values again change also dramatically in the course of the day and throughout the year. The maximum illuminance values were range from 1500 to 2000 Lux, which occurred at 12:00 pm on March 21, June 21 and September 21. These values are again much higher than the recommended task illumination provided by CIBSE which range of 300 to 500 lux.

For sawtooth 5% TFR performance in terms of illuminance level, the values again change dramatically in the course of the day and throughout the year. The maximum illuminance level value was range from 300 to 500 Lux, which occurred at 12:00 pm on March 21, June 21 and September 21. These values are within the recommended task illumination provided by CIBSE, which range of 300 to 500 lux. For roof monitor 5% TFR performance in terms of illuminance level, the values change dramatically in the course of the day and throughout the year. The maximum illuminance level value was range from 500 to 750 Lux, which occurred at 12:00 pm on March 21, June 21 and September 21. These values are slightly higher than the recommended task illumination provided by CIBSE.

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Even though skylight alternative yields a higher illuminance level than the two other toplighting alternatives during most of the year, the skylight alternative has poor lighting performance in terms of illuminance level, daylight factor, and light distribution and uniformity. This can be reduced by using diffuse film or glazing on the skylight opening.

4.1.4.3 Daylight Distribution and Uniformity Analysis

The parameters for analyzing the illuminance uniformity are illuminance gradient (or diversity of illuminance in CIBSE code) and uniformity of illuminance. For the illuminance gradient (the ratio of maximum to minimum illuminance), a lower value indicates better uniformity, while for uniformity of illuminance (the ratio of minimum to average illuminance), a higher value indicates better uniformity. The illuminance gradient is the primary parameter in the daylight quality analysis, since it is the more relaxed parameter. Therefore, it is suitable for a space without any furniture, as in the EnergyPlus base case model in this research. Figures 4.46 to 4.63 present a comparison of the illuminance maps of the three toplighting alternatives with a 1-to-1.5 spacing-to-ceiling height ratio and a TFR range from 5% to 10% under a clear sky condition at different dates and times. Tables 4.9 to 4.11 report the illuminance gradient values of the skylight, sawtooth, and roof monitor alternatives with a TFR from 5% to 15%. Tables 4.12 to 4.14 illustrate the uniformity of the illuminance values. As explained in Chapter 3, the most important parameter in evaluating the uniformity of daylight illuminance is the illuminance diversity or illuminance gradient described by CIBSE. An analysis of the daylight distribution and uniformity of the skylight, sawtooth, and roof monitor alternatives under Kuala Lumpur sky conditions is presented later in this section.

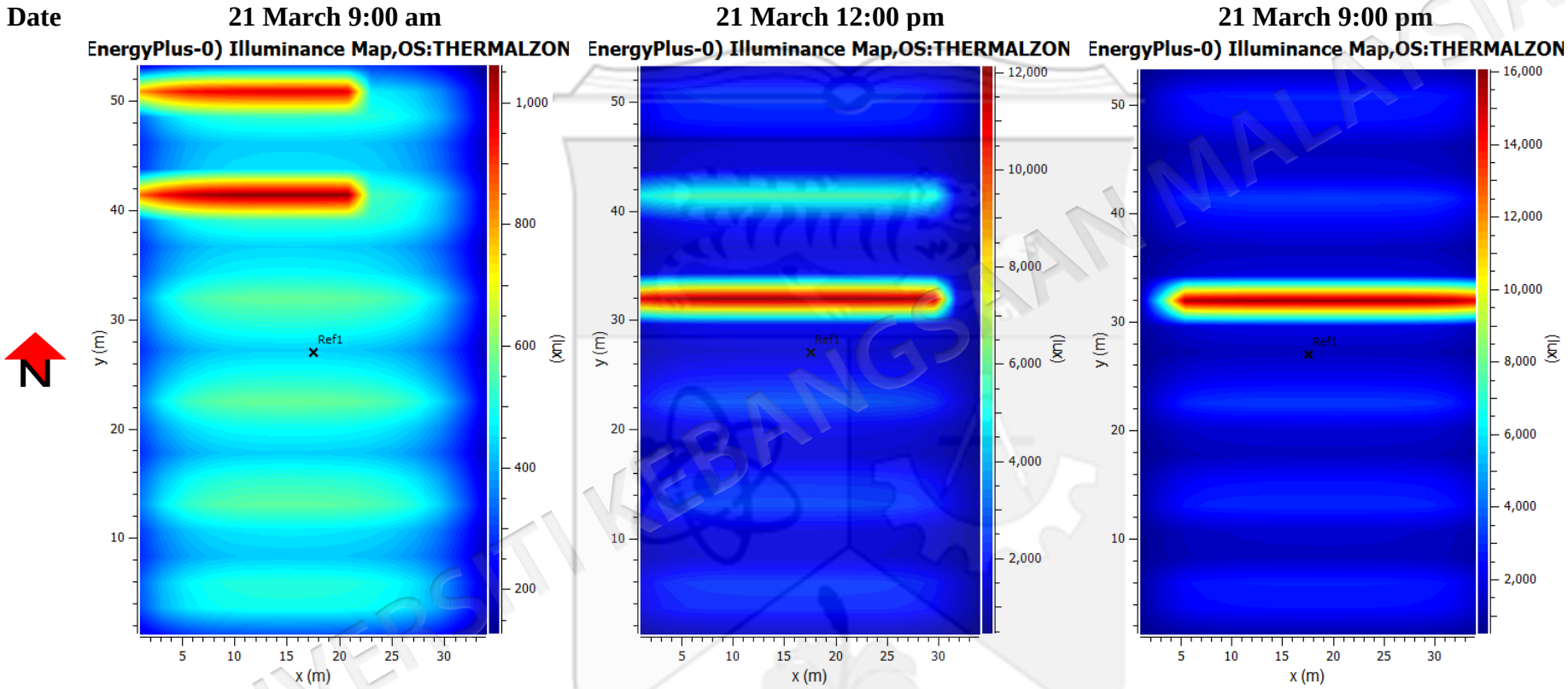

Figure 4.46 EnergyPlus **Skylight** Illuminance level maps: 1 to 1.5 spacing-to-height ratio, **5% TFR**, double low-e clear. **21 March**

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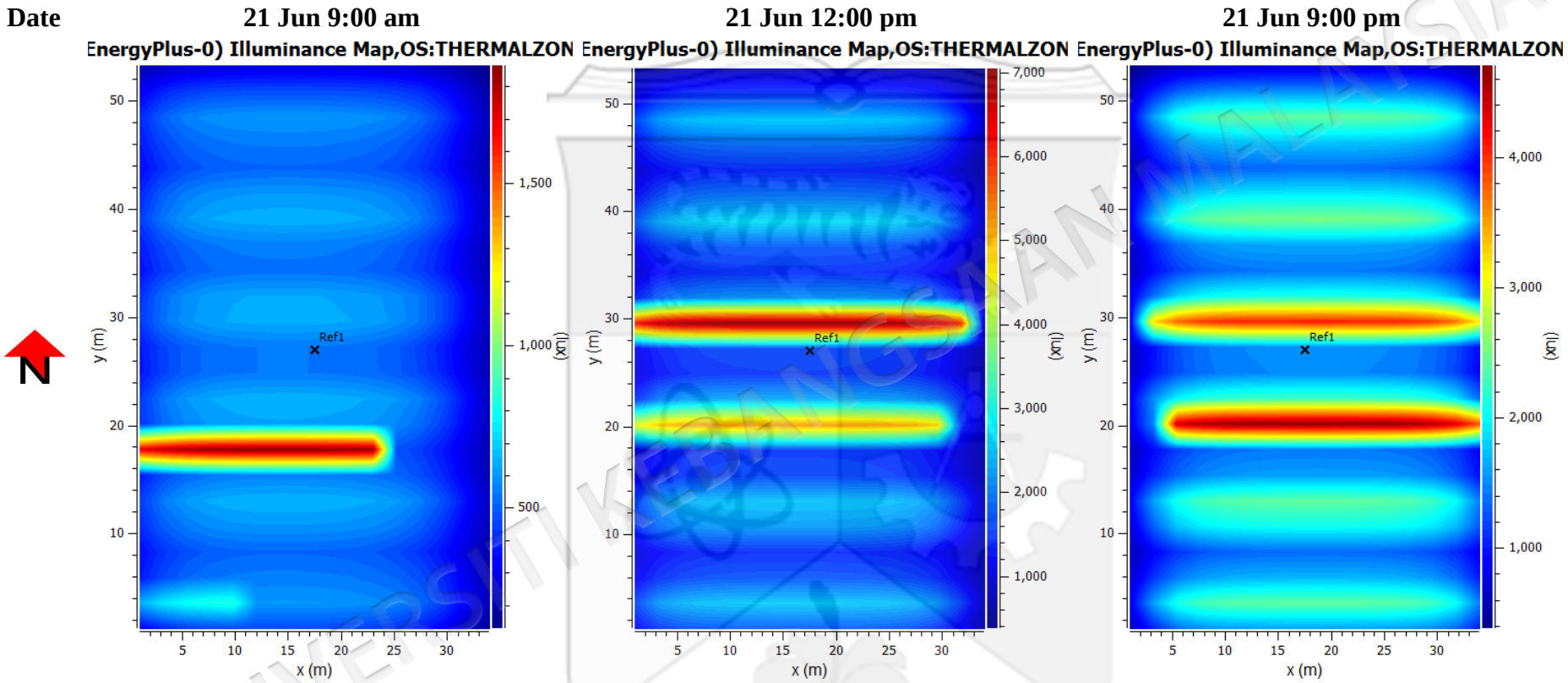

Figure 4.47 EnergyPlus **Skylight** Illuminance level maps: 1 to 1.5 spacing-to-height ratio, **5% TFR**, double low-e clear. **21 Jun**

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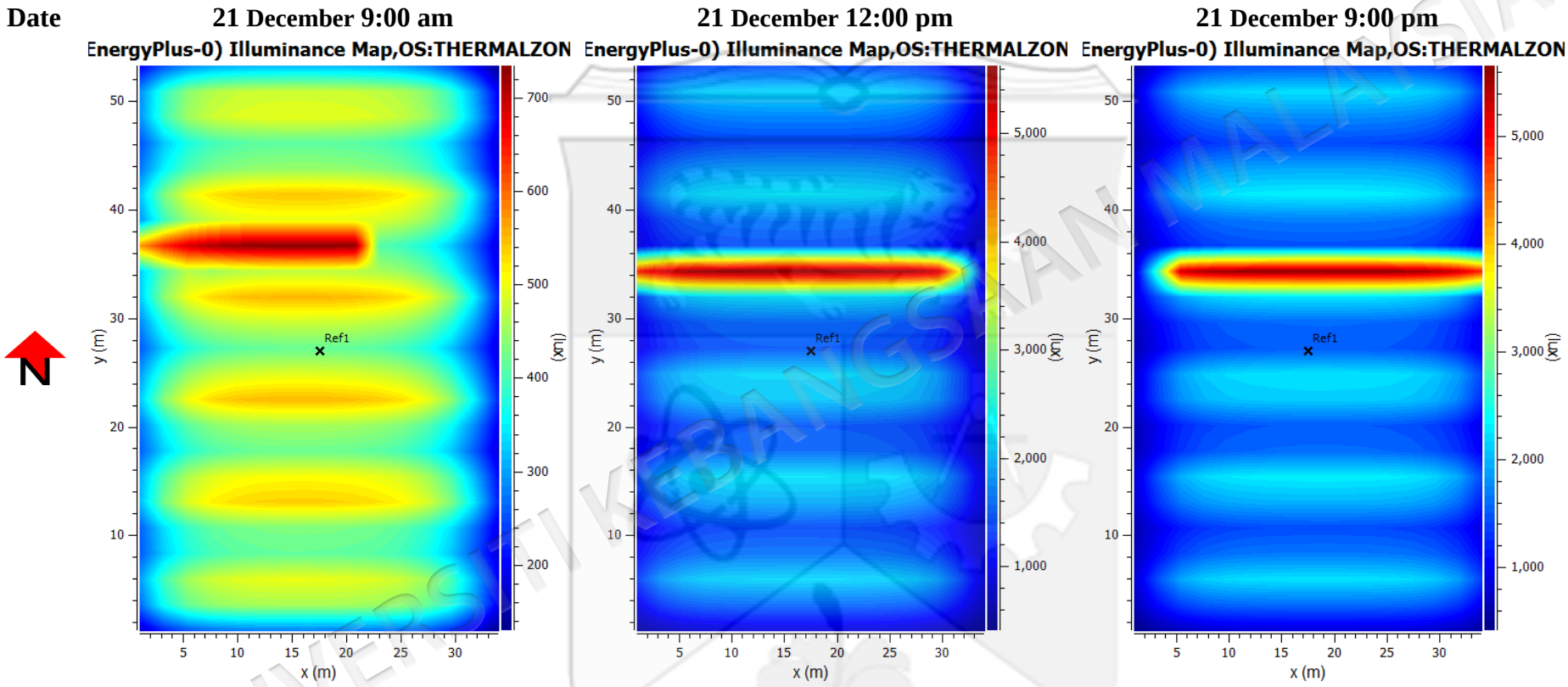

Figure 4.48 EnergyPlus **Skylight** Illuminance level maps: 1 to 1.5 spacing-to-height ratio, **5% TFR**, double low-e clear. **21 December**

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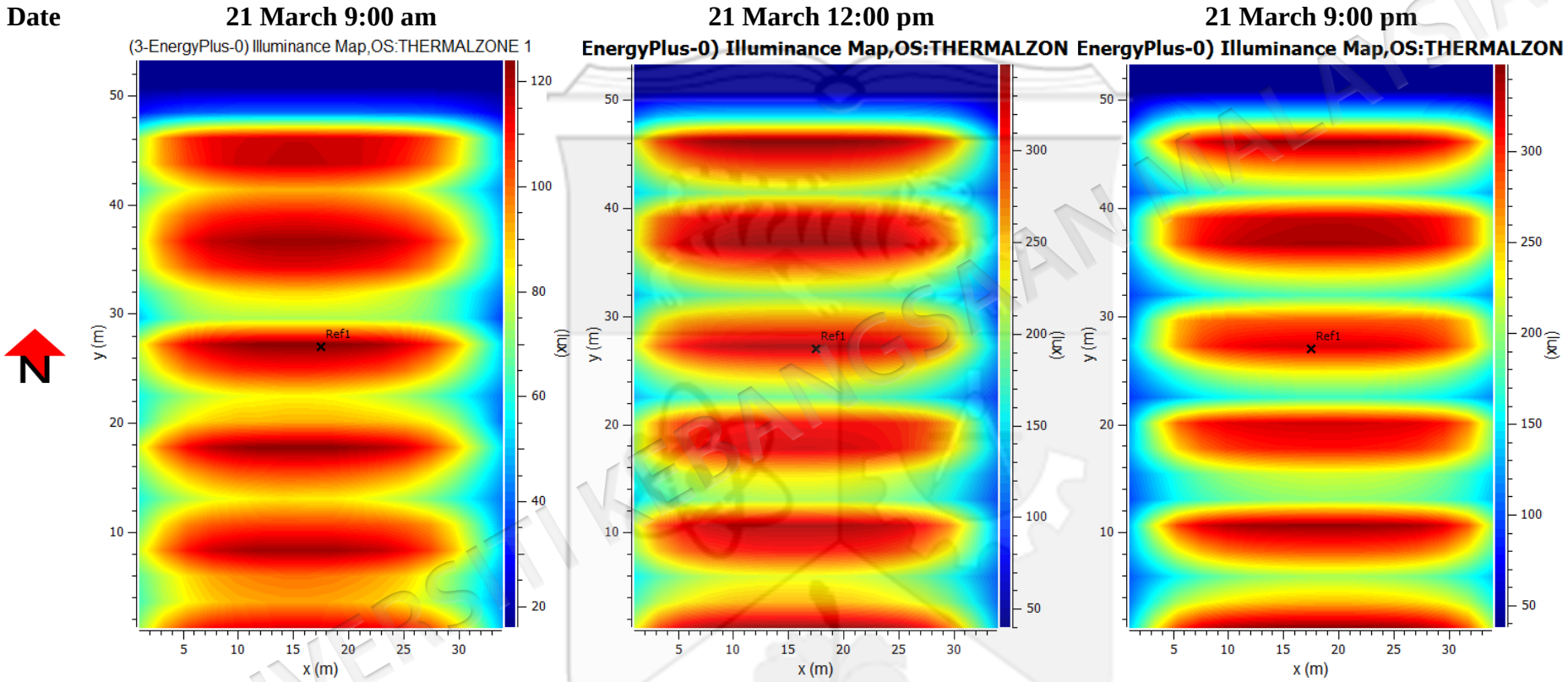

Figure 4.49 EnergyPlus **Sawtooth** Illuminance level maps: 1 to 1.5 spacing-to-height ratio, **5% TFR**, double low-e clear. **21 March**

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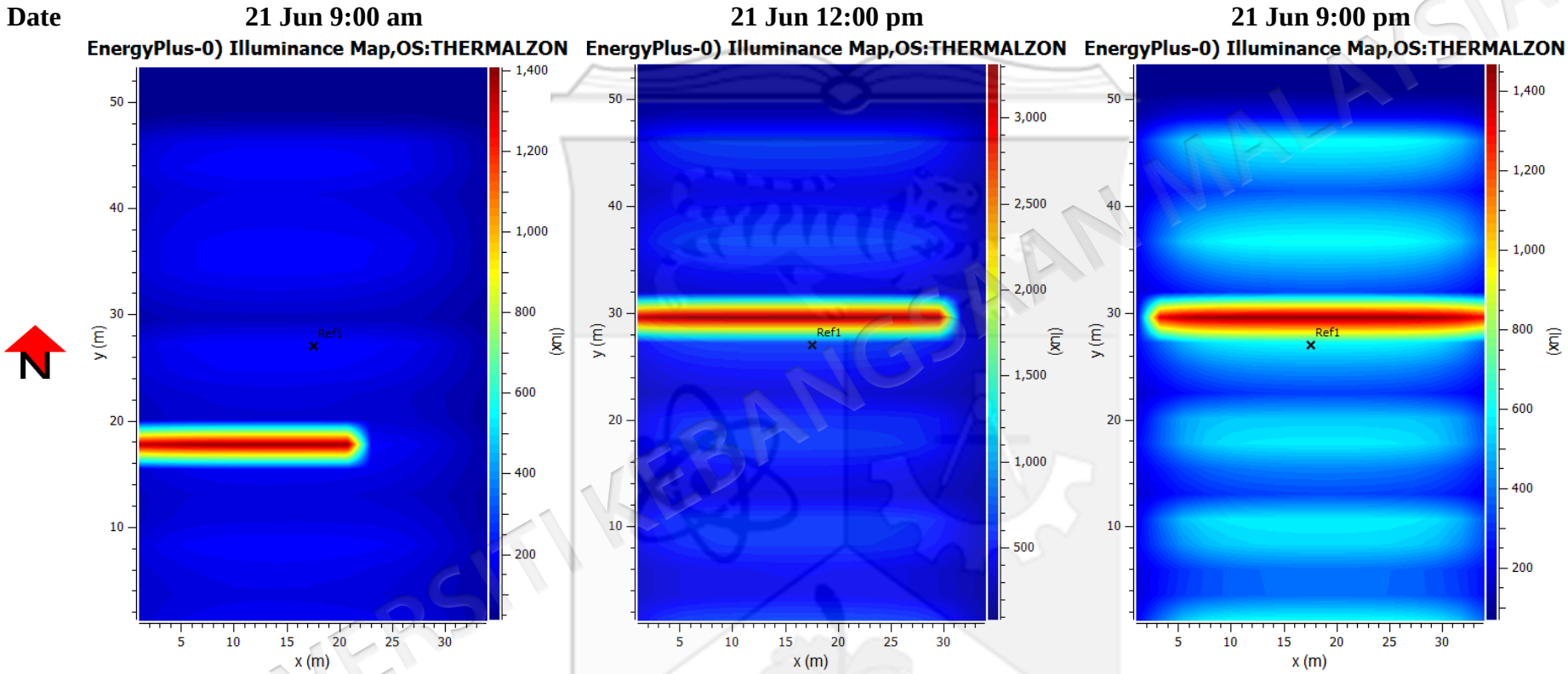

Figure 4.50 EnergyPlus **Sawtooth** Illuminance level maps: 1 to 1.5 spacing-to-height ratio, **5% TFR**, double low-e clear. **21 Jun**

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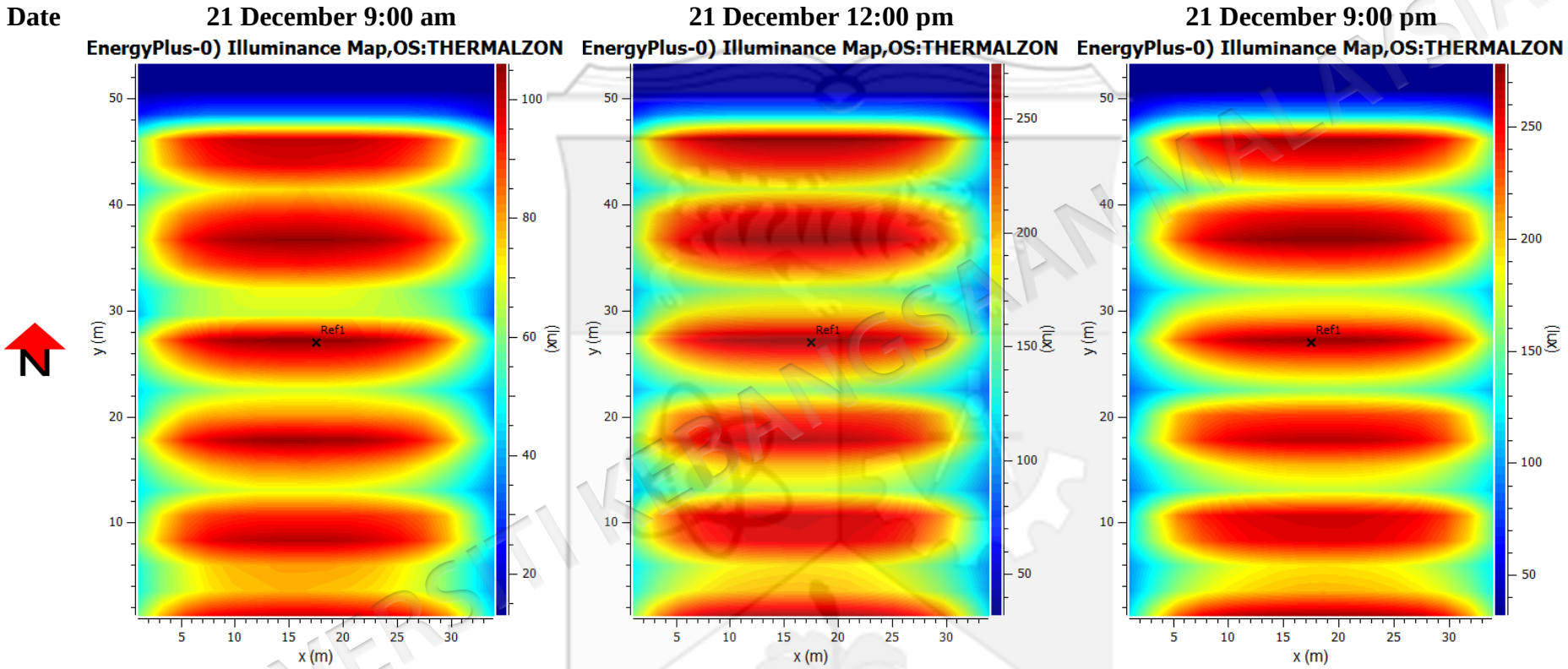

Figure 4.51 EnergyPlus **Sawtooth** Illuminance level maps: 1 to 1.5 spacing-to-height ratio, **5% TFR**, double low-e clear. **21 December**

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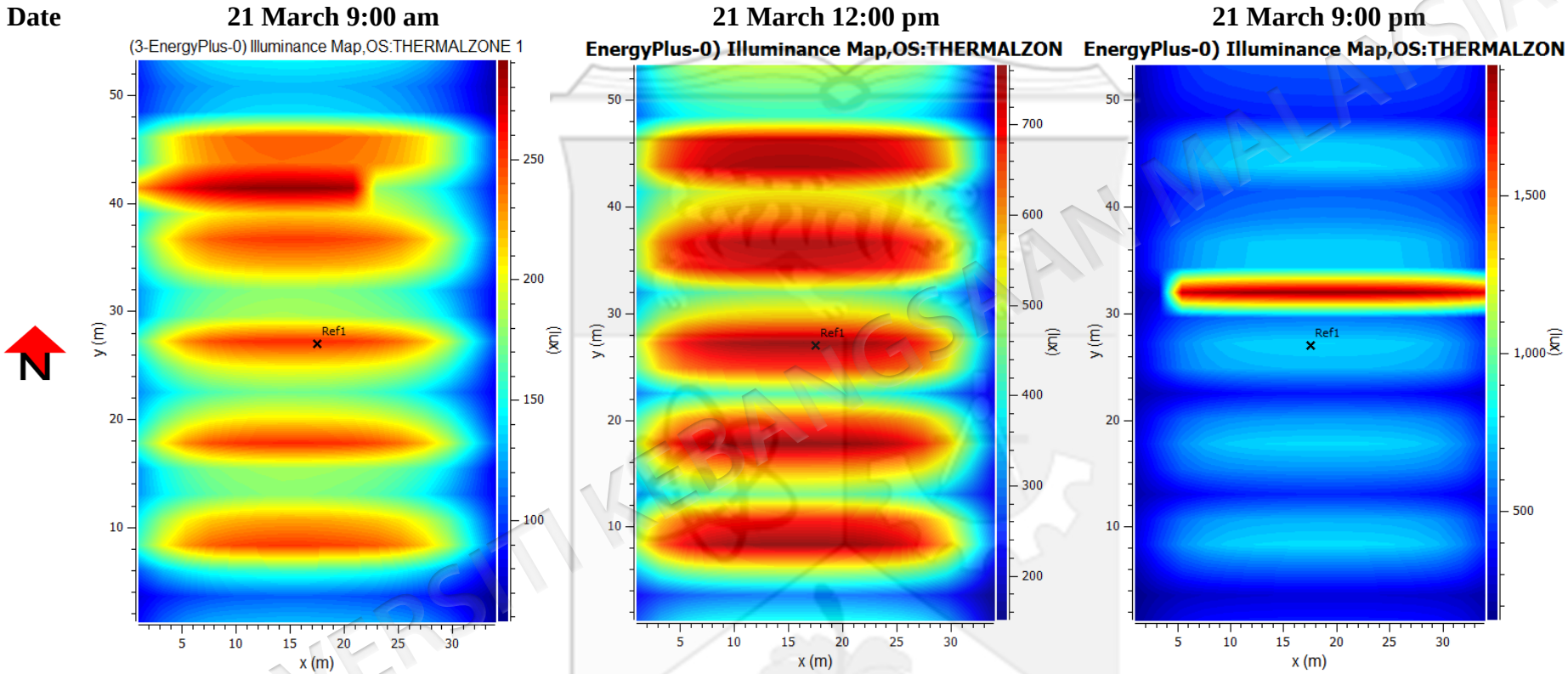

Figure 4.52 EnergyPlus **Roof Monitor** Illuminance level maps: 1 to 1.5 spacing-to-height ratio, **5% TFR**, double low-e clear. **21 March**

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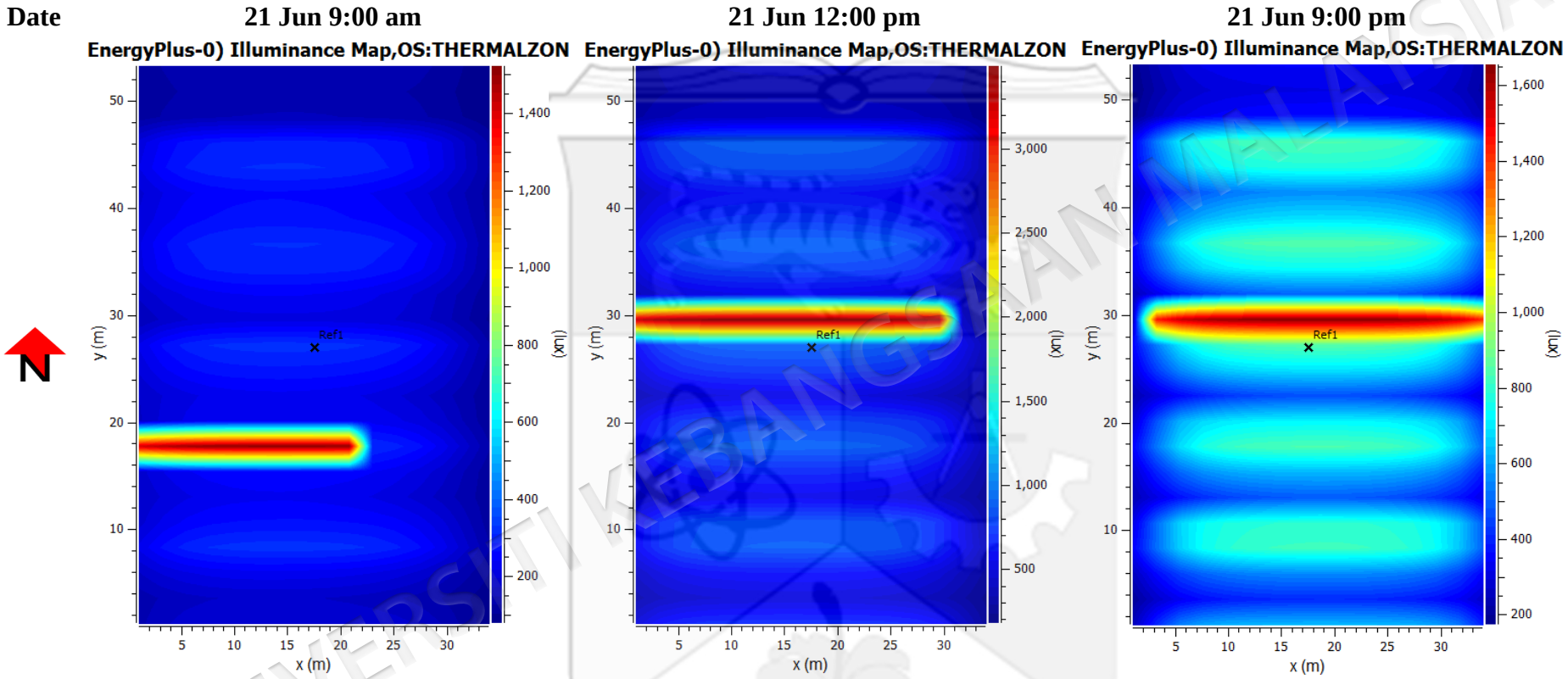

Figure 4.53 EnergyPlus **Roof Monitor** Illuminance level maps: 1 to 1.5 spacing-to-height ratio, **5% TFR**, double low-e clear. **21 Jun**

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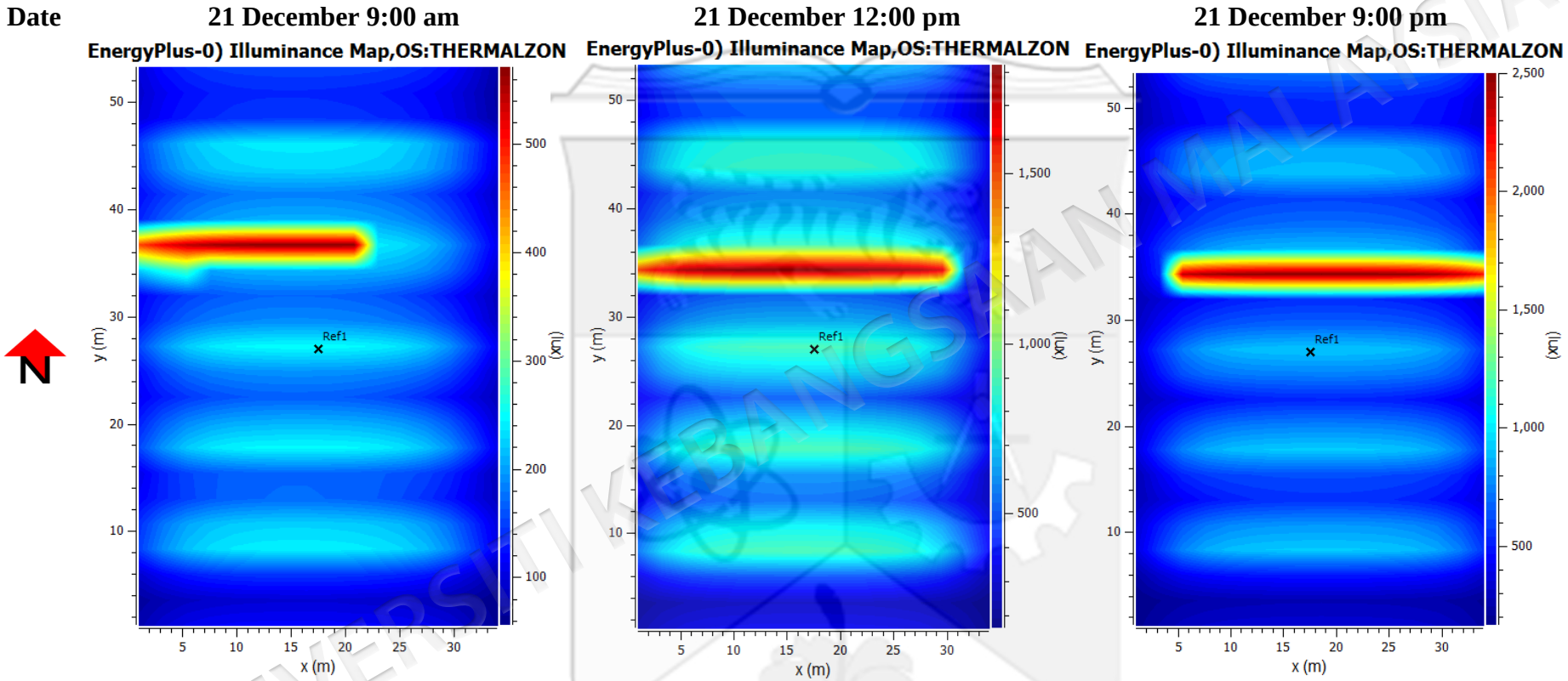

Figure 4.54 EnergyPlus **Roof Monitor** Illuminance level maps: 1 to 1.5 spacing-to-height ratio, **5% TFR**, double low-e clear. **21 December**

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Date	21 March 9:00 am	21 March 12:00 pm	21 March 9:00 pm

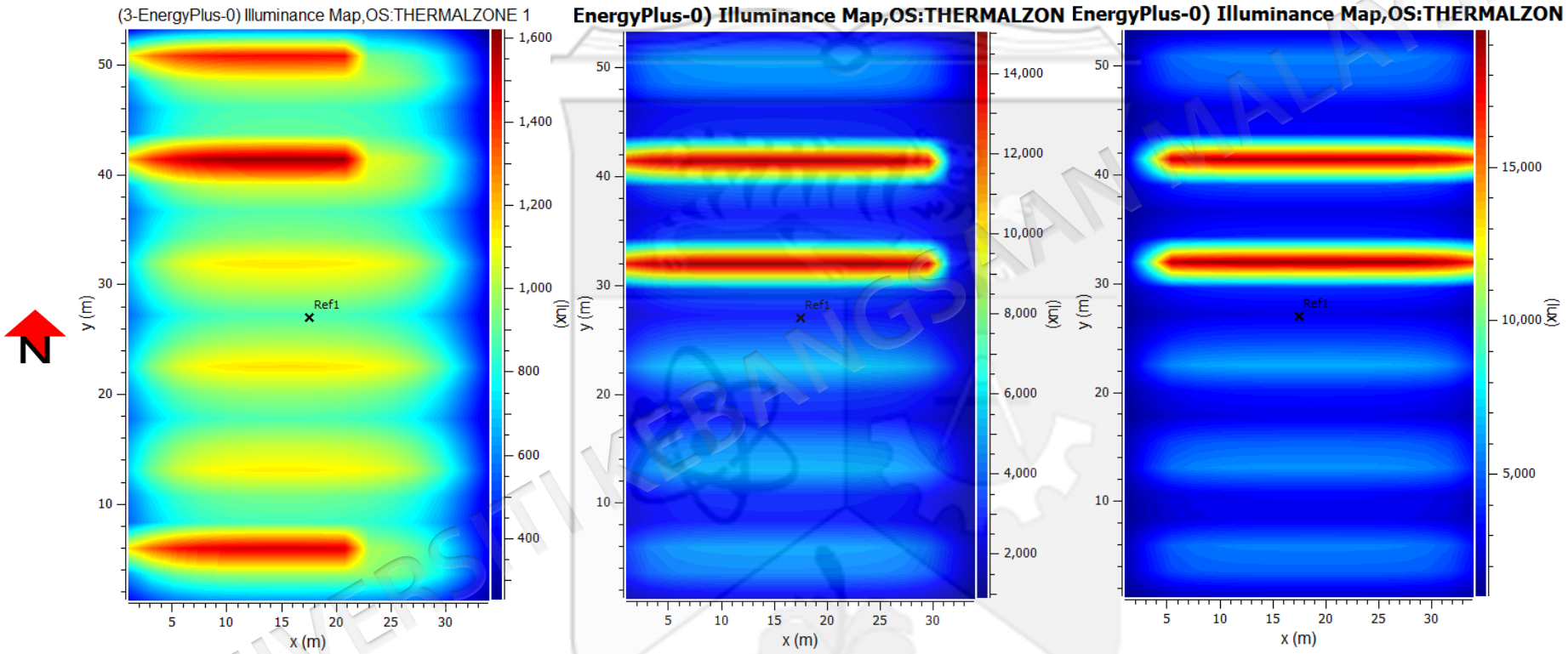

Figure 4.55 EnergyPlus **Skylight** Illuminance level maps: 1 to 1.5 spacing-to-height ratio, **10% TFR**, double low-e clear. **21 March**

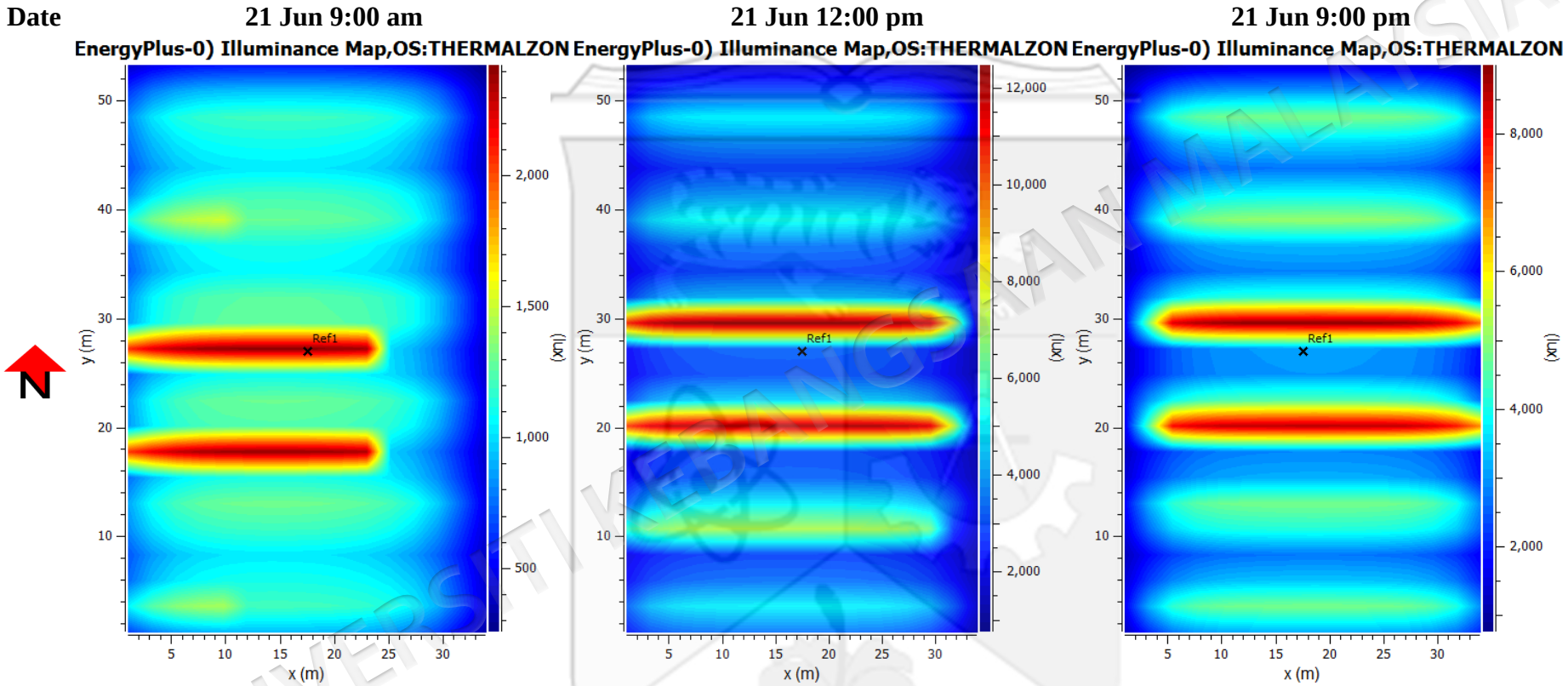

Figure 4.56 EnergyPlus **Skylight** Illuminance level maps: 1 to 1.5 spacing-to-height ratio, **10% TFR**, double low-e clear. **21 Jun**

Date	21 December 9:00 am	21 December 12:00 pm	21 December 9:00 pm

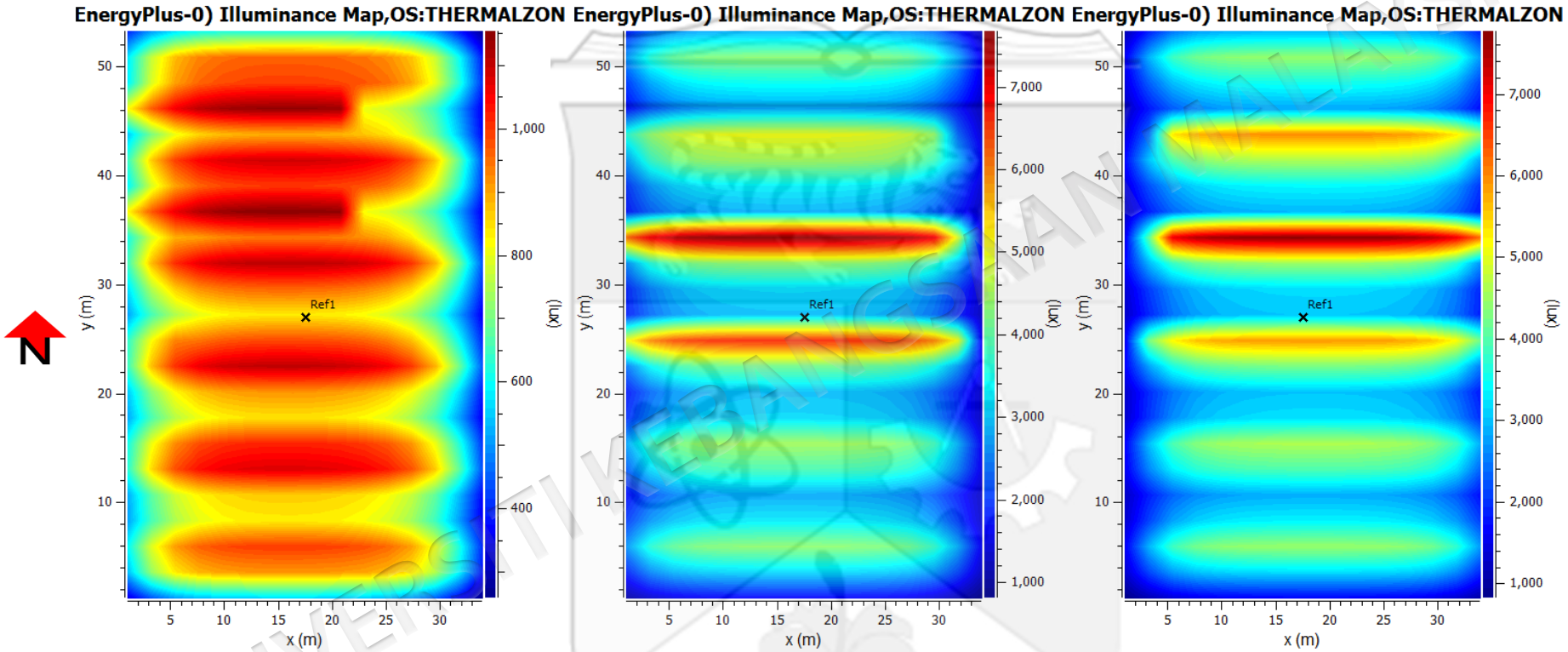

Figure 4.57 EnergyPlus **Skylight** Illuminance level maps: 1 to 1.5 spacing-to-height ratio, **10% TFR**, double low-e clear. **21 December**

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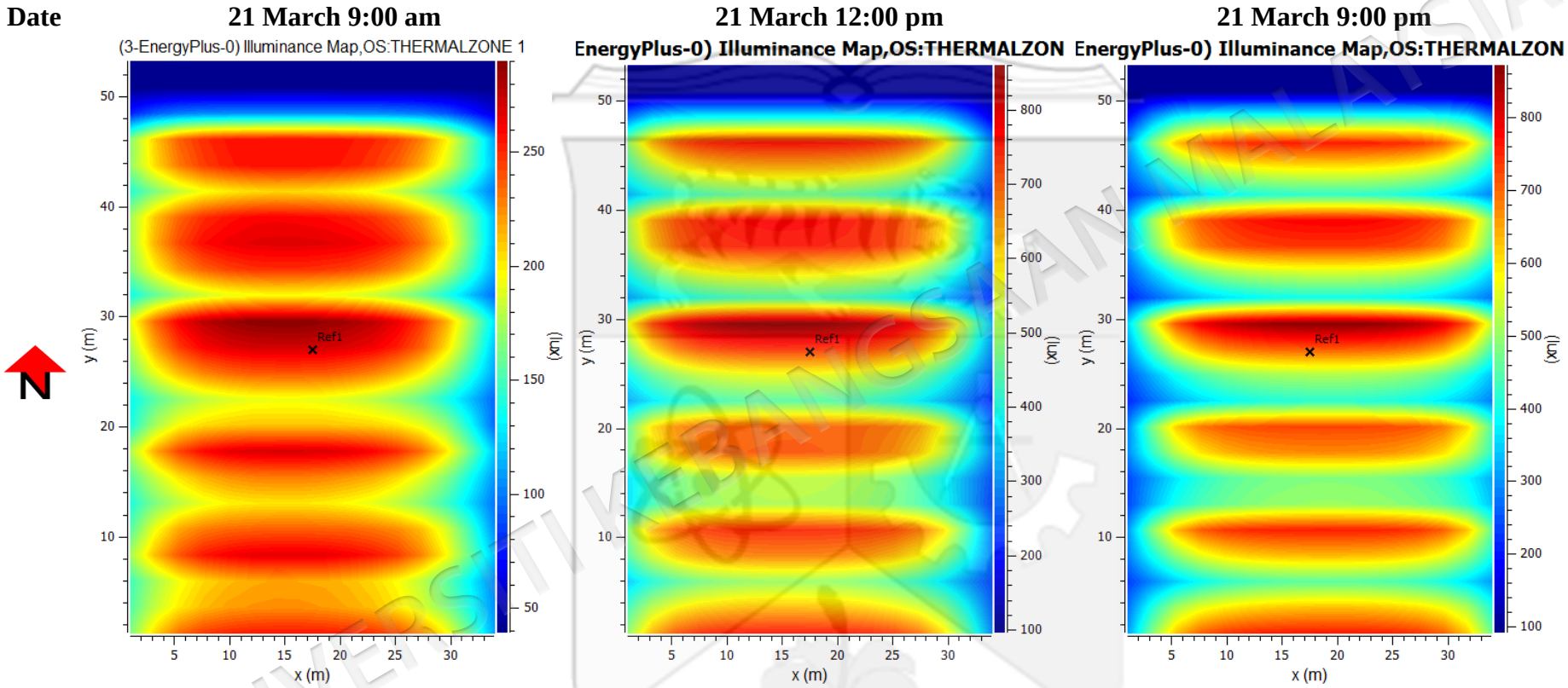

Figure 4.58 EnergyPlus **Sawtooth** Illuminance level maps: 1 to 1.5 spacing-to-height ratio, **10% TFR**, double low-e clear. **21 March**

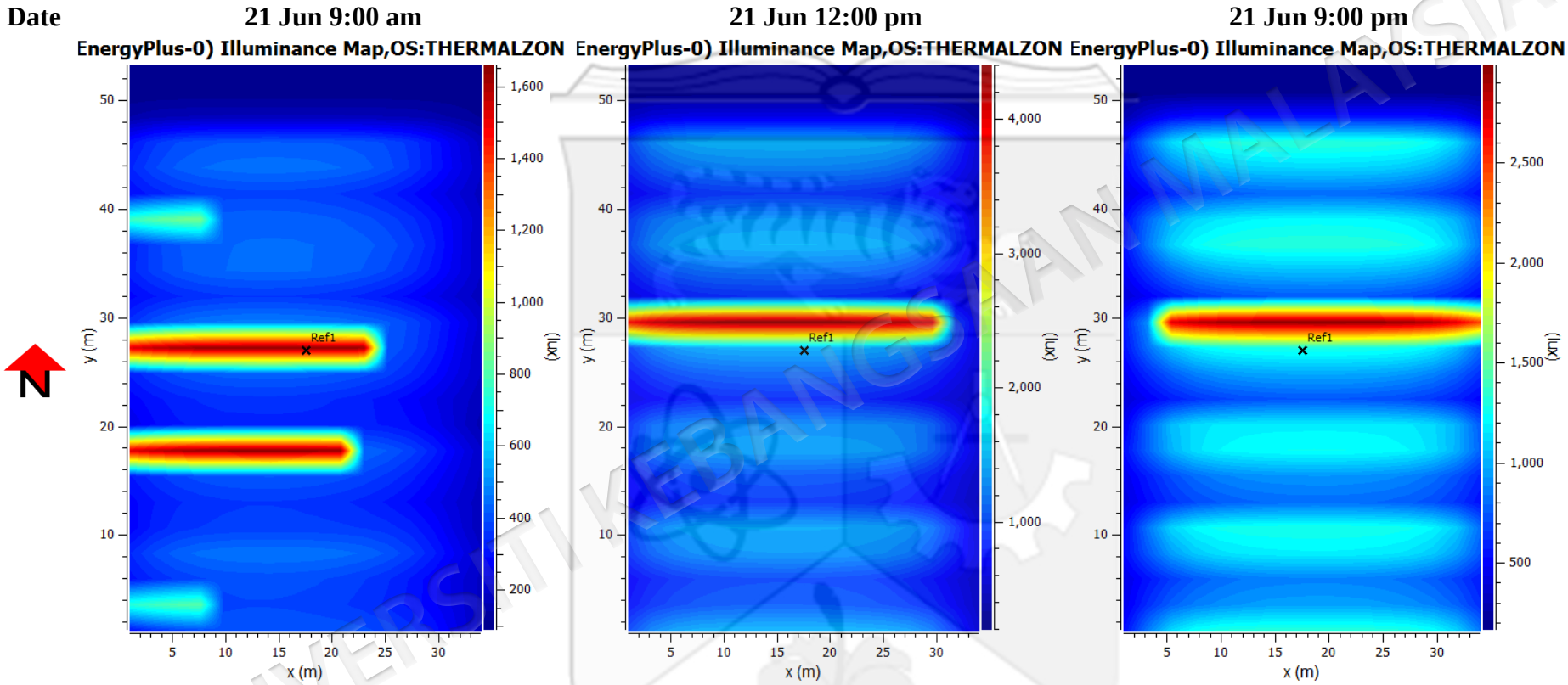

Figure 4.59 EnergyPlus **Sawtooth** Illuminance level maps: 1 to 1.5 spacing-to-height ratio, **10% TFR**, double low-e clear. **21 Jun**

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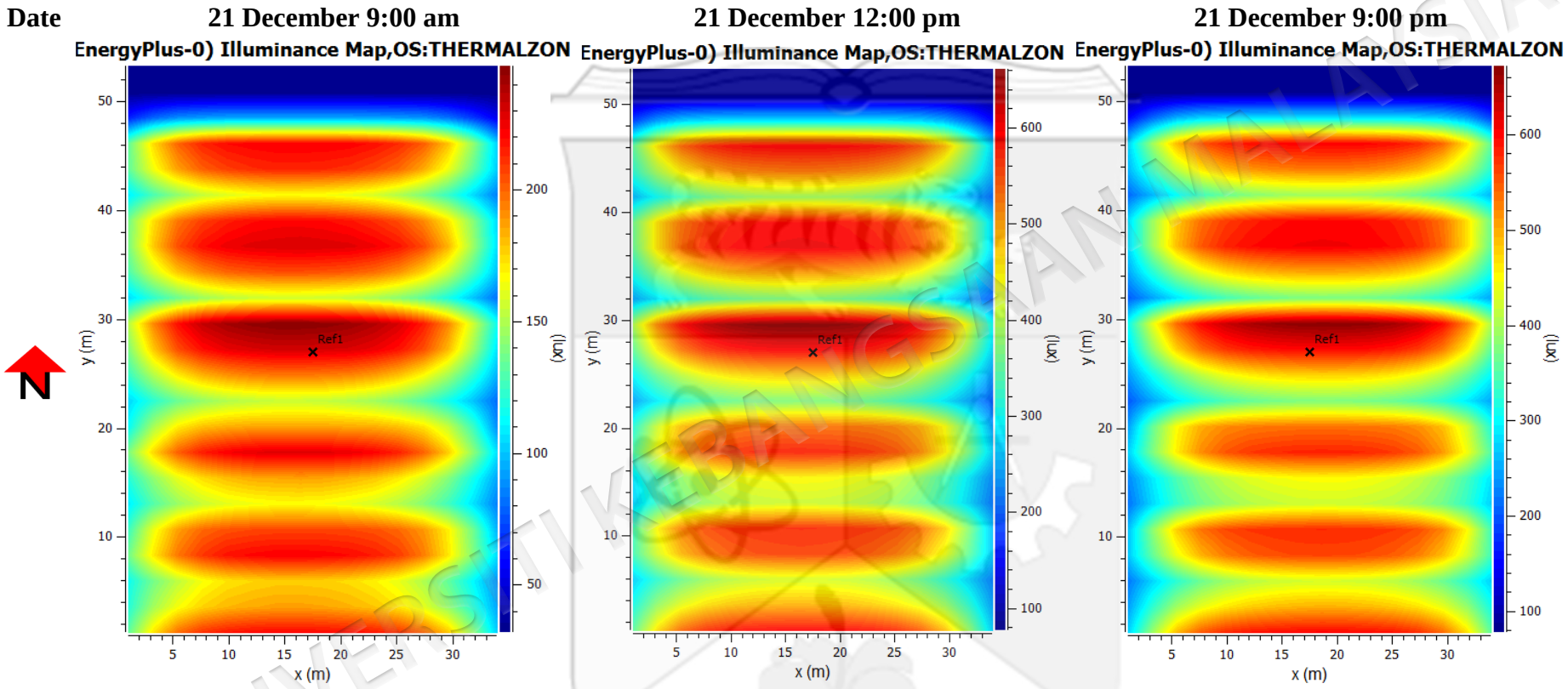

Figure 4.60 EnergyPlus **Sawtooth** Illuminance level maps: 1 to 1.5 spacing-to-height ratio, **10% TFR**, double low-e clear. **21 December**

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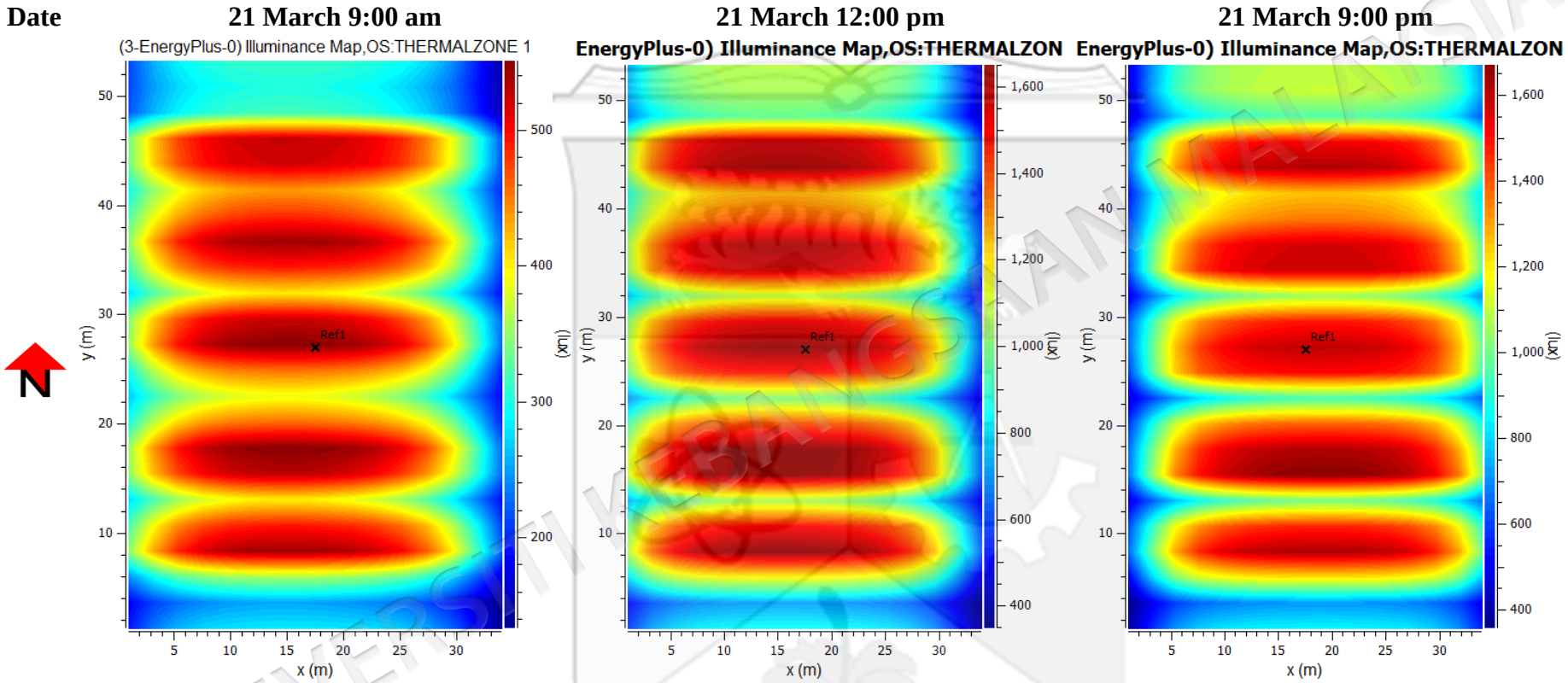

Figure 4.61 EnergyPlus **Roof Monitor** Illuminance level maps: 1 to 1.5 spacing-to-height ratio, **10% TFR**, double low-e clear. **21 March**

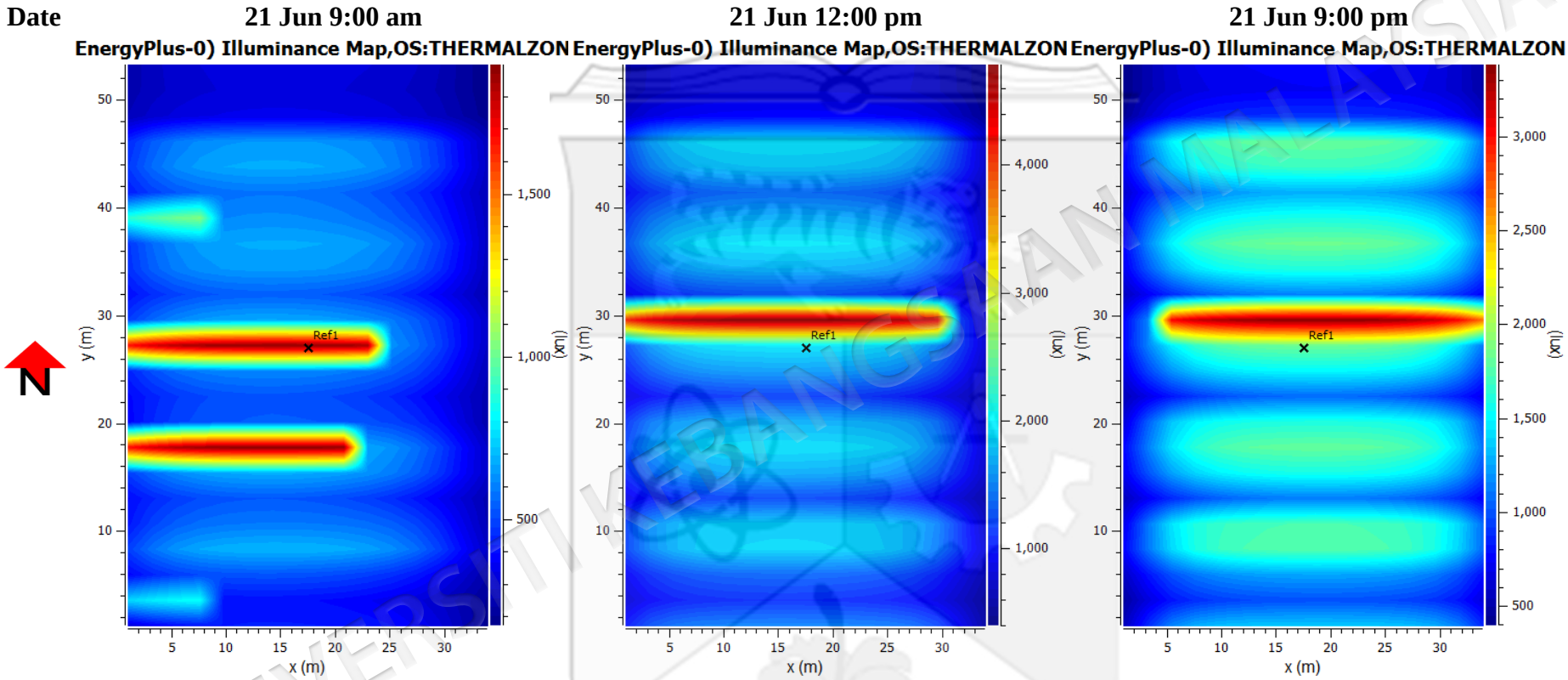

Figure 4.62 EnergyPlus **Roof Monitor** Illuminance level maps: 1 to 1.5 spacing-to-height ratio, **10% TFR**, double low-e clear. **21 Jun**

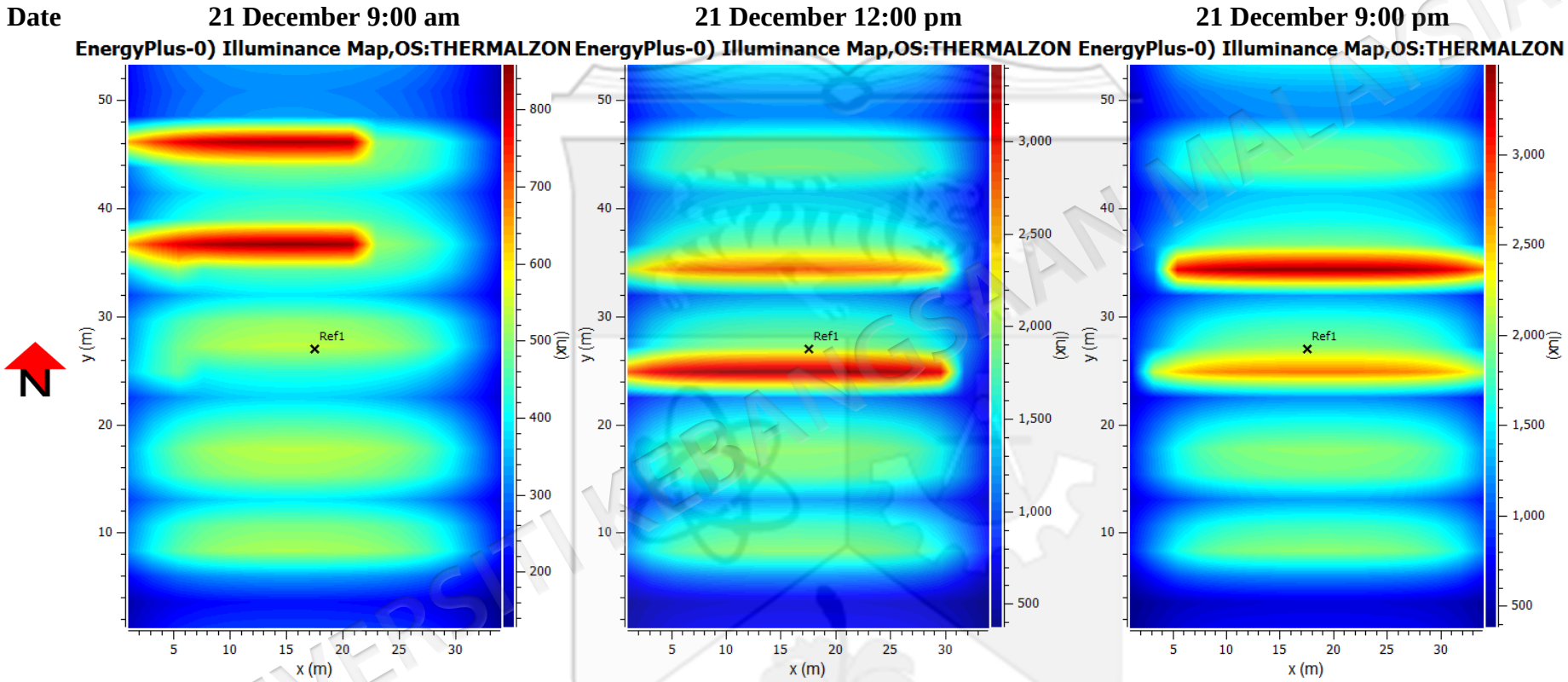

Figure 4.63 EnergyPlus **Roof Monitor** Illuminance level maps: 1 to 1.5 spacing-to-height ratio, **10% TFR**, double low-e clear. **21 December**

Table 4.9 Comparison of daylight illuminance gradient: 1 to 1.5 spacing-to-ceiling height ratio, 5% TFR

	Skylight	**Sawtooth**	**Roof Monitor**
21 Mar 9:00 am	8.4	7.8	5.0
21 Mar 12:00 pm	27.0	8.7	5.1
21 Mar 15:00 pm	31.9	9.2	12.4
21 Jun 9:00 am	14.4	38.1	19.3
21 Jun 12:00 pm	18.5	41.4	19.6
21 Jun 15:00 pm	12.3	21.6	9.5
21 Dec 9:00 am	5.6	8.2	10.2
21 Dec 12:00 pm	13.9	8.6	11.2
21 Dec 15:00 pm	13.6	8.6	11.0

Table 4.10 Comparison of daylight illuminance gradient: 1 to 1.5 spacing-to-ceiling height ratio, 10% TFR

	Skylight	**Sawtooth**	**Roof Monitor**
21 Mar 9:00 am	6.4	7.4	4.1
21 Mar 12:00 pm	16.8	9.0	4.7
21 Mar 15:00 pm	19.4	9.5	4.7
21 Jun 9:00 am	9.4	18.9	11.0
21 Jun 12:00 pm	16.5	22.8	12.0
21 Jun 15:00 pm	11.8	18.2	8.5
21 Dec 9:00 am	4.5	7.7	6.7
21 Dec 12:00 pm	9.5	8.6	9.1
21 Dec 15:00 pm	9.3	8.5	9.0

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Table 4.11 Comparison of daylight illuminance gradient: 1 to 1.5 spacing-to-ceiling height ratio, 15% TFR

	Skylight	**Sawtooth**	**Roof Monitor**
21 Mar 9:00 am	5.8	7.0	3.9
21 Mar 12:00 pm	13.2	8.2	6.1
21 Mar 15:00 pm	15.0	8.5	7.0
21 Jun 9:00 am	7.7	13.0	8.4
21 Jun 12:00 pm	13.2	15.6	9.0
21 Jun 15:00 pm	10.1	13.9	7.2
21 Dec 9:00 am	4.3	7.3	5.5
21 Dec 12:00 pm	8.3	7.9	8.8
21 Dec 15:00 pm	8.2	7.8	8.6

* The daylight gradient ratio can be found by calculating the ratio of maximum to minimum illuminance value of the space area of each case. A lower value indicates better uniformity

Table 4.12 Daylight illuminance uniformity comparison: 1 to 1.5 spacing-to-ceiling height ratio toplighting alternatives, 5% TFR

	Skylight	**Sawtooth**	**Roof Monitor**
21 Mar 9:00 am	0.29	0.20	0.34
21 Mar 12:00 pm	0.21	0.18	0.30
21 Mar 15:00 pm	0.21	0.18	0.27
21 Jun 9:00 am	0.25	0.22	0.32
21 Jun 12:00 pm	0.19	0.15	0.26
21 Jun 15:00 pm	0.22	0.16	0.29
21 Dec 9:00 am	0.32	0.19	0.32
21 Dec 12:00 pm	0.24	0.18	0.26
21 Dec 15:00 pm	0.24	0.18	0.25

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Table 4.13 Daylight illuminance uniformity comparison: 1 to 1.5 spacing-to-ceiling height ratio toplighting alternatives, 10% TFR

	Skylight	**Sawtooth**	**Roof Monitor**
21 Mar 9:00 am	0.29	0.21	0.35
21 Mar 12:00 pm	0.22	0.19	0.30
21 Mar 15:00 pm	0.21	0.19	0.31
21 Jun 9:00 am	0.25	0.22	0.31
21 Jun 12:00 pm	0.19	0.18	0.28
21 Jun 15:00 pm	0.22	0.18	0.31
21 Dec 9:00 am	0.32	0.20	0.33
21 Dec 12:00 pm	0.24	0.19	0.27
21 Dec 15:00 pm	0.24	0.19	0.26

Table 4.14 Daylight illuminance uniformity comparison: 1 to 1.5 spacing-to-ceiling height ratio toplighting alternatives, 15% TFR

	Skylight	**Sawtooth**	**Roof Monitor**
21 Mar 9:00 am	0.29	0.22	0.36
21 Mar 12:00 pm	0.21	0.21	0.31
21 Mar 15:00 pm	0.20	0.21	0.31
21 Jun 9:00 am	0.25	0.25	0.33
21 Jun 12:00 pm	0.19	0.19	0.28
21 Jun 15:00 pm	0.21	0.19	0.30
21 Dec 9:00 am	0.32	0.22	0.34
21 Dec 12:00 pm	0.24	0.21	0.28
21 Dec 15:00 pm	0.24	0.21	0.28

* The daylight illuminance uniformity ratio is the ratio of lowest illuminance value to average illuminance of the space area for each case. A higher value indicates better uniformity

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As the preceding figures and tables show, the daylight distribution of toplighting alternatives with a 1-to-1.5 spacing-to-height ratio considerably improves on that of the base case. This improvement is a result of more daylight apertures installed in the toplighting alternatives, as opposed to the base case, which has only sidelighting daylight apertures.

Based on the analysis of the daylight distribution, the roof monitor alternative provides better daylight distribution than other alternatives throughout the building space in all the simulated representative dates and days when daylight distribution is more even. As the illuminance maps (Figures 4.46 to 4.63) illustrate that the daylight distribution of the skylight alternative is mostly concentrated in the central areas directly under the skylight apertures and does not spread to the perimeter of the space. By contrast, the daylight distribution in the roof monitor or sawtooth alternatives moves slightly from the area right under the apertures to the southern and northern sides of the space. In addition, daylight from the roof monitor and sawtooth cases spread toward the perimeter of the building space more than the daylight from the skylight alternative, thereby resulting in a better daylight distribution. The daylight distribution pattern of the roof monitor case is similar throughout the year, but its illuminance level increases in June.

The daylight distribution patterns of the sawtooth alternative do not vary significantly throughout the year. More daylight spreads toward the south of the space in March and December and toward the middle of the space in June. Better uniformity is achieved in March because of lower illuminance level than in June. The daylight distribution patterns of the sawtooth also result in certain spots of light in areas directly under the sawtooth apertures. These patterns are not as apparent as in the cases of the skylight alternative because daylight spreads more toward the edges of the building space. The distribution pattern remains quite similar throughout the year. However, its illuminance levels are lower than those of the roof monitor alternative. The illuminance level at 12:00 pm in general is higher than that at either 9:00 am or 3:00 pm. Furthermore, less variable daylight can be observed compared with the cases with a 1-to-1 spacing-to-height ratio. This phenomenon may be due to the lower illuminance level provided by less units of glazing.

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The daylight distribution patterns of the roof monitor with a 1-to-1.5 spacing-to-height ratio differ only slightly throughout the year. More daylight spreads to the south of the space in June and to the north in December. The daylight distribution pattern of the roof monitor case is also better than that in the sawtooth alternative as suggested by the illuminance color maps, which are not as close as in the sawtooth alternative. The roof monitor alternative yields more illuminance level for most of the year. However, its daylight distribution pattern is similar to that of the sawtooth alternative with a 1-to-1 spacing-to-height ratio.

To summarize then, based on the illuminance maps, the roof monitor alternative provides the best illuminance distribution and uniformity, followed by the sawtooth alternative.

According to Tables 4.9 to 4.11, the roof monitor alternative with a TFR ranging from 5% to 15% results in a better illuminance gradient ratio than the other alternatives in all simulated dates and times, with the values ranging from 3.1 to 12.0. From these tables, the illuminance gradient results show that the roof monitor option can meets in some dates even exceed the standard set by CIBSE Code, which is set at 5 for the maximum. Consequently, the spacing-to-ceiling height ratio of the roof monitor case can be increased to meet the standard set by the CIBSE Code. The illuminance gradient values obtained from the simulation results correspond to the illuminance map analysis.

The illuminance gradient ratios of the skylight case with a 1-to-1.5 spacing-to-height ratio are typically from 4 to 3, which are lower than that obtained by the skylight with a 1-to-1 spacing-to-height ratio. In addition, the illuminance gradient ratio of the skylight alternative with a TFR of 5% can reach up to 31 in certain months of year, as in March at 3:00 pm.

The sawtooth alternative with a 1-to-1.5 spacing-to-height ratio has daylight illuminance gradient values ranging from 7 to 41, which are in general higher than the values of the sawtooth alternative with a 1-to-1 spacing-to-height ratio, which range from 6 to 36. This difference indicates that the 1-to-1.5 spacing-to-height ratio results

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in a worse illuminance gradient compared with the 1-to-1 spacing-to-height ratio. That is, the daylight illuminance gradient of the sawtooth option with a 1-to-1.5 spacing-to-height is worse than that of the sawtooth option with a 1-to-1.5 spacing-to-height ratio. Thus, for the sawtooth alternative, reducing the spacing-to-height ratio to 1-to-1 helps solve the daylight uniformity trouble that accrues in the 1.5-to-1 alternative by narrowing down the daylight gradient ratio of the 1-to-1 spacing-to-height to a narrower range of 6 to 36. By contrast, in the 1-to-1.5 spacing-to-height ratio, the illuminance gradient ranges from 7 to 4 through all of the five cases with a TFR from 5% to 25%.

The roof monitor alternative with a 1-to-1.5 spacing-to-height ratio yields illuminance gradient values ranging from 3 to 19, which are generally lower than the values of the roof monitor alternative with a 1-to-1 spacing-to-height, which range from 6 to 28. This difference indicates a better illuminance gradient under the 1-to-1.5 spacing-to-height ratio than the 1-to-1 spacing-to-height ratio. In other words, the daylight gradient ratios of the 1-to-1 spacing-to-height ratio alternative are higher than those of the 1-to-1.5 spacing-to-height ratio.

According to Tables 4.12 to 4.14, the roof monitor alternative yields better uniformity of illuminance ratio than the other alternatives and base case by yielding a higher illuminance uniformity ratio reaching up to approximately 0.30 to 0.36. The sawtooth alternative provides 0.30 to 0.90 less illuminance uniformity ratio than the roof monitor alternative. All of the toplighting alternatives do not meet the CIBSE standard, which is more than 0.80. As a result, this daylight parameter should not be considered as the primary parameter to determine the best-toplighting performing option. Since the base case simulation model does not take in account people or furniture, this research should use the gradient of illuminance parameters as the primary parameters of daylight uniformity.

A comparison of the illuminance gradient ratio of the three toplighting systems versus that of the base case reveals that all of the toplighting alternatives perform better in terms of illuminance diversity than the base case.

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According to Tables 4.9 to 4.11, the roof monitor alternative yields the highest illuminance uniformity ratio in all of the simulated dates, time, and cases, with the values ranging from 0.24 to 0.36. In general, these values are higher than those for the other alternatives with a 1-to-1 spacing-to-height ratio.

The illuminance uniformity ratios of the sawtooth alternative are more or less the same as those in the 1-to-1 spacing-to-height ratio sawtooth alternative, with the values ranging from 0.15 to 0.27. The illuminance uniformity values are higher in the skylight alternative with a 1-to-1.5 spacing-to-height ratio that that with a 1-to-1 spacing-to-height ratio, which range from 0.19 to 0.32. The illuminance uniformity values are higher in the roof monitor alternative with a 1-to-1.5 spacing-to-height ratio than that with a 1-to-1 spacing-to-height ratio.

In summary, the daylight distribution and uniformity of all the toplighting alternatives indicate that the roof monitor alternative provides the best daylight distribution and uniformity for all simulated sizes and spacing-to-height ratios. The skylight alternative provides better daylight distribution and uniformity with an increase in its spacing-to-height ratio, whereas the sawtooth alternative provides better daylight distribution and uniformity with a decrease in its spacing-to-height ratio. For both spacing-to-height ratios, the sawtooth alternative provides better daylight distribution and uniformity than the skylight alternative.

4.1.5 Summary

The simulation results of the daylighting analysis suggest that the application of skylight, sawtooth, and roof monitor alternatives in academic buildings and similar building types is a robust strategy to improve the visual quality.

The daylight factor analysis under an overcast sky conditions indicates that the use of the skylight alternative provides the highest daylight factor values. The roof monitor and sawtooth cases generate a lower maximum daylight factor value. For the sawtooth and roof monitor cases with a 1 to 1 spacing-to-height ratio, the sawtooth and roof monitor areas between 5% and 15% of the floor area generate average

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daylight factors between 3.2% to 7.8%. These values are recommended as ideal for reading spaces in the academic building.

Based on the analysis of the illuminance levels, the skylight alternative yields the highest illuminance level value at all simulated dates and times, whereas the sawtooth alternative yields an illuminance level that is higher in June and lower in March. However, the illuminance levels resuting from skylight alternative not able to achive the recommended range of illuminance levels of 300 to 500 lux and the recommended daylight factor 2% to 5%. The illuminance level of the roof monitor case reaches its maximum in June. In general, the sawtooth alternative yields the lowest illuminance level value. Nevertheless, its illuminance level, compared with that of the skylight and roof monitor alternatives, does not change significantly during the year. The simulation results revealed that the most recommended toplighting strategies for the studied building, under the climatic condition of Malaysia was the roof monitor alternative that able to achieve the recommended range of illuminance levels of 500 lux and daylight factor of 2% to 5%.

According to the analysis of the daylight distribution and uniformity, all of the toplighting alternatives provide better daylight distribution and uniformity when their toplighting glazing areas are increased. The increase of the aperture of toplighting unit from 6 to 9 units (or the decrease of the spacing-to-height ratio from 1 to 1.5 to 1 to 1) correspondingly increases the daylight distribution and uniformity in all of the toplighting alternatives. The roof monitor alternative provides the best daylight distribution throughout the space in all the simulated representative dates and days during which daylight distribution is more uniform. The illuminance uniformity ratios of the sawtooth alternative with a 1 to 1.5 spacing-to-height ratio are more or less the same as those of the sawtooth case with a 1 to 1 spacing-to-height ratio. The daylight distribution of skylight alternative is mostly concentrated toward the central areas directly under the skylight apertures and does not spread toward the perimeter of the space, unlike that of either the roof monitor or sawtooth alternative.

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4.2 ENERGY ANALYSIS

4.2.1 Introduction

This section analyzes the effect of daylighting on lighting, cooling, and total energy consumption and savings when toplighting strategies are applied. It includes five sections: (1) Building Energy Evaluation, (2) Comparison of Energy Use of the Base Case and Toplighting Options with 1:1 Spacing-to-Ceiling Height Ratio, (3) Comparison of Energy Use of Base Case and Toplighting Options with 1:1.5 Spacing-to-Ceiling Height Ratio, (4) Comparison of Energy Use of Skylights, Sawtooth, and Roof Monitors, and (5) Economic Analysis. The evaluation of building energy focuses on the lighting, cooling, and total energy use and savings of the existing UKM case study buildings as presented in the calibrated EnergyPlus 7.0 computer model compared with those of the buildings with the proposed toplighting strategies and other buildings with skylight, sawtooth, and roof monitors. This part also includes an analysis of the energy savings and energy cost savings resulting from toplighting strategies. The last section of this part includes a design method of selecting the suitable toplighting solutions for buildings in locations with a tropical climate, such as Malaysia.

4.2.2 Building Energy Use Evaluation

4.2.2.1 EneryPlus Base Case Model With and Without Daylighting

This section discusses the effect of using natural lighting on the electricity use of the existing UKM case study building. To study the effect of daylighting on the energy consumption of the building, we modified the calibrated EnergyPlus7.0 base case simulation model to include daylighting controls inside the building space. The daylighting control characteristics were entered into the daylight sensor command. The daylighting sensor commands include daylighting control type, illuminance set point level, minimum light output fraction, minimum input power fraction, maximum allowable discomfort glare, and the locations and heights of the daylight sensors inside the building space. The EnergyPlus 7.0 simulation software calculates the energy consumption of the building and the illuminance level and daylight factor at

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the specified daylighting sensor reference points. A comparison of the calibrated EnergyPlus 7.0 base case model with and without daylighting strategy is a critical step in understanding the effect of daylighting on building energy consumption.

4.2.2.2 Lighting and Cooling Energy Use Analysis

Figures 4.64 and 4.65 and Table 4.15 present the monthly lighting and cooling energy consumption comparative charts of the base case model without and with daylighting. The base case computer model used in all the evaluations and analysis and shown in the following graphs refers to the calibrated EnergyPlus 7.0 base case model.

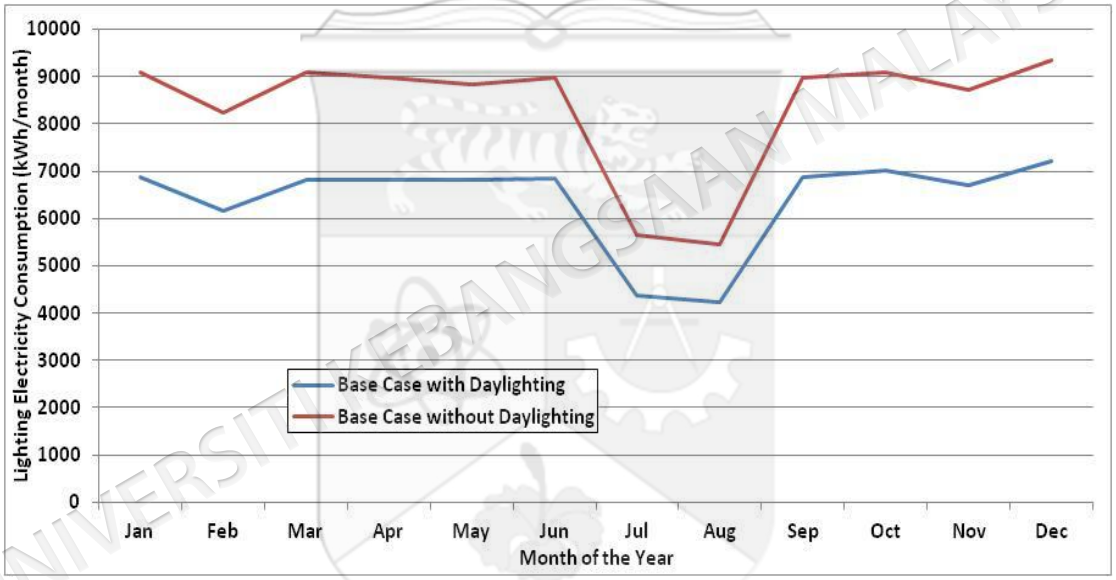

Figure 4.64 Comparison of monthly lighting energy consumption of base case model without and with daylighting

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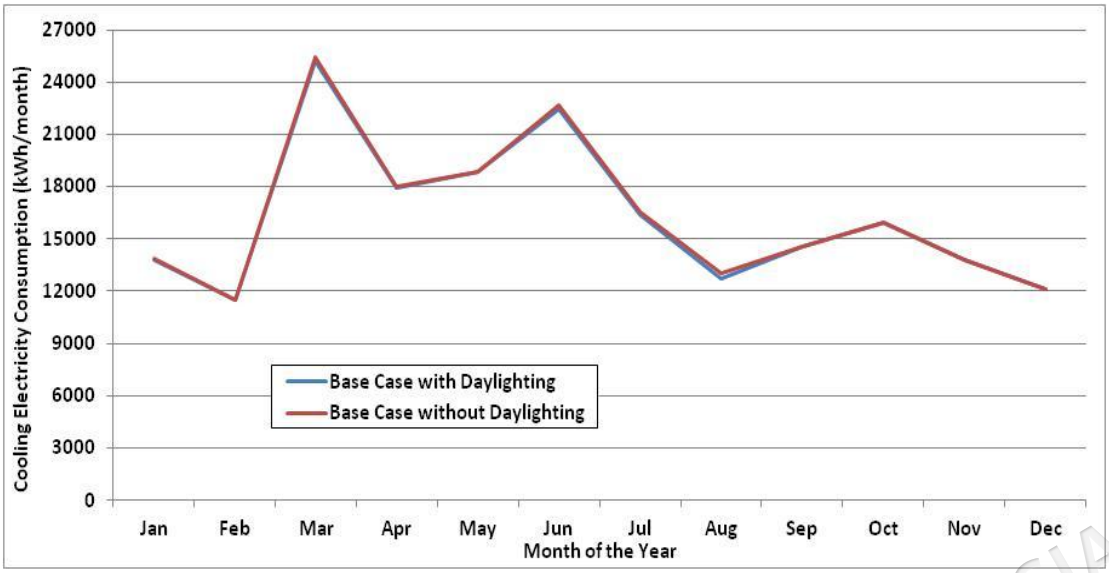

Figure 4.65 Comparison of monthly cooling energy consumption of base case model without and with daylighting

Table 4.15 Comparison of monthly lighting and cooling electricity consumption of base case model without daylighting versus the base case model with daylighting

EnergyPlus Base case Model without daylighting						
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**
Lighting energy use (kWh)	9087	8241	9087	8978	8828	8978
Cooling energy use (kWh)	13850	11510	25410	17980	18810	22680
	Jul	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Lighting energy use (kWh)	5664	5466	8978	9087	8719	9346
Cooling energy use (kWh)	16580	13020	14540	15930	13820	12110
EnergyPlus Base case Model with daylighting						
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**
Lighting energy use (kWh)	6860	6150	6824	6809	6814	6846
Cooling energy use (kWh)	13830	11460	25200	17930	18810	22480
	Jul	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Lighting energy use (kWh)	4377	4230	6878	7008	6707	7218
Cooling energy use (kWh)	16420	12750	14530	15930	13820	12110

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Daylighting can not only allow an artificial lighting consumption reduction, but also a reduction of the lighting internal loads and thus of the cooling loads. Since that artificial lighting is responsible only for 15-25% of the internal loads. Therefore, the reduction in the cooling energy use is much less compare to the reduction in lighting energy usage since it resulting from the reduction of only the internal loads associated with the artificial lighting system.

The lighting and cooling electricity consumption plots demonstrate that the base case model with daylighting control technique decreased the lighting energy consumption throughout the months of the year and resulted in 23% lighting energy savings. The cooling energy consumption also decreased slightly about -0.43(%), particularly from June to August. The decrease in lighting energy use was greater than the decrease in cooling energy.

4.2.2.3 Total Building Energy Use Analysis

The lighting and cooling energy consumption levels have a direct impact on the annual total building energy consumption. By evaluating the trends in the lighting and cooling energy consumption, we can analyze and compare the total building energy consumption of the base case model without daylighting and that of the base case model with daylighting.

Figure 4.66 and Table 4.23 present comparative charts of the monthly building energy use of the base case model without daylighting control and the base case model with daylighting control technique to evaluate the trends of the total energy consumption throughout the months of a given year. The monthly total building energy consumption indicates that the base case model with daylighting control technique decreased the electricity consumption of the building throughout the year. In these charts, the difference between the total building energy uses of the two base cases is approximately 5%.

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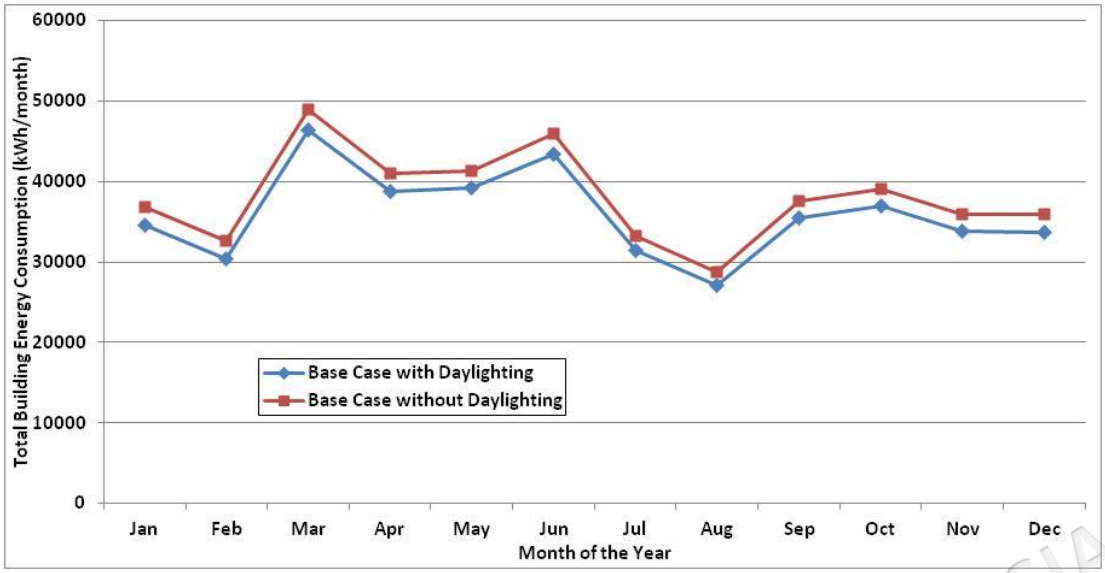

Figure 4.66 Comparison of monthly total building energy consumption of base case model with and without daylighting control technique

Table 4.16 Comparison of monthly total electricity consumption of base case model without daylighting control versus base case model with daylighting control

Base Case Model without Daylighting Control						
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**
Total energy use (kWh)	36876	32556	48952	41010	41259	45902
	Jul	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Total energy use (kWh)	33233	28760	37528	39024	35900	35873
Base Case Model with Daylighting Control						
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**
Total energy use (kWh)	34589	30335	46379	38731	39235	43360
	Jul	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Total energy use (kWh)	31455	27022	35418	36945	33888	33735

4.2.3 Toplighting Alternatives Analysis: 1 to 1 Spacing-to-Height Ratio

The energy consumption of each toplighting case with 1 to 1 spacing-to-height ratio is tested using EnergyPlus 7.0 simulation software following the approach described in Chapter 3. The OpenStudio plan and the perspective of each toplighting strategy case

are presented in Chapter 3 (Figure 3.10). Each toplighting system with 1 to 1 spacing-to-height ratio choice is contained of 9 units.

The EnergyPlus calibrated base case computer model without daylighting control strategy integrated with artificial lighting system was used as a base case model for the comparison of the various suggested toplighting strategies, namely skylight, sawtooth, and roof monitors. The energy consumption of every suggested toplighting case was compared with the base case model energy consumption in the following categories: annual lighting energy use, cooling energy use, and total energy consumption.

4.2.4 Lighting Energy Use Analysis

The implementation of daylighting strategy through toplighting options is expected to reduce the lighting energy consumption of the building. The simulation results show that lighting energy consumption is decreased as a result of integrating daylight through artificial lighting systems. Consequently, this procedure plays a major role in reducing not only the lighting energy consumption and the associated sensible cooling load caused by artificial lighting but also the cooling and total energy consumption of the building. To better understand the decrease in building lighting energy consumption, various cases using different toplighting strategies (skylight, sawtooth, and roof monitors) with different geometries, orientations, and 1-to-1 spacing-to-height ratio were analyzed for one whole year. The simulation results were obtained from "Annually Report," the simulation program of EnergyPlus 7.0.

4.2.4.1 Comparison of the Lighting Energy Use of Skylight Cases

Figure 4.4 shows the annual lighting energy consumption evaluation for the four orientations and four glazing types with a toplighting-to-roof (TFR) ratio of 5% to 60% skylight cases. These 12 cases were selected to represent the skylight designs with the largest and smallest skylight-to-roof area ratio used in this study. In all of the skylight cases for the four orientations and four glazing types, the annual lighting energy consumption was lower than the base case lighting energy consumption. The

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annual lighting energy consumption gradually decreased as the TFR increased. The decrease in lighting energy use was 60% more than the base case lighting energy use, with a maximum of 63.1% reduction for the 60% skylight-to-roof ratio and a minimum of 54.7% reduction for the 5% skylight-to-roof ratio. The highest lighting energy savings, compared with the base case, occurred in cases where skylights with double low-e clear glass were used because the amount of light transmitted into the space was higher when the glazing type was used, which in turn reduced the artificial lighting usage of the building. The results also demonstrate that the higher the visible light transmission of the glazing type, the greater the annual lighting energy savings.

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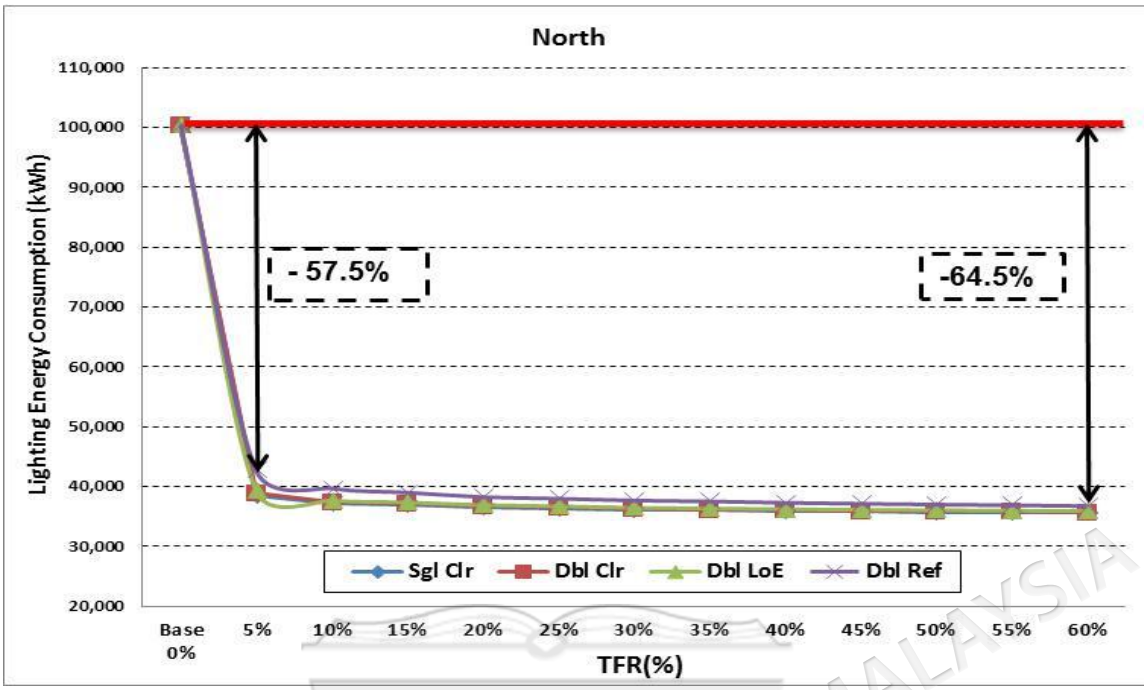
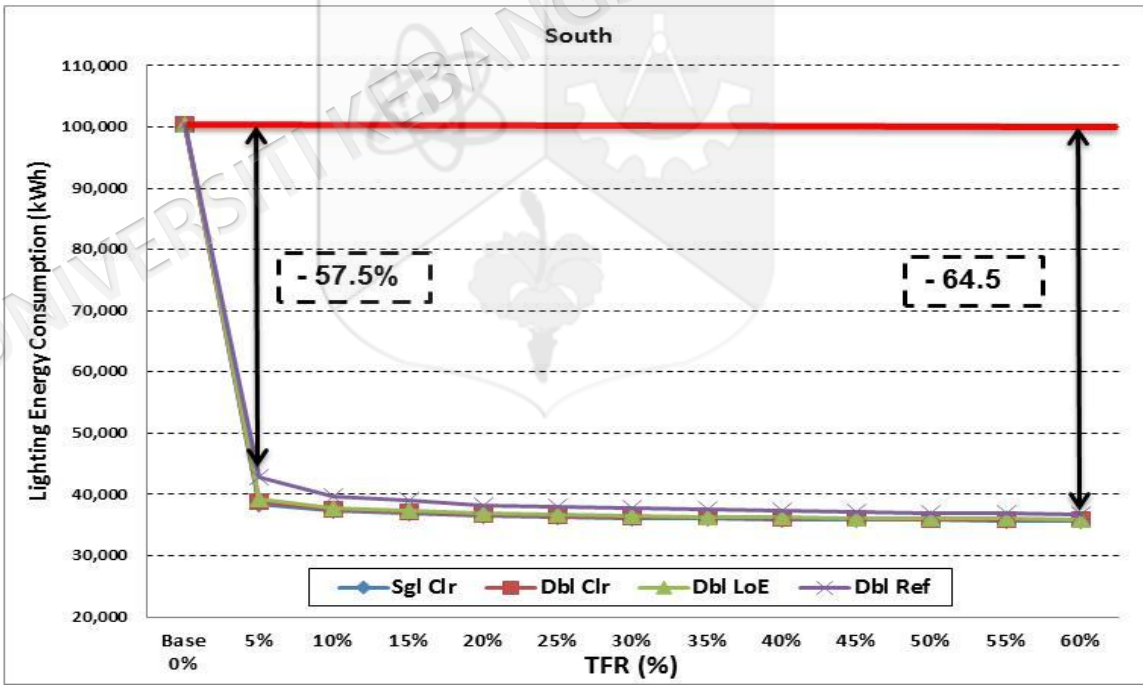


(a) North



(b) South

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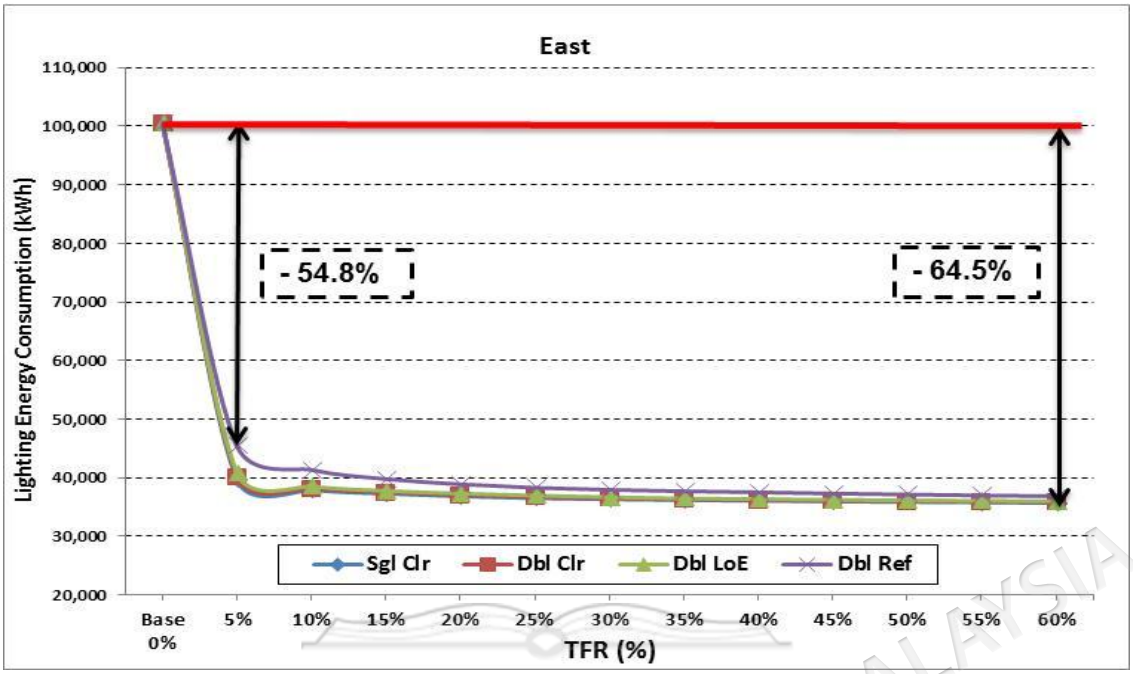
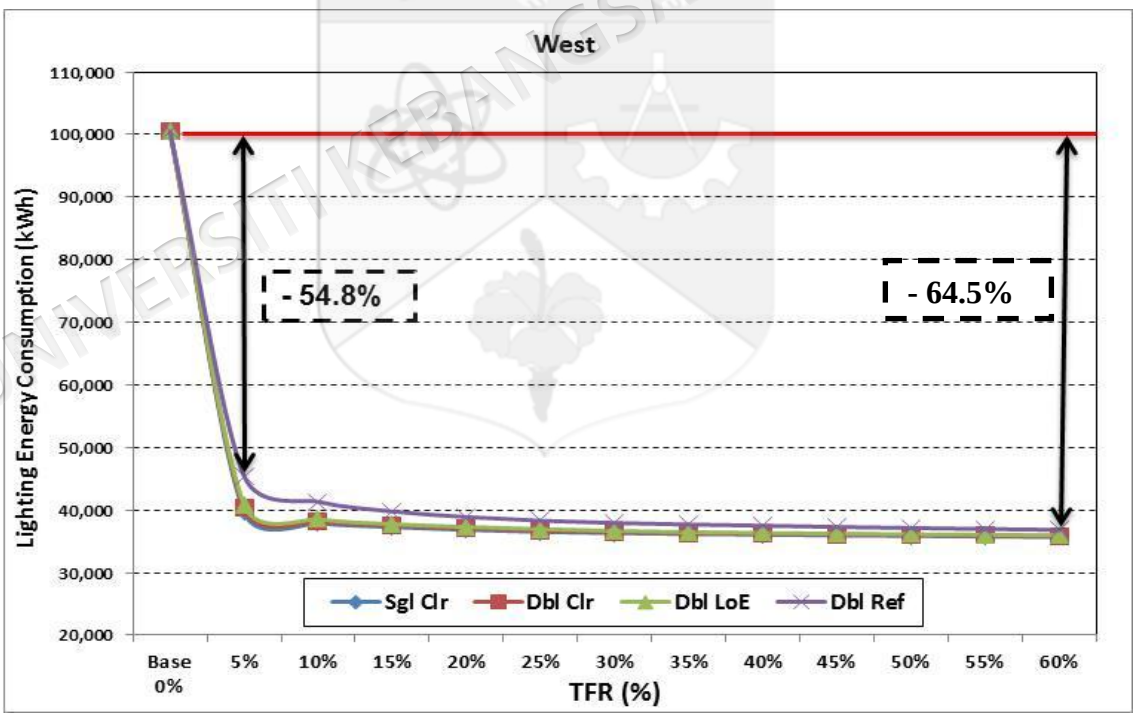


(C) East



(d) West

Figure 4.67 Comparison of annual lighting energy consumption of skylight cases with different glazing types for [a) North, b) South, c) East, and d) West orientations] and base case computer model without daylighting

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4.2.4.2 Comparison of Lighting Energy Use of Sawtooth Cases

The twelve sawtooth cases selected for the evaluation were of 5% to 60% sawtooth cases to represent the sawtooth designs with smallest and largest sawtooth design used in the current study. From the results of the sawtooth cases also, the annual lighting energy consumption was observed to be lower compare to the base case lighting energy consumption in all the sawtooth cases for the four orientations and four glazing types. It was found that the reduction on the lighting energy use more than 60% lower than the base case lighting energy use, with a maximum of 63% reduction for the 60% sawtooth-to-roof ratio case, and a minimum of 27.4% reduction in lighting energy use for 5% sawtooth-to-roof ratio. The highst lighting energy savings, compared to the base case, were noticed to be occurred on the sawtooth cases with south orientation, followed by north orientation. Figure 4.68 present the annual lighting energy consumption evaluation for the four orientations and four glazing types with TFR of 5% to 60% sawtooth cases.

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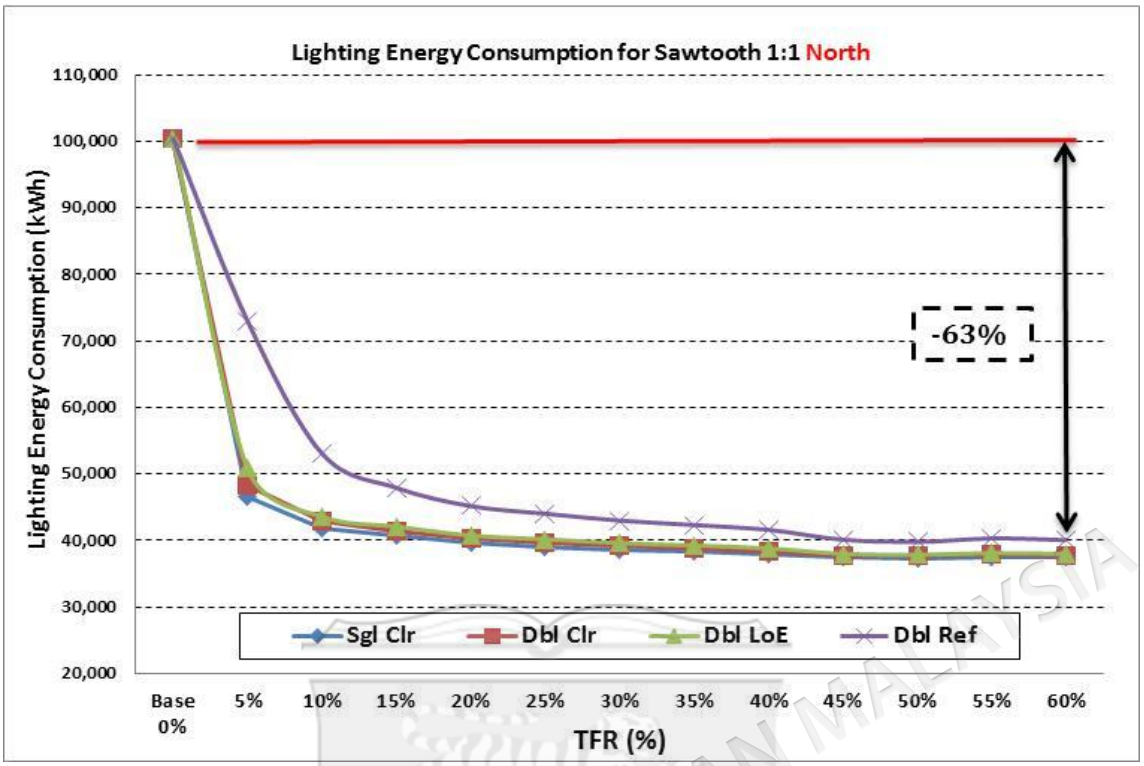
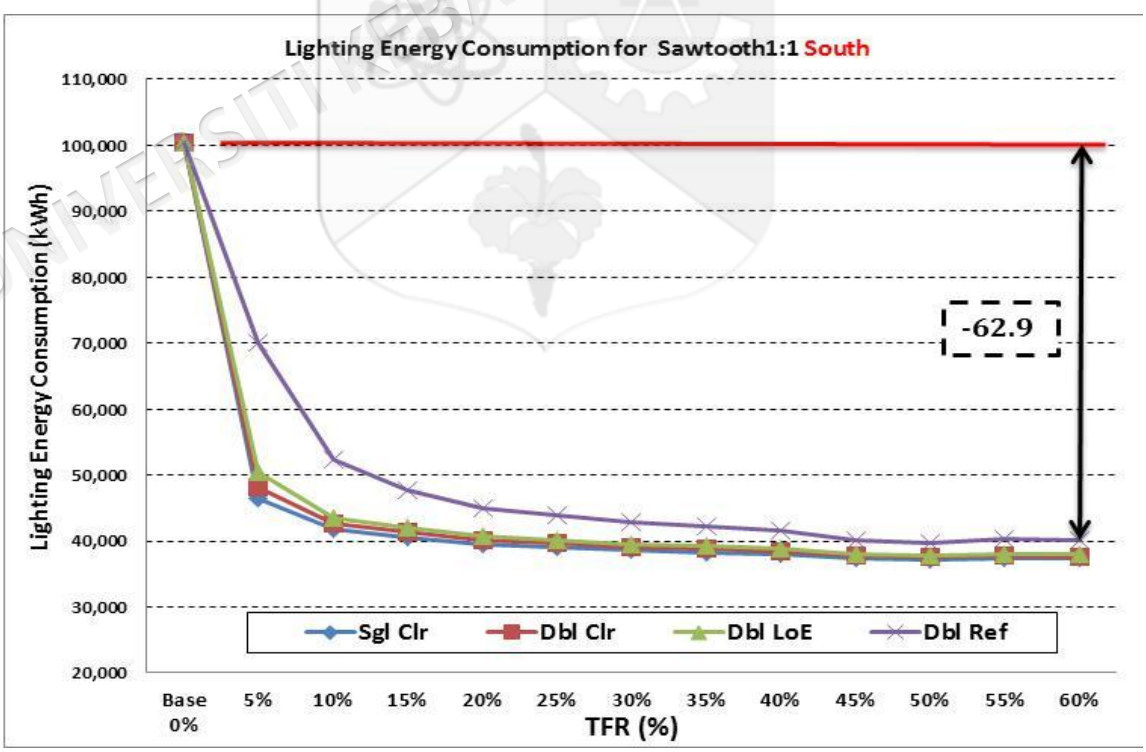


(a) North



(b) South

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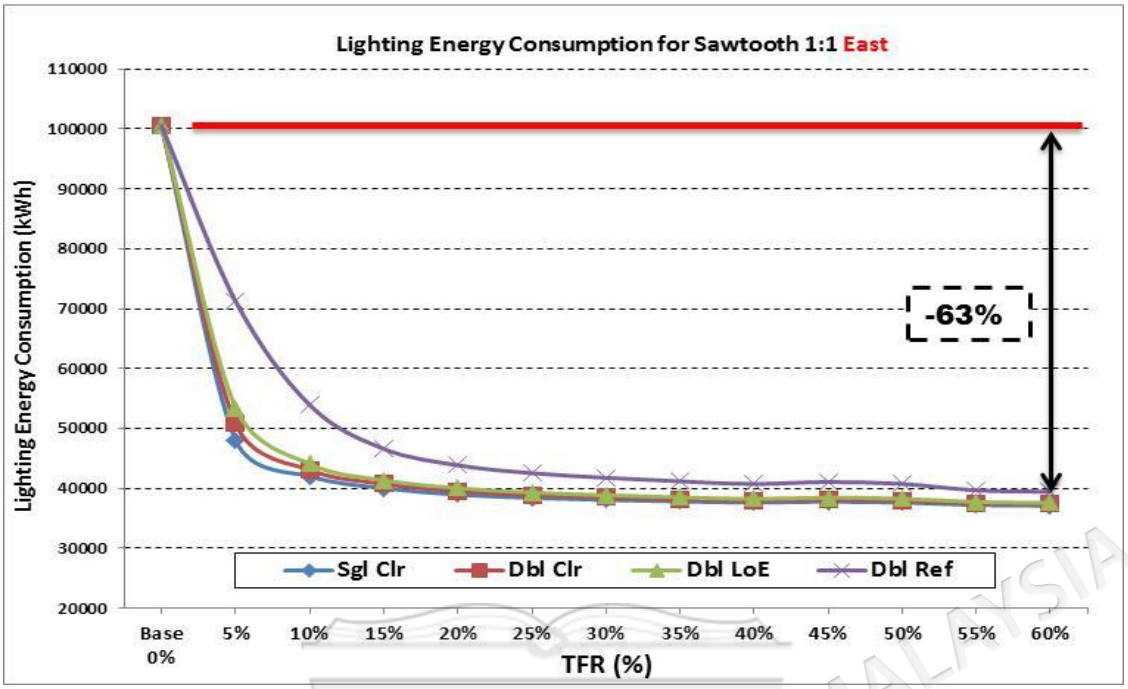
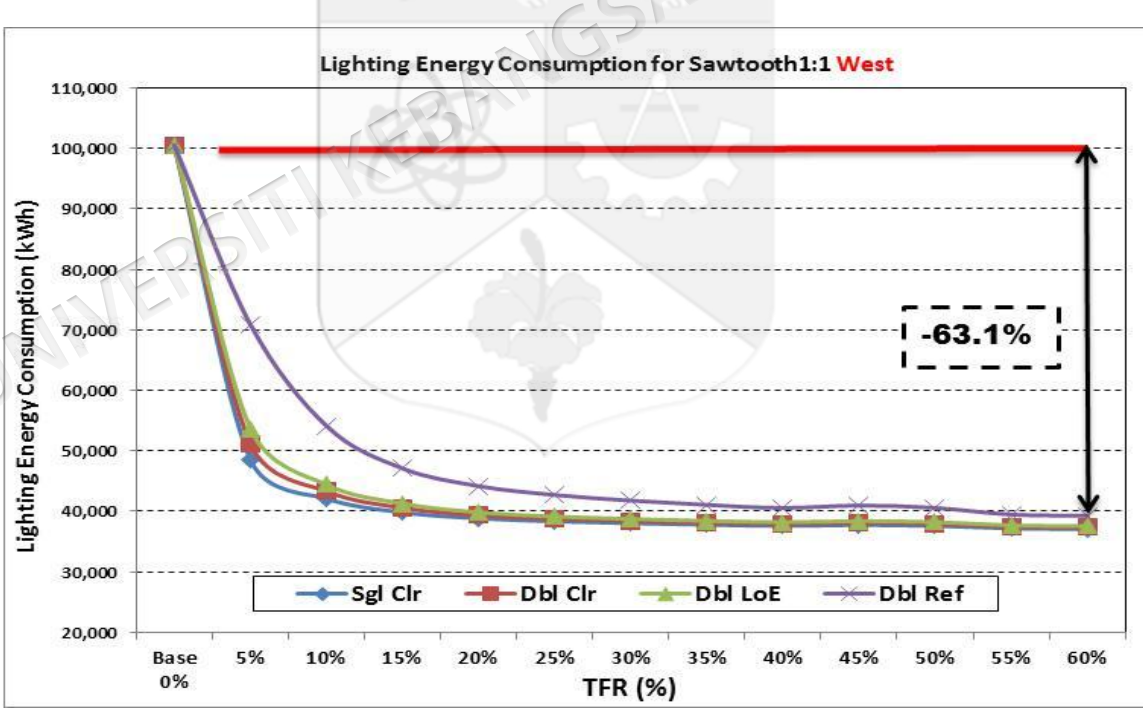


(C) East



(d) West

Figure 4.68 Comparison of annual lighting energy consumption of sawtooth cases with different glazing types for [a) North, b) South, c) East, and d) West orientations] and base case computer model without daylighting

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4.2.4.3 Comparison of Lighting Energy Use of Roof Monitor Cases

Figure 4.69 illustrates an analysis of the annual lighting electric energy use of the four orientations and four glazing types with a TFR of 5% to 60% for the roof monitor cases. These 12 roof monitor cases were selected to represent the roof monitor designs with the largest and smallest roof-monitor-to-roof area ratio used in this study. In all of the orientations for all four glazing types, the simulation results demonstrated that the lighting electric energy consumption was significantly lower than the base case with daylight combined with the artificial lighting system. Figure 4.15 also shows that a significant reduction occurred in the lighting electric energy use when the TFR was increased from 0% to 5%. The lighting electric energy consumption gradually decreased as the TFR was increased up to 60%. The decrease in lighting electric energy consumption ranged from 49% to 63.2% for all four glazing types in all orientations. The lighting electric energy use decreased when the TFR was increased for all four glazing types used in the simulation analysis because of the increase in the light transmitted into the zone. The results also indicate that at a higher TFR, the difference in the lighting electric energy use of the four glazing types decreases and becomes negligible.

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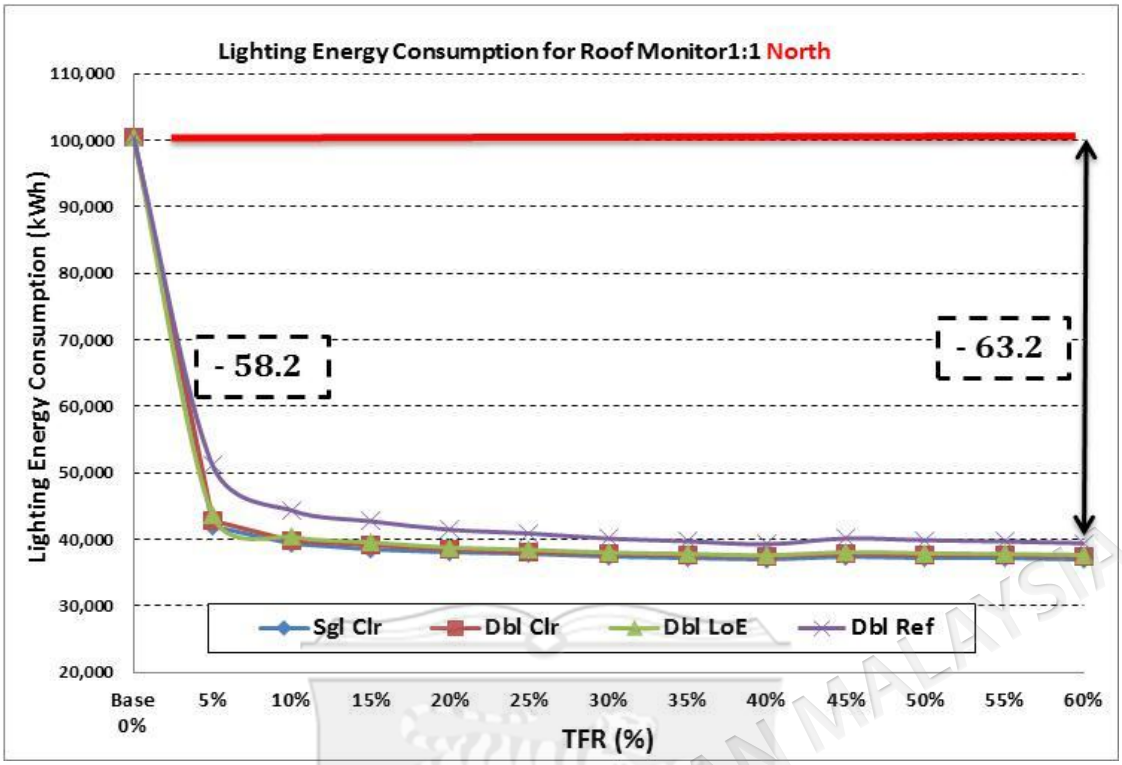
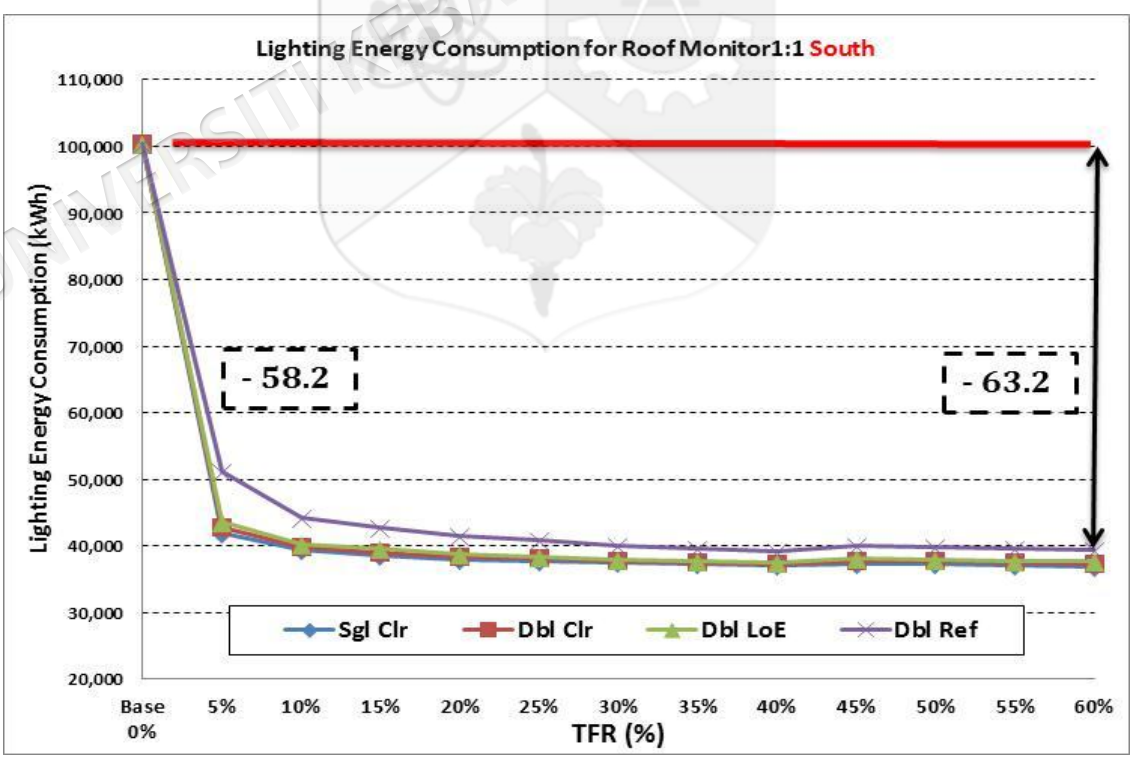


(a) North



(b) South

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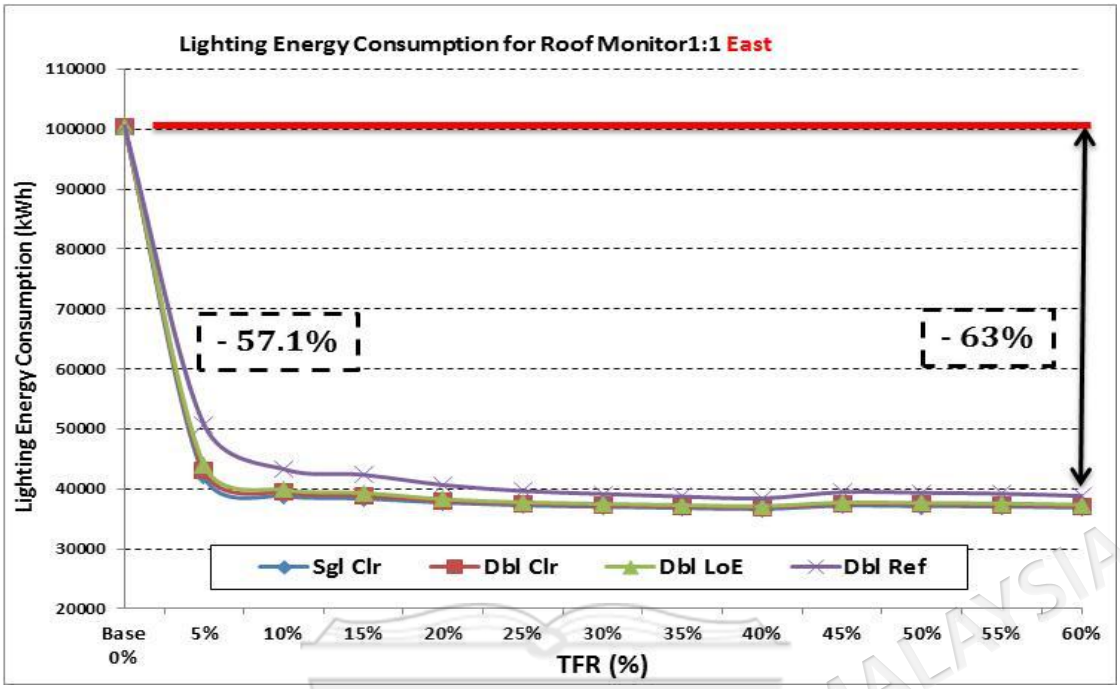
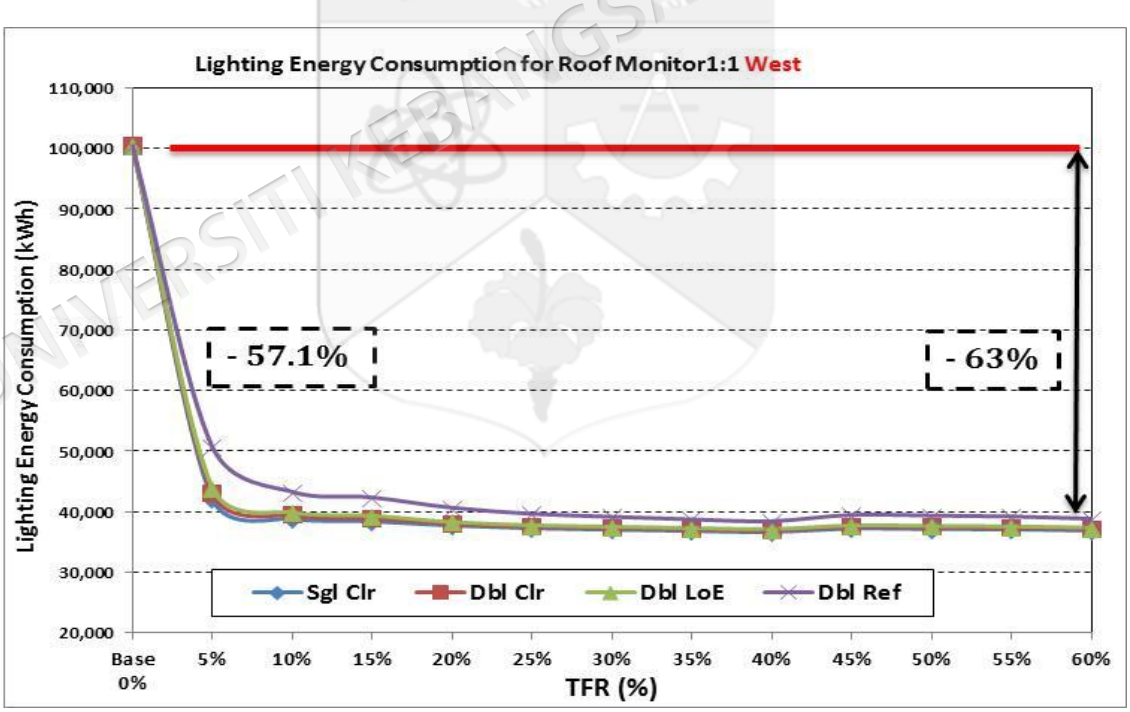


(C) East



(d) West

Figure 4.69 Comparison of annual lighting energy consumption of roof monitor cases with different glazing types for [a) North, b) South, c) East, and d) West orientations] and base case computer model without daylighting

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4.2.5 Cooling Energy Use Analysis

The use of daylighting through toplighting systems can influence the cooling energy consumption by decreasing heat generated from artificial lighting systems. The results demonstrate that the cooling energy consumption decreases as a result of integrating daylight via artificial lighting systems. Thus, this practice plays a major role in reducing not only the cooling energy consumption and the associated sensible cooling load caused by artificial lighting but also the total energy consumption of the entire building. The simulation results were obtained from "Annually Report," the simulation program of EnergyPlus 7.0.

4.2.5.1 Comparison of Cooling Energy Use of Skylight Cases

Annual cooling energy consumption was plotted vis-à-vis the total cooling energy consumption of the base case to analyze the energy required to remove conduction heat gains from the skylight window. Figure 4.70 presents a comparison of the cooling energy consumption of the base case without daylighting control and the different skylight daylighting cases. Based on the results, although the cooling energy use in both the base case and the skylight cases decreased noticeably, the cooling energy use in the skylight cases and the base case also show an increase. This increase in the cooling energy consumption is due to the conduction heat gains from the glazing properties of the skylight cases, which have higher u-values than the exterior walls and roof of the building. As shown in the charts, the maximum difference in the cooling energy use occurs in the 60% skylight-to-roof ratio with a 10% increase in cooling energy consumption, and the minimum difference in the 10% skylight-to-roof ratio, which corresponds to the minimum amount of solar radiation gains and conduction heat gains entering the space through the skylights. The results highlight the importance of TFR in transferring the conduction heat gains, and the cooling energy required to cool the building to 24 °C in a hot and humid climate, such as Malaysia's.

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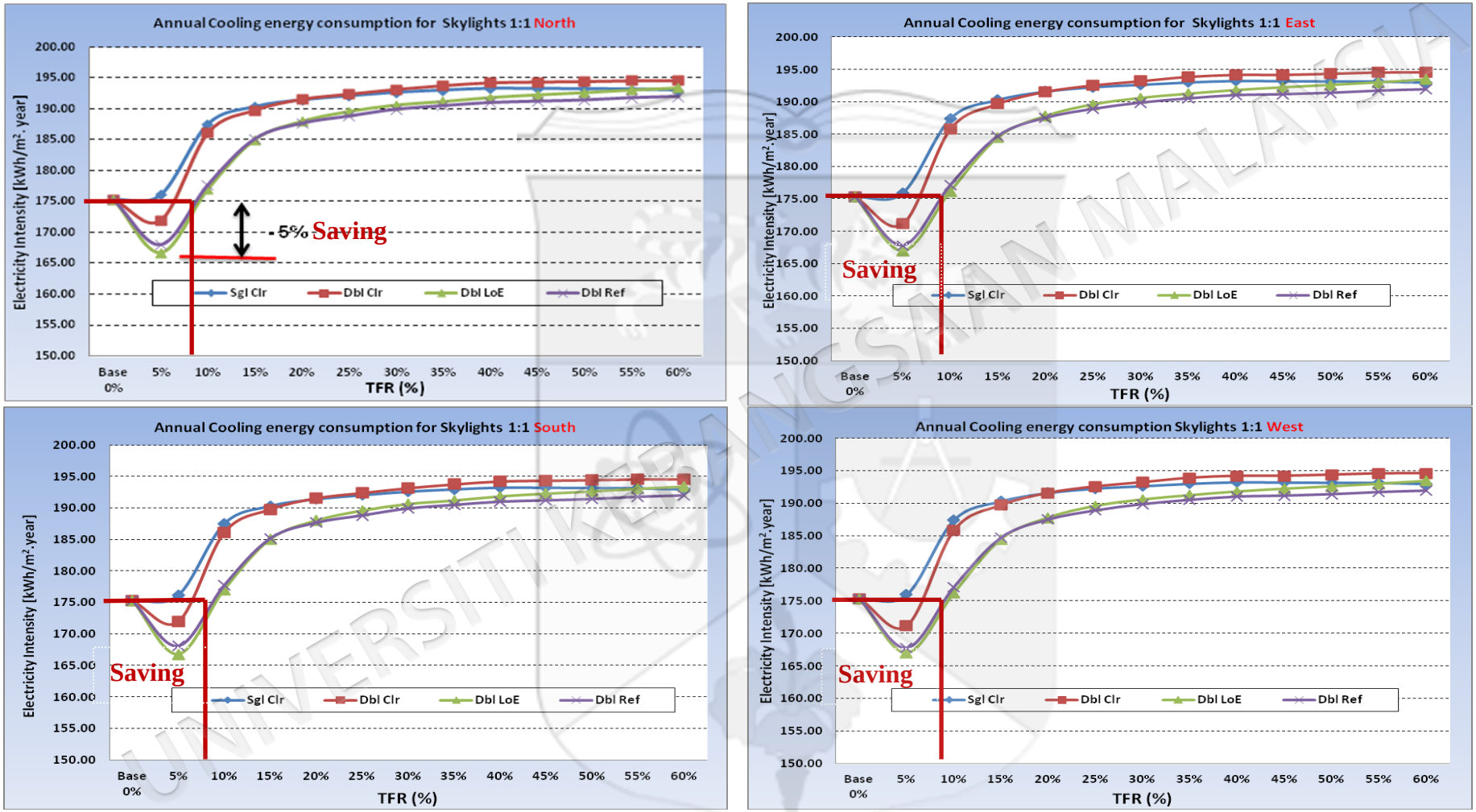

Figure 4.70 Comparison of annual cooling energy consumption of different skylight cases with different glazing types and orientations and versus base case model without daylighting

4.2.5.2 Comparison of Cooling Energy Use of Sawtooth Cases

Annual cooling electric energy consumption is plotted vis-à-vis the total annual cooling energy consumption of the base case to analyze the energy required to remove the conduction heat gains from the sawtooth window. Figure 4.71 presents a comparison of the annual cooling energy consumption of the base case without daylighting and the sawtooth daylighting cases. The results indicate that although the annual cooling energy consumption of the different sawtooth cases and the base case apparently decreased, it also dramatically increased because of the conduction heat gains through the glazing areas of the sawtooth, which had higher u-values than the exterior walls and roof of the building. In the sawtooth cases, the volume and surface of the building also increased compared with the base case with no added glazing area, which increased heat conduction through glazing and opaque building materials.

The results also show that the cooling electric energy consumption increased when the sawtooth glazing area increased. The 5% sawtooth was the best among the sawtooth cases with a 5.3% decrease in cooling energy consumption compared with the base case without daylighting technique. The results highlight the significance of conduction heat gains from glazing and opaque building materials in hot and humid climate and the cooling energy required for the removal of heat gains during occupation hours when cooling is always available.

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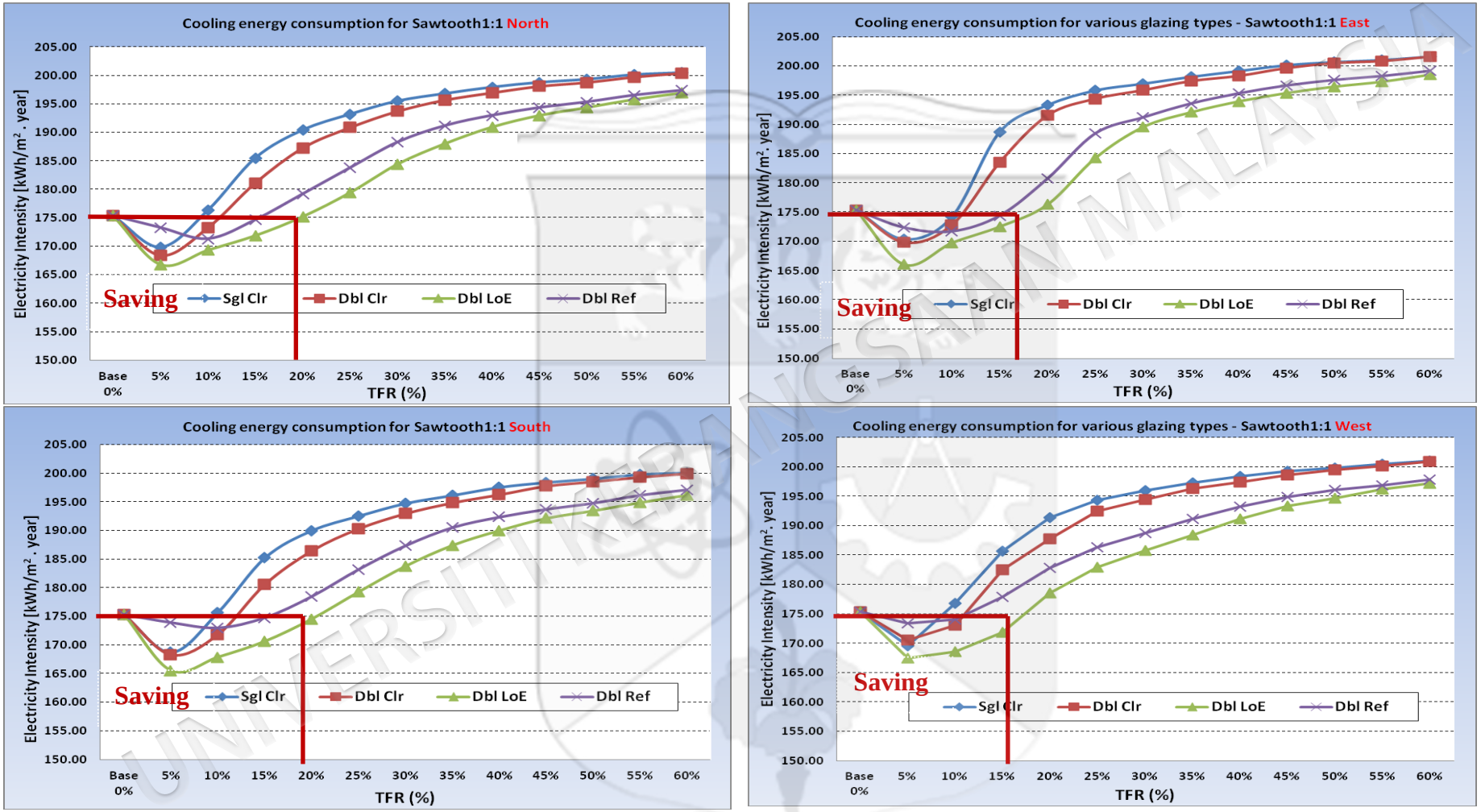

Figure 4.71 Comparison of annual cooling energy consumption of sawtooth cases with different glazing types and orientations and the base case computer model without daylighting

4.2.5.3 Comparison of Cooling Energy Use of Roof Monitor Cases

In the case roof monitors, the results show that although the annual cooling energy consumption in the different roof monitor cases and the base case obviously decreased, it also steadily increased because of conduction heat gains through the glazing areas of the roof monitors, which had higher u-values than the building envelope. In the roof monitor cases, the volume and the exterior wall of the building are higher than those in the base case with no added glazing area, which increased conduction heat gains through glazing and opaque building materials.

The results also indicate that the cooling electric energy consumption increased when the glazing area of the roof monitors was increased. The 5% roof monitor was the best among the roof monitor cases with a 3.8% decrease in cooling electric energy consumption compared to the base case without daylighting technique. The results emphasize the importance of conduction heat gains through glazing materials in hot and humid climate, as well as the cooling energy required to remove heat gains and cool the building to 24 °C during occupation hours when cooling is always available. Figure 4.72 presents a comparison of the annual cooling energy consumption of the base case without daylighting and the roof monitor daylighting cases.

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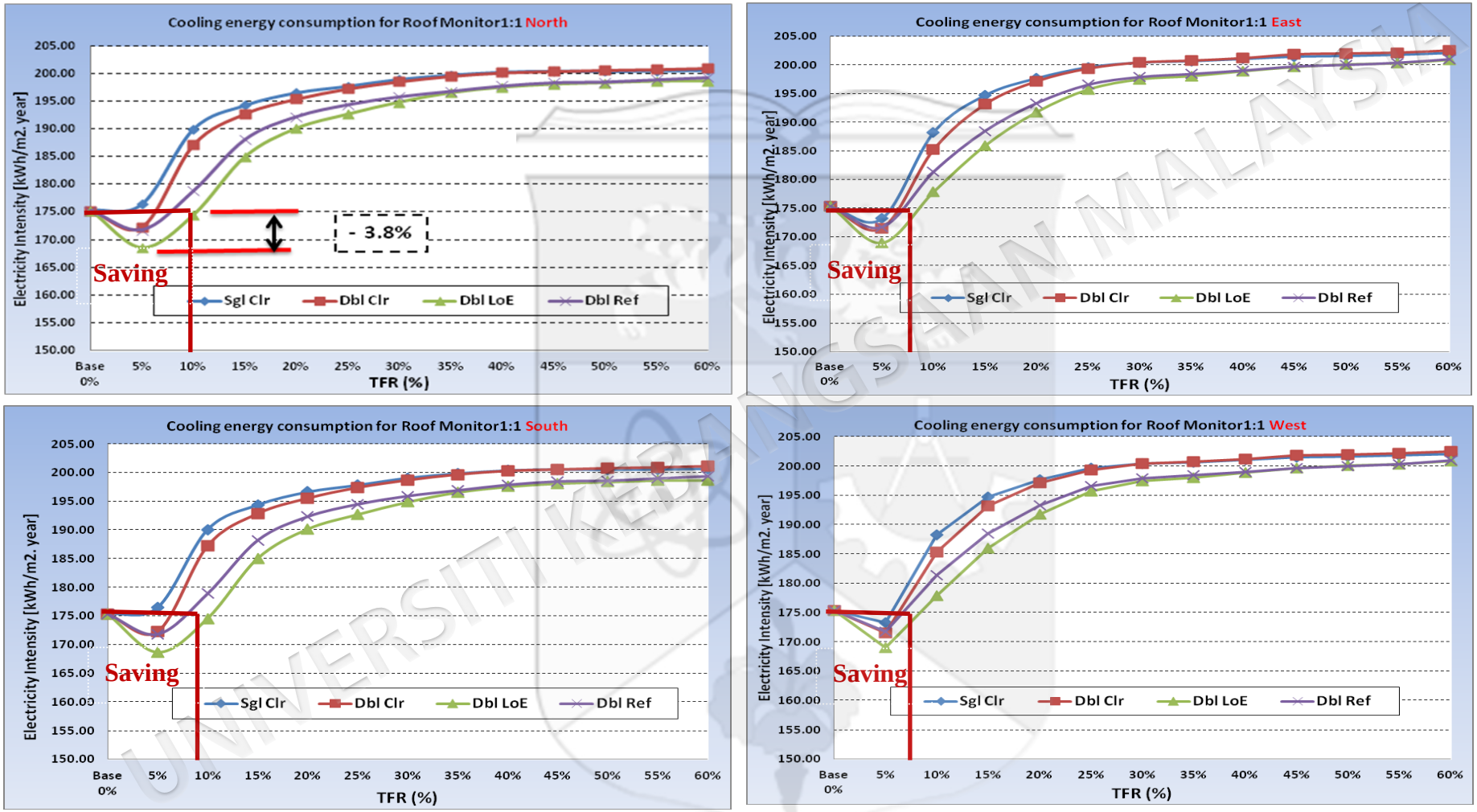

Figure 4.72 Comparison of annual cooling energy consumption of roof monitor cases with different glazing types and orientations and base case computer model without daylighting

4.2.6 Total Building Energy Analysis

This section analyzes the effect of toplighting strategies on the total energy consumption of skylight, sawtooth, and roof monitor cases with various glazing types and orientations compared with their effect on the base case model without daylighting control.

4.2.6.1 Comparison of Total Energy Use of Skylight Cases

Figure 4.73 shows the trends observed in the total energy consumption of skylight cases with various glazing types and orientations. The annual total energy consumption (lighting, cooling, and others) sharply decreases in terms of total energy use in the 5% and 10% TFR skylight cases, whereas it gradually increases in the skylight cases with 15%, 20%, 25%, and 30% TFR. In the skylight cases with a TFR of 35% to 60%, the annual total energy consumption slightly increases relative to the base case. By contrast, in the skylight cases with a TFR of more than 60%, the annual total energy consumption remains almost the same as expacted from figure 4.10 that TFR more than 25%, the annual total energy consumption remains almost the same.

As shown in Figure 4.73, the 5% TFR skylight case with a double low-e clear 6 mm to 13 mm air glass type was the best among the skylight cases: it resulted in a 17.1% decrease in annual total building energy consumption compared with the base case without daylighting. By contrast, the 60% TFR skylight case with a double clear 6 mm to 13 mm air glass type was the worst among the skylight cases: it resulted in a 6.2% decrease in annual total building energy consumption compared with the base case with no daylighting.

The results show that different glazing types result in different energy consumption levels, with the highest occurring in the single clear glazing type, followed by the double clear and double reflect clear types. The least energy consumption in the building occurs in the double low-e clear glass type. Further analysis is presented in Section 4.6.

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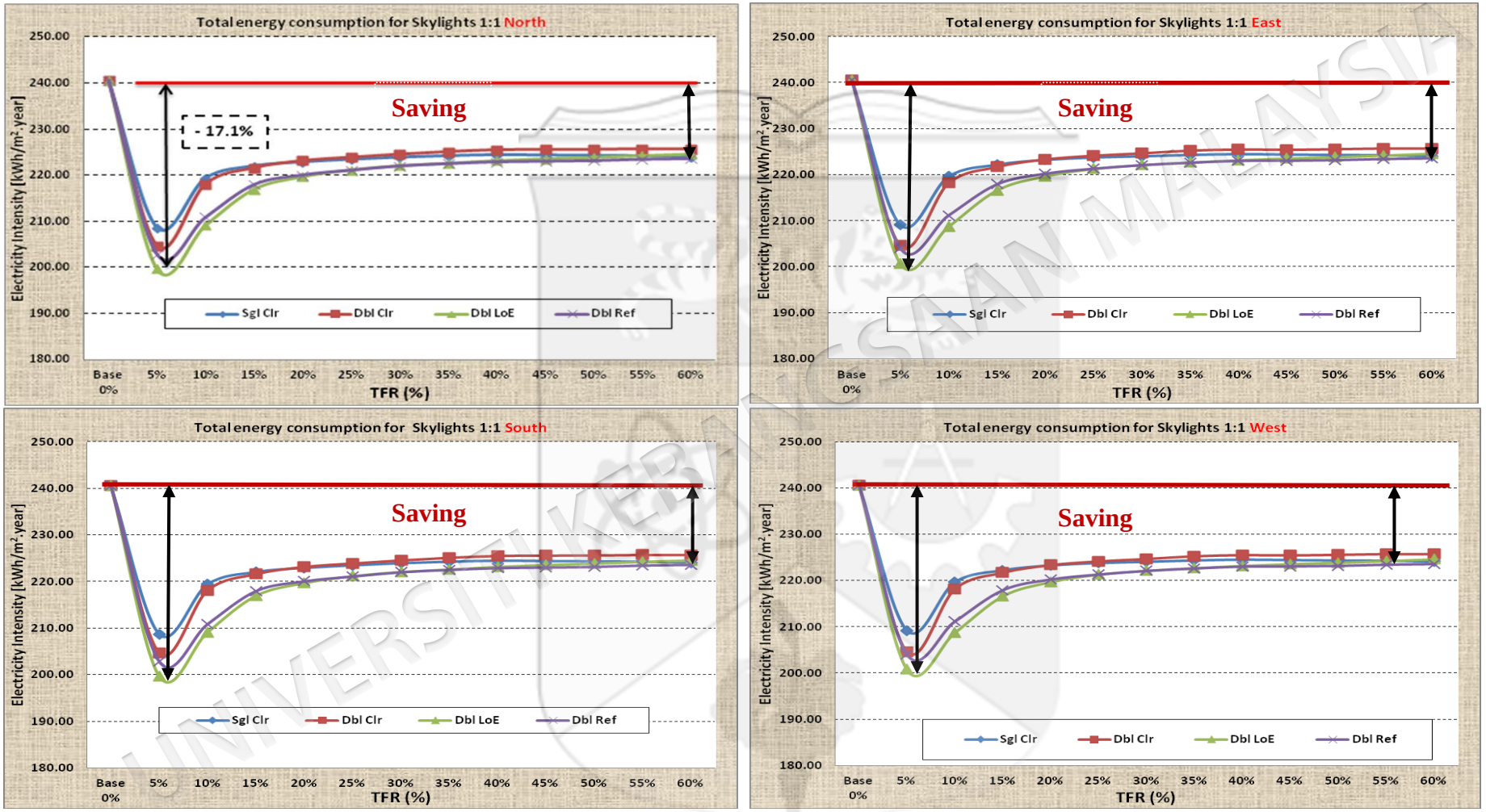

Figure 4.73 Comparison of total energy consumption of skylight cases with various glazing types and four orientations versus base case model without daylighting

4.2.6.2 Comparison of Total Energy Use of Sawtooth Cases

The annual total energy use (lighting, cooling, and others) sharply decreases in terms of total energy consumption in the 5% and 10% TFR sawtooth cases, whereas it gradually increases in the 15%, 20%, 25%, and 30% TFR sawtooth cases. In the sawtooth cases with a 35% to 60% TFR, it slightly increases compared with the base case. This is due to that daylighting through sawtooth cases can not only allow an artificial lighting consumption reduction, but also a reduction of the lighting internal loads and thus of the cooling loads. However, increase the TFR allow the admission of too much daylight introduces solar heat gains that increase cooling loads associated with the toplighting options that results from daylighting and thus increase the the total energy consumption of the academic hall. Figure 4.74 presents the trends observed in the total energy consumption of sawtooth cases with various glazing types and orientations.

As Figure 4.74 shows, a TFR ranging from 5% to 15% results in approximately 13% to 15.6% decrease in the total energy consumption of most sawtooth cases except in the case of the glazing type of a double reflect clear pane. This type reduces the total energy consumption from 7% to 11% compared with base case without daylighting.

The results also demonstrate that different glazing types result in different energy consumption levels, with the highest energy consumption occurring in the single clear glazing type, followed by the double clear and double reflect clear types. The least energy consumption in the building occurs in the double low-e clear glass type.

The four orientations also lead to different energy consumptions, with the highest energy use occurring in the sawtooth with an eastward orientation, followed by those with westward and southward orientations. The least energy consumption in the building occurs in the sawtooth cases with a northward orientation. Additional analysis is provided in Section 4.6.

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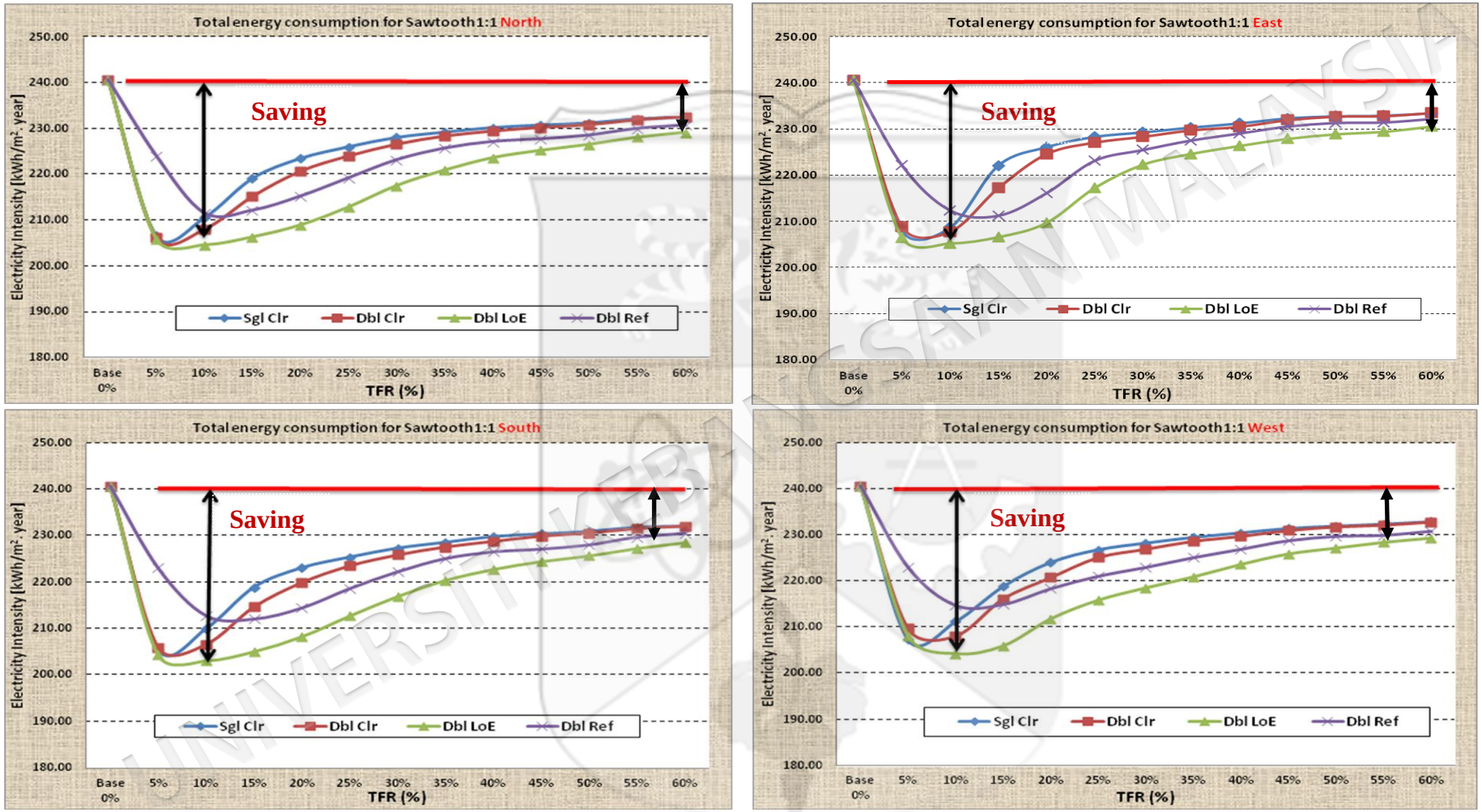

Figure 4.74 Comparison of total energy consumption of sawtooth cases with various glazing types and orientations versus base case model with no daylighting control

4.2.6.3 Comparison of Total Energy Use of Roof monitor Cases

Figure 4.75 illustrates the trends observed in the total energy consumption of roof monitor cases with various glazing types and orientations. The total annual energy consumption sharply declines in terms of total energy use in the 5% TFR roof monitor case, whereas it steadily rises in the 10%, 15%, 20%, 25%, and 30% TFR roof monitor cases. In the roof monitor cases with a TFR of 35% to 60%, it slightly increases relative to the base case without daylighting.

The differences observed suggest that a TFR ranging from 5% to 15% results in approximately 6% to 15.3% decrease in the total energy consumption of most of the roof monitor cases except in the case with a double reflect pane clear glazing type. This type reduces the total energy consumption by approximately 7% to 11% relative to the base case without daylighting, as shown in Figure 4.75.

The four orientations also exhibit different energy consumption levels, with the highest energy use occurring on the roof monitor with an eastward orientation, followed by that with a westward orientation. The lowest amount of total energy consumption occurs in the roof monitor cases with northward and southward orientations.

As in the skylight and sawtooth cases, roof monitor cases with different glazing types also result in different energy consumption levels, with the highest total energy consumption occurring in the single clear glazing type, followed by the double clear and double reflect clear types. The lowest total energy consumption occurs in the double low-e clear glass type. Additional analysis is presented in the subsequent section.

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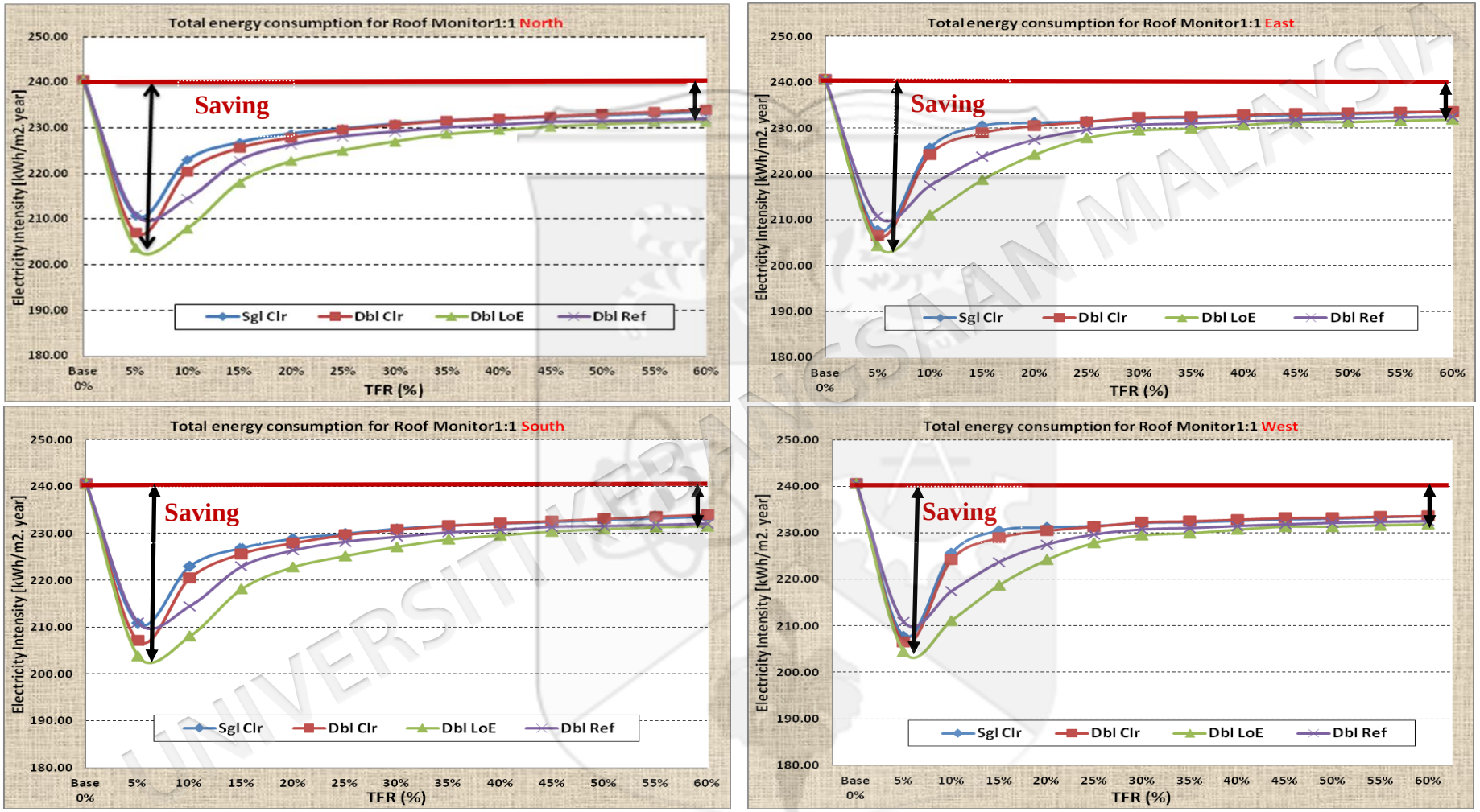

Figure 4.75 Comparison of total energy consumption of roof monitor cases with different glazing types and orientations versus base case model without daylighting

4.2.7 Comparison of Energy Savings from Various Toplighting Alternatives

This section focuses on the annual lighting, cooling, and total energy savings of the case study building with three different toplighting systems, namely, skylight, sawtooth, and roof monitors, compared with the base case model with long sides of these toplighting exposures facing north, south, east, and west (N, S, E, and W). The contributions of these toplighting options to building energy savings are analyzed separately. The goal is to determine the effect of these toplighting options on the energy savings of the case study building with four different types of glasses, such as the single clear-Sgl Clr type (Tvis=0.88/ U=5.778/ SHGC=0.819), double clear-Dbl Clr type (Tvis=0.78/ U=2.67/ SHGC=0.703), and double reflect clear-Dbl Ref type (Tvis=0.308/ U=2.65/ SHGC=0.426) types, with a TFR of 5% to 60%. The base case model is the case without daylighting control systems, which is typically used in energy comparisons with the suggested toplighting simulations cases. All simulation test cases were conducted only for the state climate of Kuala Lumpur.

Tables 4.17 to 4.18 report the effect of daylighting on the lighting, cooling, and total energy savings of the skylight, sawtooth, and roof monitor cases as well as their particular savings (positive or negative) relative to the base case computer model without daylighting. A negative percentage value represents an increase in the energy consumed. The total energy saving is classified under the categories of lighting and cooling energy savings similar to the Annual Building Utility Performance Summary report from the EnergyPlus output file. The detailed lighting, cooling, and total energy savings per meter square per year of the skylight, sawtooth, and roof monitor cases with a TFR of 5% to 60% across all four orientations are presented in Tables A-9 to A-15 of Appendix A

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Table 4.17 Comparison of total energy savings (%) from the various toplighting options with different glazing types and orientations and 5% TFR compared with the base case model. A negative value represents an increase in the energy consumed.

TFR **5%**		North				South				East				West			
		Sgl	Dbl	LoE	Ref	Sgl	Dbl	LoE	Ref	Sgl	Dbl	LoE	Ref	Sgl	Dbl	LoE	Ref
Skylight	Lighting	62%	61%	61%	57%	62%	61%	61%	57%	60%	60%	59%	55%	60%	60%	59%	55%
	Cooling	-0.5%	1.9%	4.9%	4.1%	-0.5%	1.9%	4.9%	4.1%	-0.4%	2.4%	4.8%	4.3%	-0.4%	2.4%	4.8%	4.3%
	Total	**13%**	**15%**	**17%**	**16%**	**13%**	**15%**	**17%**	**16%**	**13%**	**15%**	**17%**	**15%**	**13%**	**15%**	**17%**	**15%**
Sawtooth	Lighting	54%	52%	49%	27%	54%	52%	50%	30%	52%	49%	47%	29%	52%	49%	47%	29%
	Cooling	3.1%	3.9%	4.9%	1.2%	3.8%	4.0%	5.6%	0.8%	2.8%	3.2%	5.3%	1.7%	3.3%	2.7%	4.5%	1.1%
	Total	**14%**	**14%**	**14%**	**7%**	**15%**	**14%**	**15%**	**7%**	**14%**	**13%**	**14%**	**8%**	**14%**	**13%**	**14%**	**7%**
Roof Monitor	Lighting	58%	57%	57%	49%	58%	57%	57%	49%	58%	57%	56%	50%	58%	57%	56%	50%
	Cooling	-0.6%	1.7%	3.8%	2.0%	-0.6%	1.7%	3.8%	2.0%	1.2%	2.2%	3.6%	2.0%	1.2%	2.2%	3.6%	2.0%
	Total	**12%**	**14%**	**15%**	**12%**	**12%**	**14%**	**15%**	**12%**	**14%**	**14%**	**15%**	**12%**	**14%**	**14%**	**15%**	**12%**

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Table 4.18 Comparison of total energy savings (%) from the various toplighting options with different glazing types and orientations and 10% TFR compared with the base case model. A negative value represents an increase in the energy consumed.

TFR **10%**		North				South				East				West			
		Sgl	Dbl	LoE	Ref	Sgl	Dbl	LoE	Ref	Sgl	Dbl	LoE	Ref	Sgl	Dbl	LoE	Ref
Skylight	Lighting	63%	63%	62%	60%	63%	63%	62%	60%	62%	62%	62%	59%	62%	62%	62%	59%
	Cooling	-6.9%	-6.1%	-1.0%	-1.4%	-6.9%	-6.1%	-1.0%	-1.4%	-6.9%	-6.0%	-0.5%	-1.0%	-6.9%	-6.0%	-0.5%	-1.0%
	Total	**8.8%**	**9.4%**	**13%**	**12%**	**8.8%**	**9.4%**	**13%**	**12%**	**8.7%**	**9.3%**	**13%**	**12%**	**8.7%**	**9.3%**	**13%**	**12%**
Sawtooth	Lighting	58%	57%	57%	47%	58%	57%	57%	48%	58%	57%	56%	46%	58%	57%	56%	46%
	Cooling	-0.6%	1.2%	3.4%	2.3%	-0.2%	2.0%	4.3%	1.3%	0.6%	1.4%	3.2%	2.1%	-0.8%	1.3%	3.9%	0.7%
	Total	**12%**	**14%**	**15%**	**12%**	**13%**	**14%**	**16%**	**12%**	**13%**	**14%**	**15%**	**12%**	**12%**	**14%**	**15%**	**11%**
Roof Monitor	Lighting	61%	60%	60%	56%	61%	60%	60%	56%	61%	61%	60%	57%	61%	61%	60%	57%
	Cooling	-8.4%	-6.8%	0.4%	-2.0%	-8.4%	-6.8%	0.4%	-2.0%	-7.4%	-5.7%	-1.4%	-3.4%	-7.4%	-5.7%	-1.4%	-3.4%
	Total	**7.3%**	**8.4%**	**14%**	**11%**	**7.3%**	**8.4%**	**14%**	**11%**	**6.2%**	**6.8%**	**12%**	**10%**	**6.2%**	**6.8%**	**12%**	**10%**

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Figures 4.76 to 4.77 present the trends observed in the different energy savings of the skylight, sawtooth, and roof monitor cases. The results also indicate that when daylighting is applied to the case study building, the double clear glaze type generally results in better lighting energy savings than other glazing types across all orientations and TFRs.

With the double clear glass type, the skylight cases result in the highest lighting energy savings. The sawtooth and roof monitor cases result in lower lighting energy savings than skylights across all orientations.

The cooling energy savings rapidly increase in the 5% and 10% TFR skylight, sawtooth, and roof monitor. By contrast, in all of the other cases (15% to 60%) across all orientations, the cooling energy savings rapidly decreases relative to the base. The highest cooling energy savings, compared with the base case, occurs when the sawtooth with 5% TFR and double low-e glazed clear type is used.

The sawtooth cases with the double low-e clear glazed type result in higher total energy savings than the skylight and roof monitor cases. This difference is due to an increase in the cooling energy consumed in the skylight and roof monitor cases, as well as the lower energy required in the sawtooth cases. The highest total energy savings relative to the base case without daylighting occurs when the double low-e clear glasses are used in northward and southward orientations.

For a larger toplighting glazing area with TFR=60%, the total energy savings ranged from 2.9% to 3.9% in roof monitor cases and from 6% to 7.1% in skylight cases. For smaller toplighting glazing areas with TFR=5%, the total energy savings ranged from 12% to 15.3% in roof monitor cases, 6% to 14.5% in sawtooth cases, and 13% to 17% in skylight cases. The effect of daylighting use is proportional to the TFRs across all glazing types and orientations.

The results also indicate that the energy savings mainly come from lighting energy savings. The cooling energy decreases with the application of 5% and 10% TFRs

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across all glazing types and orientations. The single clear glazed type saves only a negligible amount of cooling energy, but results in substantial lighting energy savings.

The results also indicate that the four orientations present slight differences in energy savings, with the highest energy savings occurring in the toplighting with a southward orientation, followed by those with northward and westward orientations. The lowest energy savings occur in the toplighting with an eastward orientation.

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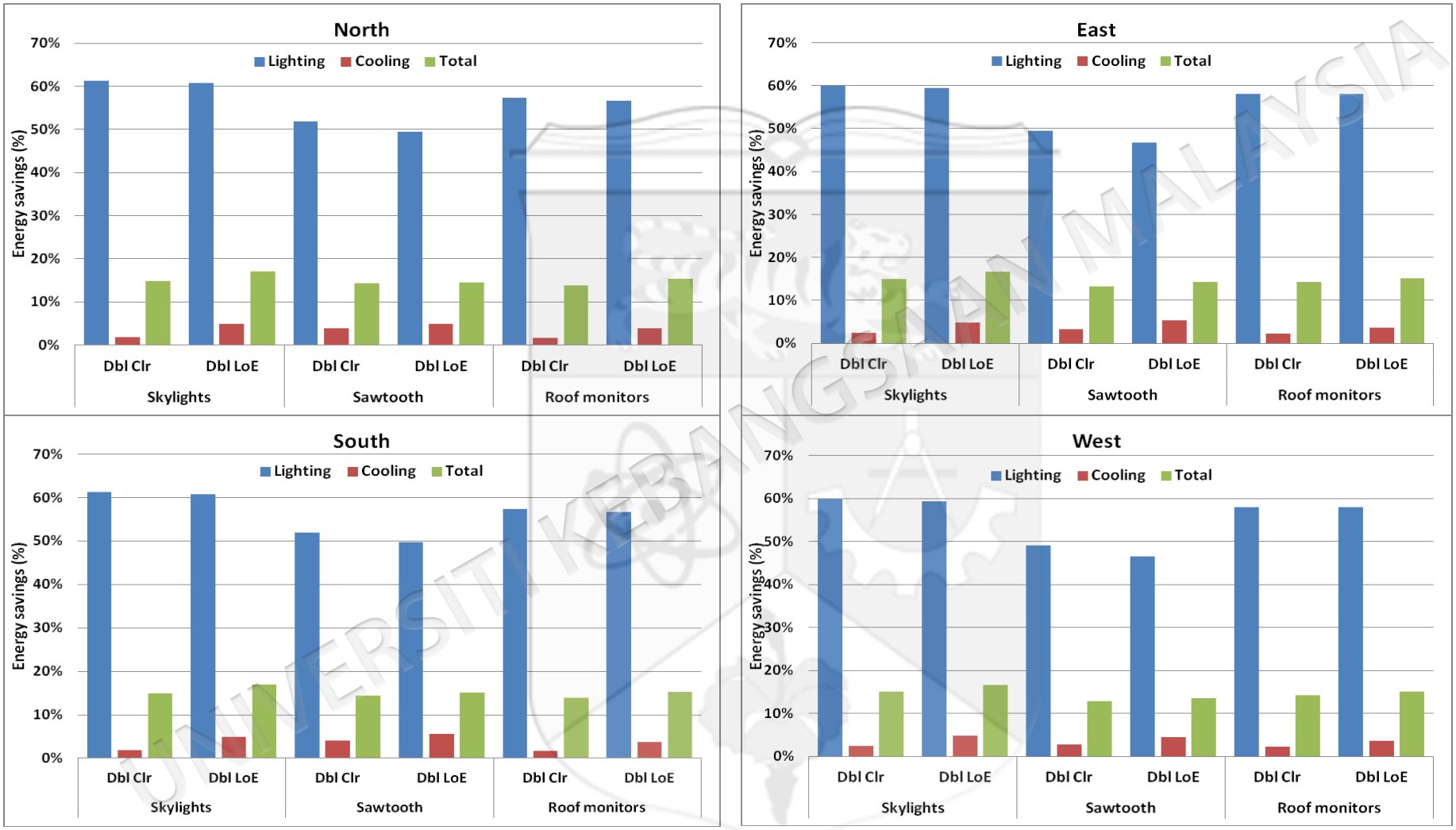

Figure 4.76 Lighting, cooling, and total energy savings for skylight, sawtooth, and roof monitor cases with better performance glazing (double clear and double low-e) and 5% TFR across all orientations compared with base case model

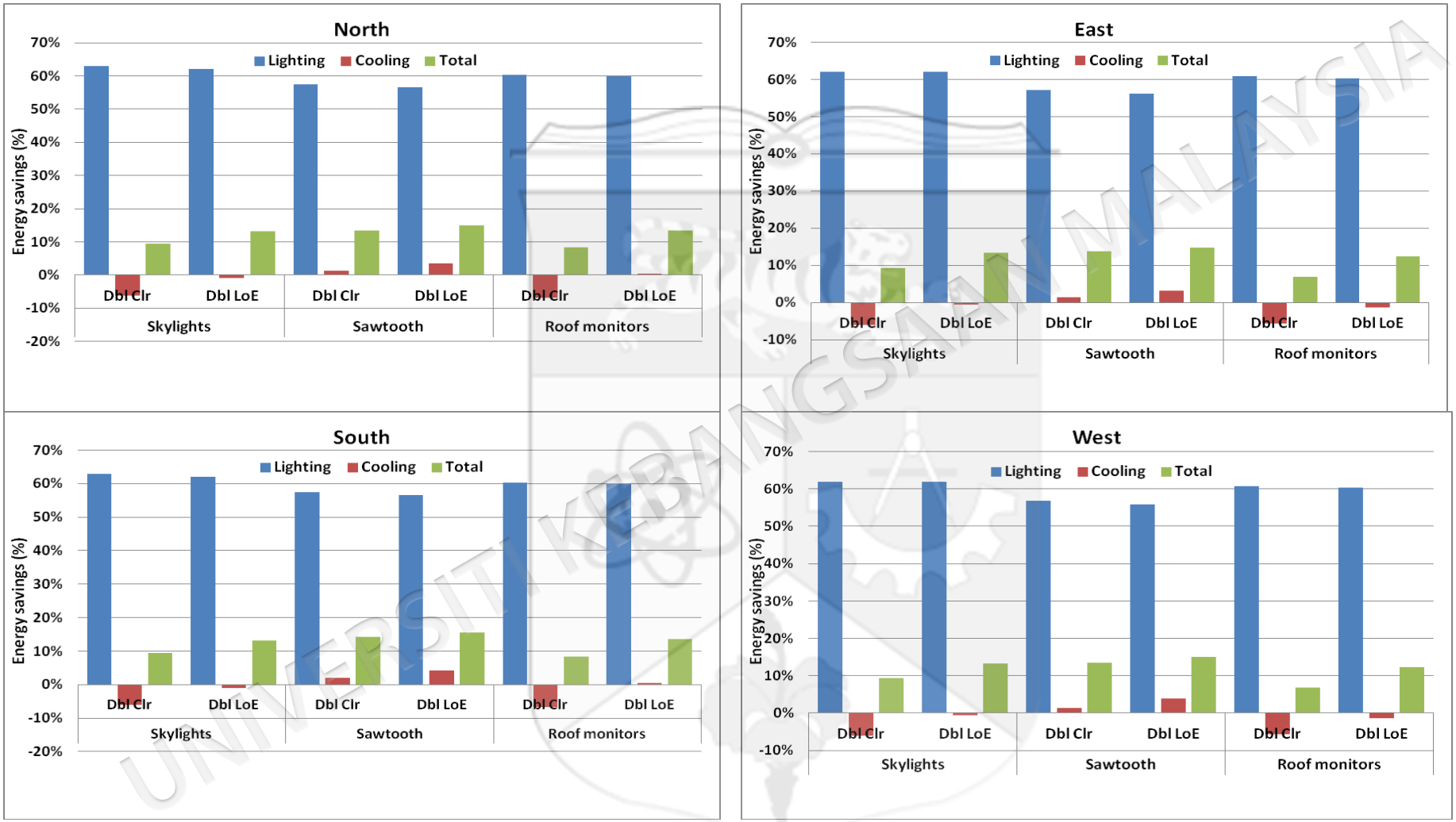

Figure 4.77 Lighting, cooling, and total energy savings for skylight, sawtooth, and roof monitor cases with better performance glazing (double clear and double low-e) and 10% TFR across all orientations as compared with base case model

4.2.8 Toplighting Alternatives Analysis: 1 to 1.5 Spacing-to-Height Ratio

The energy savings of each toplighting alternative with 1-to-1.5 spacing-to-height ratio is tested using OpenStudio with EnergyPlus simulation software following the methodology described in Chapter 3. The plan and perspective of each toplighting alternative is presented in Chapter 3 (Figure 3.12). Each toplighting alternative with 1-to-1.5 spacing-to-height ratio comprises 6 units.

This part of the study focuses on the total lighting, cooling, and total energy savings (L, C, T) of the case study building with three different toplighting systems as compared with the calibrated base case computer model with long sides of these toplighting exposures facing north, south, east, and west (N, S, E, and W). The goal is to determine the effect of these daylighting systems on the energy savings of the case study building with four different types of glasses, such as the single clear-Sgl Clr type (Tvis=0.88/ U=5.778/ SHGC=0.819), double clear-Dbl Clr type (Tvis=0.78/ U=2.67/ SHGC=0.703), double reflect clear-Dbl Ref type (Tvis=0.308/ U=2.65/ SHGC=0.426), and double low-e clear-Dbl LoE type (Tvis=0.68/ U=1.626/ SHGC=0.421) with a TFR of 5% to 60%. The base case model is the case without daylighting control systems, which are normally used in energy comparisons with the suggested toplighting simulations cases. All simulation test cases are analyzed based only on the state climate of Kuala Lumpur. The base case computer model is the case without daylighting alternatives, which is commonly used in building simulations during the early stage of design.

4.2.8.1 Comparison of Lighting Energy Savings

Table 4.19 reports the effect of toplighting alternatives on annual total lighting energy savings and their energy savings relative to the base case model without daylighting strategies. The detailed annual total lighting energy savings of the toplighting alternative cases with a TFR of 5% to 60% across all orientations are presented in Table A-14 of Appendix A.

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The calibrated base case model without daylighting strategy and daylighting control considered as the reference base case model for all future simulations comparisons. The base case model was then modified to include toplighting systems and daylighting control and was simulated again to determine the effect of all toplighting alternatives cases on the energy savings and daylight quality in EnergyPlus. Toplighting alternatives generally perform better than the base case model without daylighting strategies and daylighting control. The simulated results also indicate that energy savings mainly result from the highest percentage of lighting, generally the skylight alternative, across all glazing types, orientations, and TFRs. The annual energy saving is highest when no artificial lighting is used for the entire year (8:00 am until 6:00 pm) and only daylight is used. As the lighting power density is 13.56 W/m^2 and the required illuminance level is 500 lux, the highest annual total lighting energy savings occurred in skylight cases with an eastward–westward orientation range from 54% to 64% for Kuala Lumpur climate.

A roof monitor with a northward–southward orientation results in the second highest annual total lighting energy savings, whereas the sawtooth toplighting option leads to the lowest total lighting energy savings in all orientations.

Based on the results, only negligible differences exist in the total lighting energy savings of the toplighting glazed areas, whereas significant differences are reported for the glazing types.

Figure 4.78 presents the results of toplighting with different glazed types and TFRs for the cases with a northward orientation. The results show that the glazed type has a high light transmittance (e.g., 0.88 for the single clear glazed type and 0.78 for the double clear glazed type), which results in the highest annual lighting energy savings of approximately 59.4% to 64.5% and stays constant when the TFR is increased from 25% to 60%. By contrast, when the glazed type with a low visible light transmittance (0.308 for the double reflect clear glazed type) is used, the lighting energy saving increases when TFR ratio increases.

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The results also show that when the visible light transmittance is high, even if the TFR is 15%, the illuminance level at the work plan is often greater than 500 lux because of daylight alone, and the artificial lighting is not used at all. Therefore, when the TFR is increased, annual lighting energy saving does not increase. Conversely, when the light transmittance of the glass type is low, the illuminance level at the work plan is less than 500 lux because of daylight alone, and the illuminance level increases as the TFR increases.

Figure 4.79 shows the effect of toplighting orientation on the total annual lighting energy savings. Only the simulation results of the 5% TFR case are presented. The results of the other TFR are reported in Tables 4.5 and A-14. As the figure shows, when the single clear glazed type (Tvis. high = 0.88) is used, annual lighting energy saving is slightly different in all orientations and depends on the toplighting shape. This finding is a result of more daylight entering through these glazed types, which is adequate to keep the lighting level at the work plan at 500 lux. When the double reflect clear-Dbl Ref type (Tvis. too low = 0.308) is used, annual lighting energy saving is smallest (27.3%) in the northward orientation for the sawtooth option. Annual lighting energy saving is at its maximum in the other three orientations (greater than 50%) for both skylight and roof monitor options.

This finding is a result of the lower level of daylight from the north glazed orientation compared with that from the three other orientations. When the double low-e clear glazed type (Tvis. intermediate = 0.68) is used, the lighting energy saving is at its maximum in the southward orientation for the sawtooth option (48.5%), whereas it is at its minimum in the westward orientation (45%). Annual lighting energy savings for both northward and eastward orientations remains the same at approximately 46%. This finding is a result of more reflected daylight entering from the sawtooth glazed type with a southward orientation as compared with other sawtooth orientations. When the toplighting system is oriented north, a smaller amount of reflected daylight enters through the glazed toplighting and results in relatively less lighting energy savings. In addition, the level of daylight entering the toplighting with a southward orientation is higher relative to that with a northward orientation.

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Table 4.19 Comparison of annual total lighting energy savings (%) of different skylights, sawtooth, and roof monitor cases with different glazing types, orientations, and TFR of 5% to 20% versus base case model with 1-to-1.5 spacing-to-height ratio.

TFR (%)		North				South				East				West			
		Sgl Clr	Dbl Clr	Dbl LoE	Dbl Ref	Sgl Clr	Dbl Clr	Dbl LoE	Dbl Ref	Sgl Clr	Dbl Clr	Dbl LoE	Dbl Ref	Sgl Clr	Dbl Clr	Dbl LoE	Dbl Ref
Skylights	**5%**	60.0	59.4	58.8	54.0	60.0	59.4	58.8	54.0	60.1	59.5	58.9	54.0	60.1	59.5	58.9	54.0
	10%	62.0	61.7	61.2	58.2	62.0	61.7	61.2	58.2	62.1	61.7	61.3	58.3	62.1	61.7	61.3	58.3
	15%	62.7	62.4	62.2	59.9	62.7	62.4	62.2	59.9	62.7	62.5	62.2	60.0	62.7	62.5	62.2	60.0
	20%	63.1	62.9	62.7	60.9	63.1	62.9	62.7	60.9	63.2	62.9	62.7	60.9	63.2	62.9	62.7	60.9
Sawtooth	**5%**	52.9	50.7	48.0	26.3	53.0	51.0	48.5	29.2	51.5	48.7	46.0	28.2	51.0	48.3	45.6	28.3
	10%	58.3	57.3	56.5	47.3	58.3	57.4	56.5	48.0	56.9	55.7	54.5	41.7	56.6	55.2	54.0	41.2
	15%	60.0	59.4	58.7	53.5	60.0	59.4	58.7	53.7	59.8	59.1	58.5	52.8	60.0	59.2	58.5	52.2
	20%	60.9	60.4	59.9	55.8	60.9	60.4	59.9	55.8	60.8	60.2	59.7	55.4	61.0	60.4	59.9	55.0
Roof Monitor	**5%**	57.8	56.9	56.1	48.6	57.8	56.9	56.1	48.6	57.8	56.9	56.0	48.6	57.8	56.9	56.0	48.6
	10%	60.8	60.3	59.8	55.8	60.8	60.3	59.8	55.8	60.2	59.6	59.1	54.7	60.2	59.6	59.1	54.7
	15%	61.9	61.5	61.1	58.1	61.9	61.5	61.1	58.1	61.9	61.6	61.1	58.3	61.9	61.6	61.1	58.3
	20%	62.4	62.1	61.8	59.4	62.4	62.1	61.8	59.4	62.4	62.1	61.8	59.5	62.4	62.1	61.8	59.5

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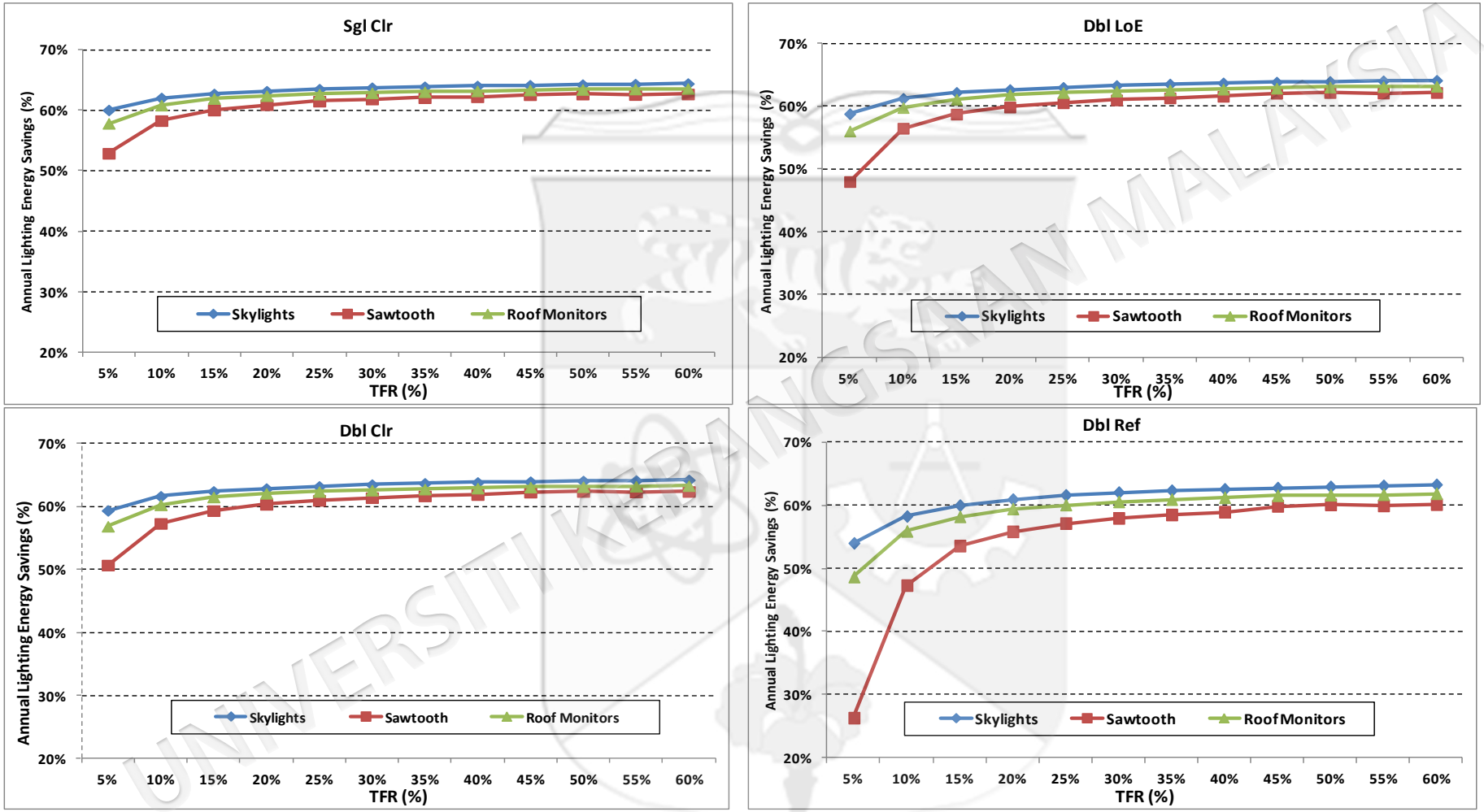

Figure 4.78 Comparison of annual total lighting energy savings (%) of toplighting cases with different glazing types, different glazed area (TFR), and northward orientation versus base case model with 1-to-1.5 spacing-to-height ratio

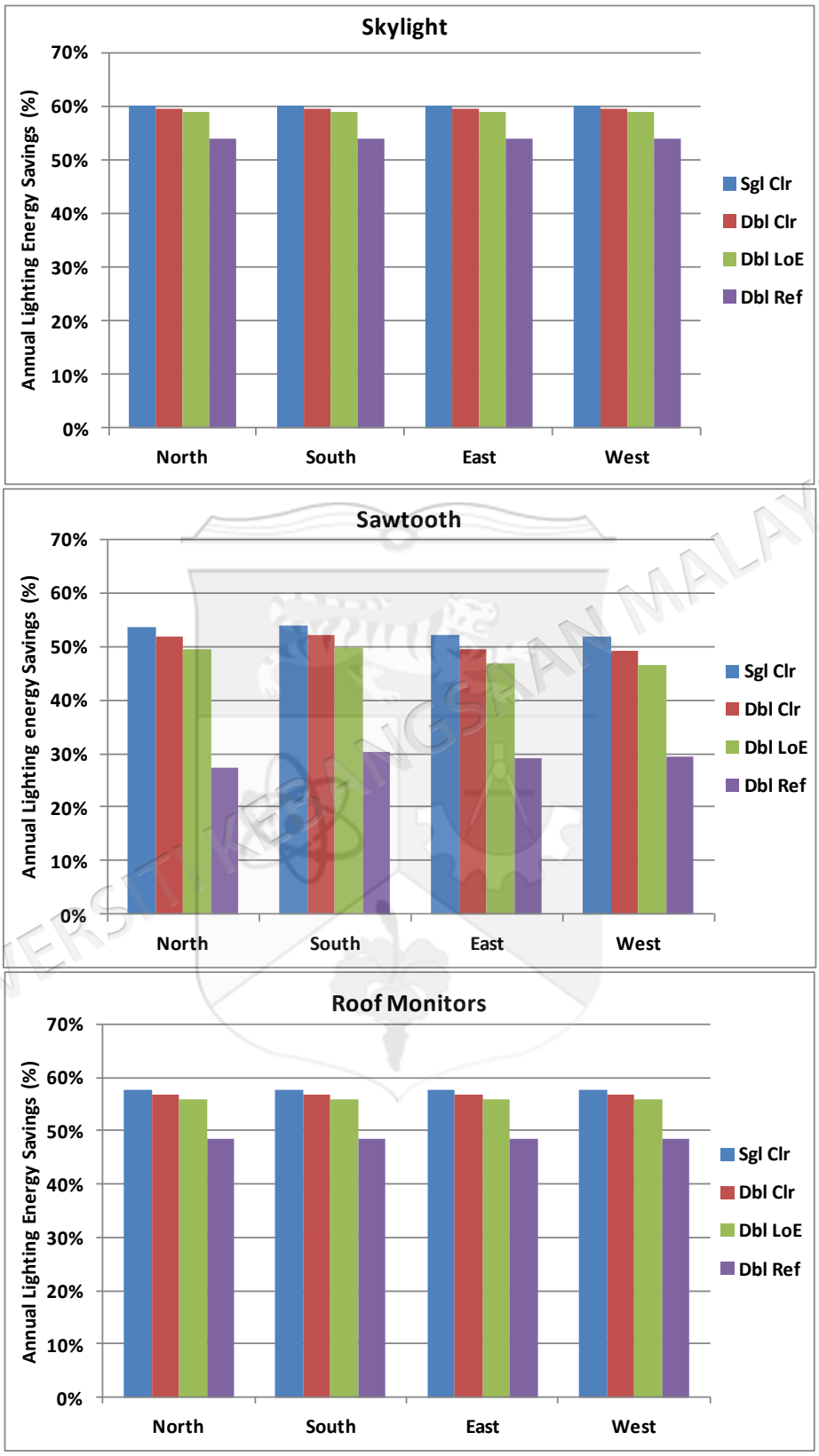

Figure 4.79 Impact of toplighting orientation on the total annual lighting energy savings of 5%TFR case.

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4.2.8.2 Comparison of Total Energy Savings

Space cooling energy consumption considers the largest portion of building energy use in the context of a tropical climate such as Malaysia's. The percentage of space total lighting (L), cooling (C), and total (T) energy savings for Kuala Lumpur is tested throughout the four main orientations with a TFR range of 5% to 60%.

To determine the effect of toplighting designs on total energy savings, daylighting integrated with artificial lighting through automatic lighting control systems are simulated. Toplighting cases with the standard single clear type (Tvis=0.88/ U=5.778/ SHGC=0.819), double clear type (Tvis=0.78/ U=2.67/ SHGC=0.703), double reflect clear type (Tvis=0.308/ U=2.65/ SHGC=0.426), and double low-e clear type (Tvis=0.68/ U=1.626/ SHGC=0.421) are applied in an existing building with a TFR ranging from 5% to 60%.

Tables 4.20 to 4.21 and Figures 4.80 to 4.81 report the effect of skylight, sawtooth, and roof monitor geometry with a TFR of 5% and 10% on total energy savings per percentage (%) and their energy saving (positive or negative) relative to the base case computer model without daylighting strategies. A negative percentage value represents an increase in the energy consumed. The detailed results of total energy savings with a TFR range from 15% to 60% are presented in Tables A-16 to A-18 of Appendix A.

The simulation results show that when toplighting alternatives with a 1-to-1.5 spacing-to-height ratio are applied to an existing building (base case model), sawtooth cases contribute more to the total energy savings than the skylight and roof monitor cases because TFRs are increased across all glazing types and orientations. Roof monitor cases show the second highest energy savings followed by the skylight cases because of the higher glazed area exposed to intense solar radiation, thereby resulting in lower total energy savings results from introduces solar heat gains that increase cooling loads associated with the toplighting systems.

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In sawtooth cases, a TFR of 10% and a southward orientation yield the highest total annual energy savings. The skylight and roof alternatives present lower energy savings across all TFRs and orientations. However, a 5% TFR for the skylight and roof monitor options with a double low-e clear glazed type yields an increase in the total energy savings compared with the base case model without daylighting strategies.

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Table 4.27 Comparison of total energy savings (%) from the various toplighting options with different glazing types in all orientations and 5%TFR versus base case model. A negative value represents an increase in amount of the energy consumed.

TFR **5%**		North				South				East				West			
		Sgl	Dbl	LoE	Ref	Sgl	Dbl	LoE	Ref	Sgl	Dbl	LoE	Ref	Sgl	Dbl	LoE	Ref
Skylight	Lighting	60%	59%	59%	54%	60%	59%	59%	54%	60%	59%	59%	54%	60%	59%	59%	54%
	Cooling	-0.6%	1.9%	4.7%	3.6%	-0.6%	1.9%	4.7%	3.6%	-0.3%	2.5%	4.6%	4.1%	-0.3%	2.5%	4.6%	4.1%
	Total	**13%**	**14%**	**16%**	**15%**	**13%**	**14%**	**16%**	**15%**	**13%**	**15%**	**16%**	**15%**	**13%**	**15%**	**16%**	**15%**
Sawtooth	Lighting	53%	51%	48%	26%	53%	51%	49%	29%	52%	49%	46%	28%	51%	48%	46%	28%
	Cooling	4.0%	3.9%	5.5%	1.8%	4.3%	4.6%	5.6%	0.9%	2.8%	3.0%	5.2%	1.9%	3.1%	2.6%	4.1%	1.1%
	Total	**15%**	**14%**	**15%**	**7.1%**	**15%**	**15%**	**15%**	**7.1%**	**13%**	**13%**	**14%**	**7.6%**	**13%**	**13%**	**13%**	**7.1%**
Roof Monitor	Lighting	58%	57%	56%	49%	58%	57%	56%	49%	58%	57%	56%	49%	58%	57%	56%	49%
	Cooling	2.1%	3.0%	4.3%	3.2%	2.1%	3.0%	4.3%	3.2%	1.1%	2.1%	3.4%	1.9%	1.1%	2.1%	3.4%	1.9%
	Total	**14%**	**15%**	**16%**	**13%**	**14%**	**15%**	**16%**	**13%**	**14%**	**14%**	**15%**	**12%**	**14%**	**14%**	**15%**	**12%**

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Table 4.21 Comparison of total energy savings (%) from the various toplighting options with different glazing types in all orientations and 10%TFR versus base case model. A negative value represents an increase in amount of the energy consumed.

TFR **10%**		North				South				East				West			
		Sgl	Dbl	LoE	Ref	Sgl	Dbl	LoE	Ref	Sgl	Dbl	LoE	Ref	Sgl	Dbl	LoE	Ref
Skylight	Lighting	62%	62%	61%	58%	62%	62%	61%	58%	62%	62%	61%	58%	62%	62%	61%	58%
	Cooling	-6.9%	-6.2%	-1.1%	-1.8%	-6.9%	-6.2%	-1.1%	-1.8%	-6.9%	-6.0%	-0.5%	-1.2%	-6.9%	-6.0%	-0.5%	-1.2%
	Total	**8.6%**	**9.1%**	**13%**	**12%**	**8.6%**	**9.1%**	**13%**	**12%**	**8.7%**	**9.3%**	**13%**	**12%**	**8.7%**	**9.3%**	**13%**	**12%**
Sawtooth	Lighting	58%	57%	56%	47%	58%	57%	57%	48%	57%	56%	54%	42%	57%	55%	54%	41%
	Cooling	0.5%	1.9%	3.7%	2.6%	1.2%	2.6%	4.5%	1.6%	1.4%	2.0%	3.4%	2.0%	1.1%	2.6%	4.2%	0.9%
	Total	**13%**	**14%**	**15%**	**12%**	**14%**	**15%**	**16%**	**12%**	**14%**	**14%**	**15%**	**11%**	**13%**	**14%**	**15%**	**10%**
Roof Monitor	Lighting	61%	60%	60%	56%	61%	60%	60%	56%	60%	60%	59%	55%	60%	60%	59%	55%
	Cooling	-7.7%	-5.9%	1.6%	-0.9%	-7.7%	-5.9%	1.6%	-0.9%	-7.3%	-4.6%	1.8%	0.1%	-7.3%	-4.6%	1.8%	0.1%
	Total	**7.9%**	**9.0%**	**14%**	**12%**	**7.9%**	**9.0%**	**14%**	**12%**	**8.0%**	**10%**	**14%**	**12%**	**8.0%**	**9.8%**	**14%**	**12%**

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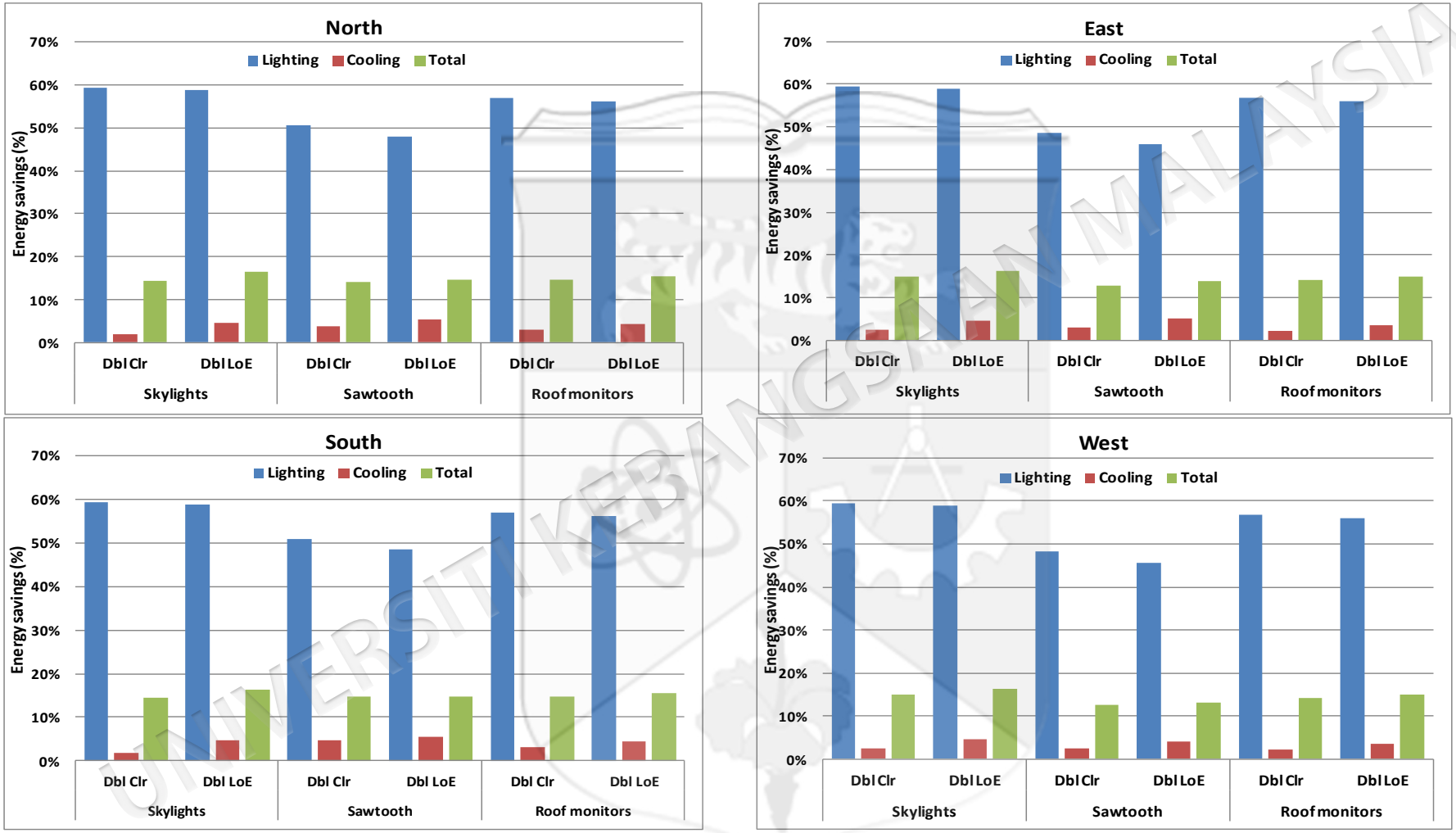

Figure 4.80 Lighting, cooling, and total energy savings from skylight, sawtooth, and roof monitor cases with better performance glazing (double clear and double low-e) and 5%TFR across all orientations versus base case model

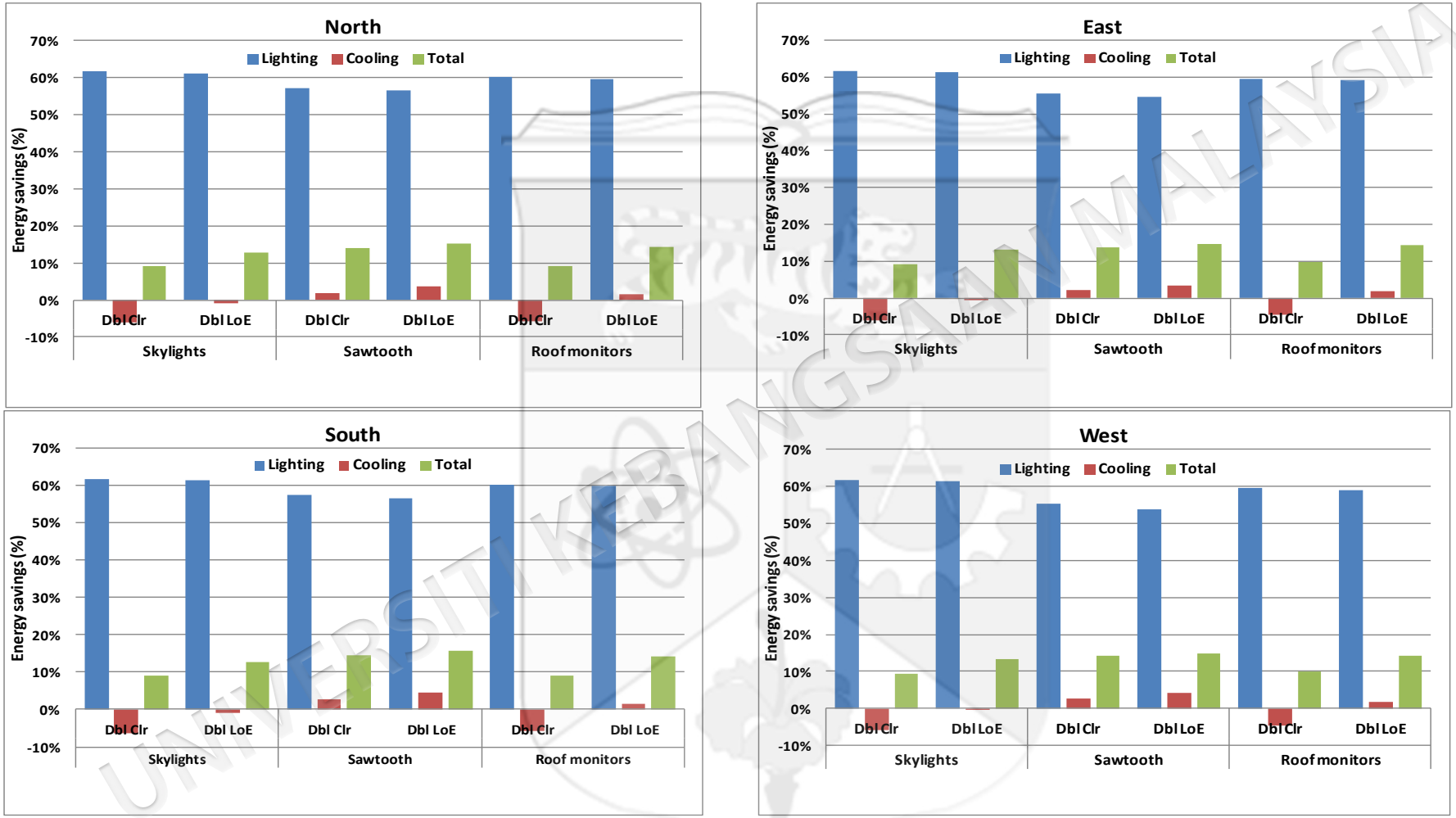

Figure 4.81 Lighting, cooling, and total energy savings from skylight, sawtooth, and roof monitor cases with better performance glazing (double clear and double low-e) and 10%TFR across all orientations versus base case model

The double low-e clear glass type yields higher total energy savings than the single clear, double clear, and double reflect clear types. This difference is a result of an increase in the cooling energy required when using the latter three glazing types with a high U-value and SHGC and the higher cooling energy generally required in the tropical climate of Kuala Lumpur.

The highest total annual energy savings (bold values in Tables 4.7 and 4.8) are compared with the base case model when toplighting alternatives are used in a tropical climate.

The skylight cases with 1-to-1.5 spacing-to-height ratios yield annual total energy savings ranging from 6% to 16%, which is lower than that obtained in skylight alternatives with 1-to-1 spacing-to-height ratio across different glazing types and orientations. However, in some cases of the skylight alternative with a double low-e clear glazed type and 5% TFR, the total energy savings can reach as much as 16.4%.

The sawtooth cases with a 1-to-1.5 spacing-to-height ratio yield total energy savings ranging from 3% to 15.7%. This yield is in general slightly higher than the values of the sawtooth option with a 1-to-1 spacing-to-height ratio, which range from 3% to 15.6%. Such a difference indicates that a 1-to-1.5 spacing-to-height ratio yields better total energy savings than a 1-to-1 spacing-to-height ratio. The simulated results indicate that for the sawtooth alternative, a reduction of the spacing-to-height ratio to 1-to-1 could help decrease slightly the total energy savings that accrues in the 1-to-1.5 sawtooth case by narrowing down the total energy savings of the 1-to-1 spacing-to-height into a range from 9% to 15.7%. By contrast, in the 1-to-1.5 spacing-to-height ratio, the total energy savings ranges from 7.7% to 15.6% for all three cases with a 5% to 15% TFR across all types and orientations.

The roof monitor cases with a 1-to-1.5 spacing-to-height ratio yield total energy savings ranging from 3% to 15.5%. This yield is in general slightly higher than that generated in roof monitor cases with a 1-to-1 spacing-to-height ratio, which ranges from 3% to 15.3%. Such a difference indicates that a 1-to-1.5 spacing-to-height ratio generates higher total energy savings than a 1-to-1 spacing-to-height ratio.

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Given a higher TFR (i.e., TFR=60%), the sawtooth base case yields total energy savings ranging from 3% to 5.4%, skylight cases yield 6.2% to 7.1%, and roof monitor cases yield 2.3% to 4% across all glazing types and orientations. Given a lower TFR (i.e., TFR=5%), the sawtooth base case yields total energy savings ranging from 7% to 15.2%, skylight cases yield 12.8% to 16.4%, and roof monitor cases yield 12% to 15.5% across all glazing types and orientations. The impact of toplighting use is proportional to the TFRs in all orientations. Thus, toplighting strategies do not show significant energy savings as TFRs increase from 25% to 60% regardless of their orientations and glazing types.

The results also demonstrate that the savings mainly come from lighting energy savings. By contrast, the cooling energy is reduced with the application of the double low-e clear toplighting glazing. Other toplighting glazing types with a TFR of more than 15% save only a negligible amount of cooling energy and increases and decreases cooling energy consumption as the TFR increases.

For a city such as Kuala Lumpur, where no heating period occurs for most of the year, cooling energy is required throughout the entire year. The results indicate that sawtooth cases provide the highest cooling energy savings throughout the year. Furthermore, the results show that toplighting strategy can be efficiently used in academic buildings in tropical climates if proper design considerations are made.

4.2.9 Economic Analysis

4.2.9.1 Energy Savings Potential from Alternatives Toplighting Designs

The energy performance of buildings varies significantly and depends on toplighting designs, glazing area, type of glazing, and toplighting orientation. Figures 4.82 to 4.84 show the lighting, cooling, and total energy savings for all skylight, sawtooth, and roof monitor cases.

As the figures show, the 5% skylight case, the 5% to 20% sawtooth cases, and the 5% and 10% roof monitor cases, all of which were equipped with a double low-e

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glazing type, yielded only a certain level of cooling energy savings. All the other cases yielded an increase in the energy required as a result of space cooling. The highest lighting energy savings were at 64.4% for the 60% skylight glazing case with a single clear glass type, followed closely by the 63.2% savings for the 60% roof monitor case and the 63.1% savings for the 60% sawtooth glazing case. These three skylight, roof monitor, and sawtooth cases exhibited the worst performance in terms of cooling energy savings. The sawtooth cases performed better than the skylight and roof monitor cases in terms of cooling energy savings, with at least three TFRs exhibiting positive cooling energy savings across all glazing types and orientations. The total annual energy savings was the best in the 5% skylight glazing case, the 10% sawtooth glazing case, and the 5% roof monitor glazing case, yielding values at 17%, 15.6%, and 15.3%, respectively.

The figures also indicate the percentage of energy savings for all the suggested skylight, sawtooth, and roof monitor cases. Among the skylight cases, the case with a 5% TFR and double low-e clear glazing type performed best in terms of total energy savings. Among the sawtooth cases, the case with a 10% TFR and double low-e clear glazing type performed best in terms of total energy savings. Among the roof monitor cases, the case with a 5% TFR case performed best. In general, all the suggested skylight, sawtooth, and roof monitor cases exhibited better performance in terms of total energy savings than the base case model without daylighting strategy.

Figures 4.82 to 4.84 show the performance of all the suggested skylight, sawtooth, and roof monitor cases, starting with the case with a 5% TFR to that with a 60% TFR in the individual categories of lighting energy, cooling energy, and total annual energy savings. As the figures show, the 5% TFR sawtooth case with a double low-e clear glazing type performed best in cooling energy savings, whereas the 60% TFR roof monitor glazing case was the least efficient. The 60% TFR skylight case showed the best performance in lighting energy savings, whereas the 5% TFR sawtooth case with a double reflect clear glazed type was the least efficient in lighting energy savings. The 5% skylight glazing case performed best in total annual energy savings, whereas the 60% TFR roof monitor case with a double clear glazed type was the last efficient in total energy savings.

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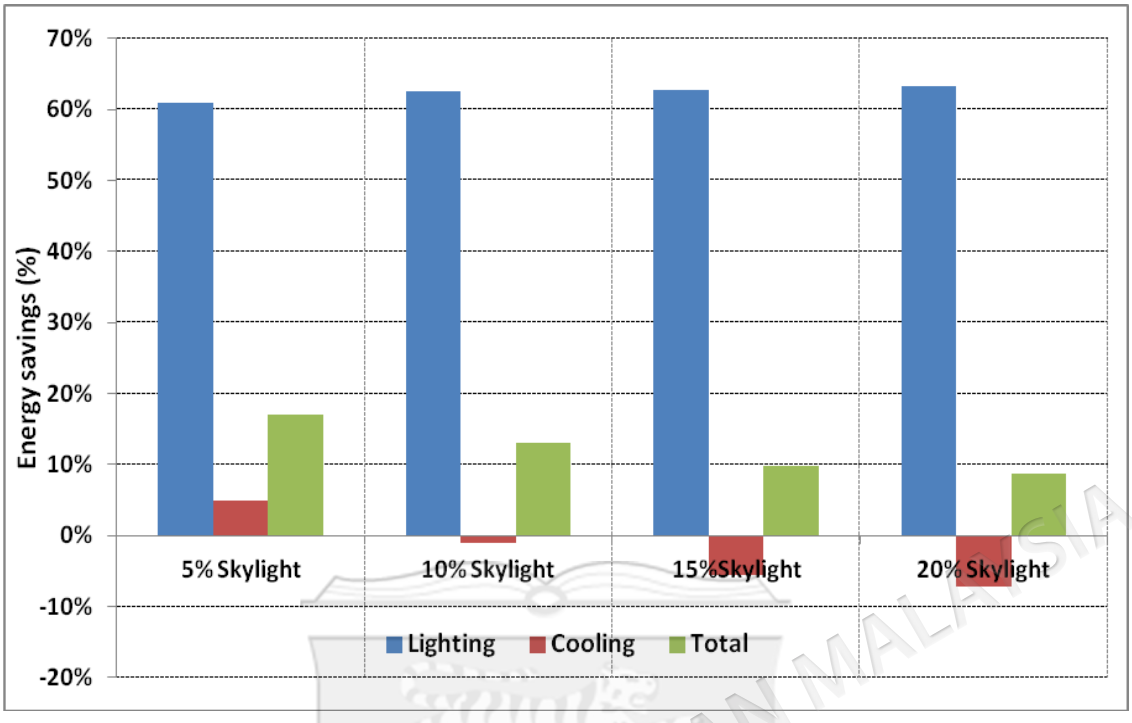

Figure 4.82 Lighting, cooling, and total energy savings for the suggested skylight cases with better performance yielded by the glazing double low-e clear type and northward orientation

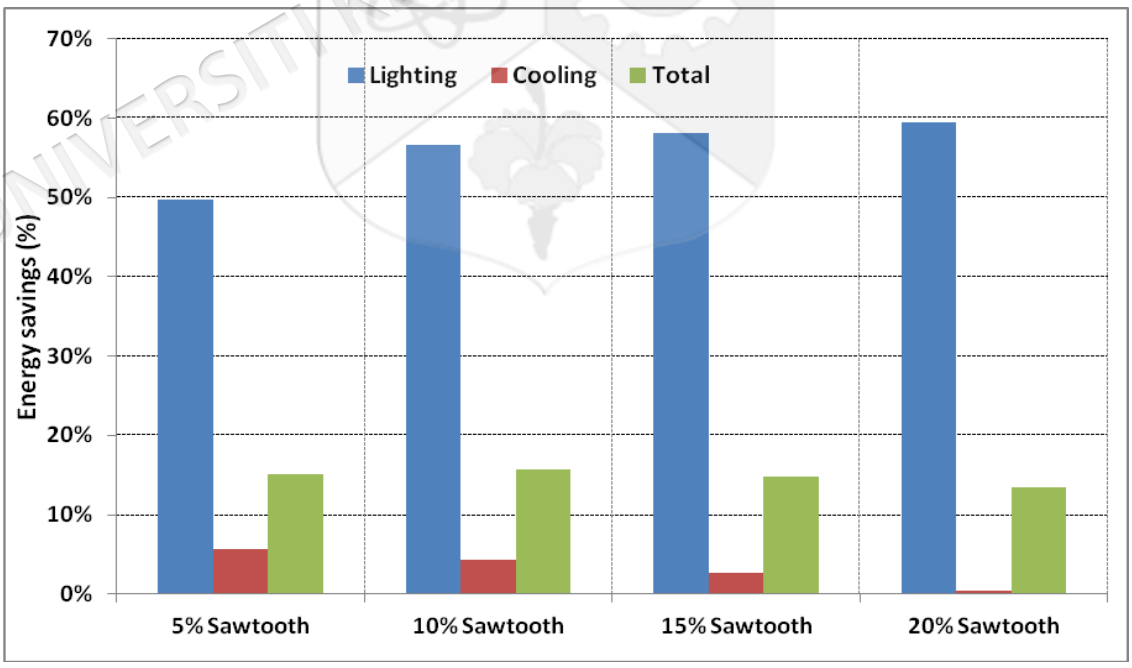

Figure 4.83 Lighting, cooling, and total energy savings for the suggested sawtooth cases with better performance yielded by the glazing double low-e clear type and southward orientation

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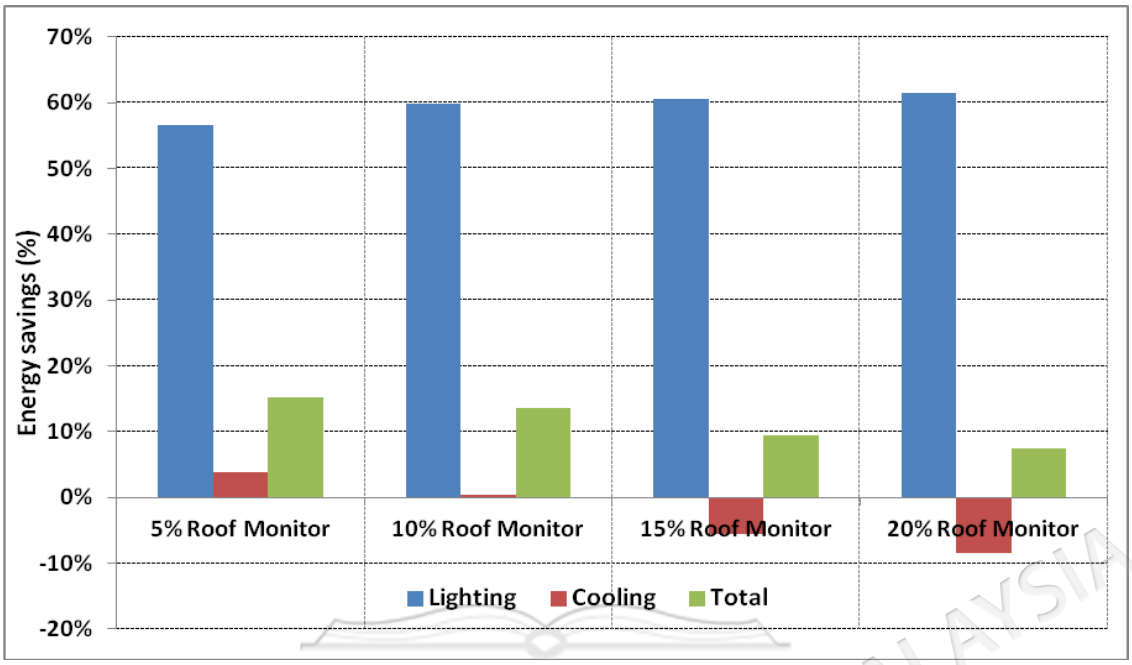

Figure 4.84 Lighting, cooling, and total energy savings for the suggested roof monitor cases with better performance yielded by the glazing double low-e clear type and southward orientation

4.2.9.2 Energy Cost Savings Potential from Toplighting Designs

In general, all the proposed skylight, sawtooth, and roof monitor cases were analyzed for their individual energy cost savings relative to the base case model without daylighting strategy. Figures 4.85 to 87 present the total annual energy and energy cost savings of all the suggested skylight, sawtooth, and roof monitor cases. The energy and energy cost savings are classified into end use lighting, cooling, and total energy savings, that is, the savings obtained over the lighting energy, cooling energy, and total energy consumption. Among all of the suggested skylight cases, the 5% skylight glazing area exhibits the highest annual energy cost savings. Among all of the suggested sawtooth cases, the 10% sawtooth glazing area shows the highest annual energy cost savings. Among all of the suggested roof monitor cases, the 5% roof monitor glazing area shows the highest annual energy cost savings. The Malaysian energy cost of the energy consumption for all the cases is calculated to be RM 0.288 per kWh, the computation of which is presented in the following tables. This result was obtained based on utility bills and official electricity rates published on the

Tenaga Nasional Berhad website for commercial tariffs for offices, universities, shops, restaurants, and hotels.

The detailed results of the total annual energy and energy cost savings for all of the suggested skylight, sawtooth, and roof monitor cases are shown in Tables A-20 to A-22 of Appendix A.

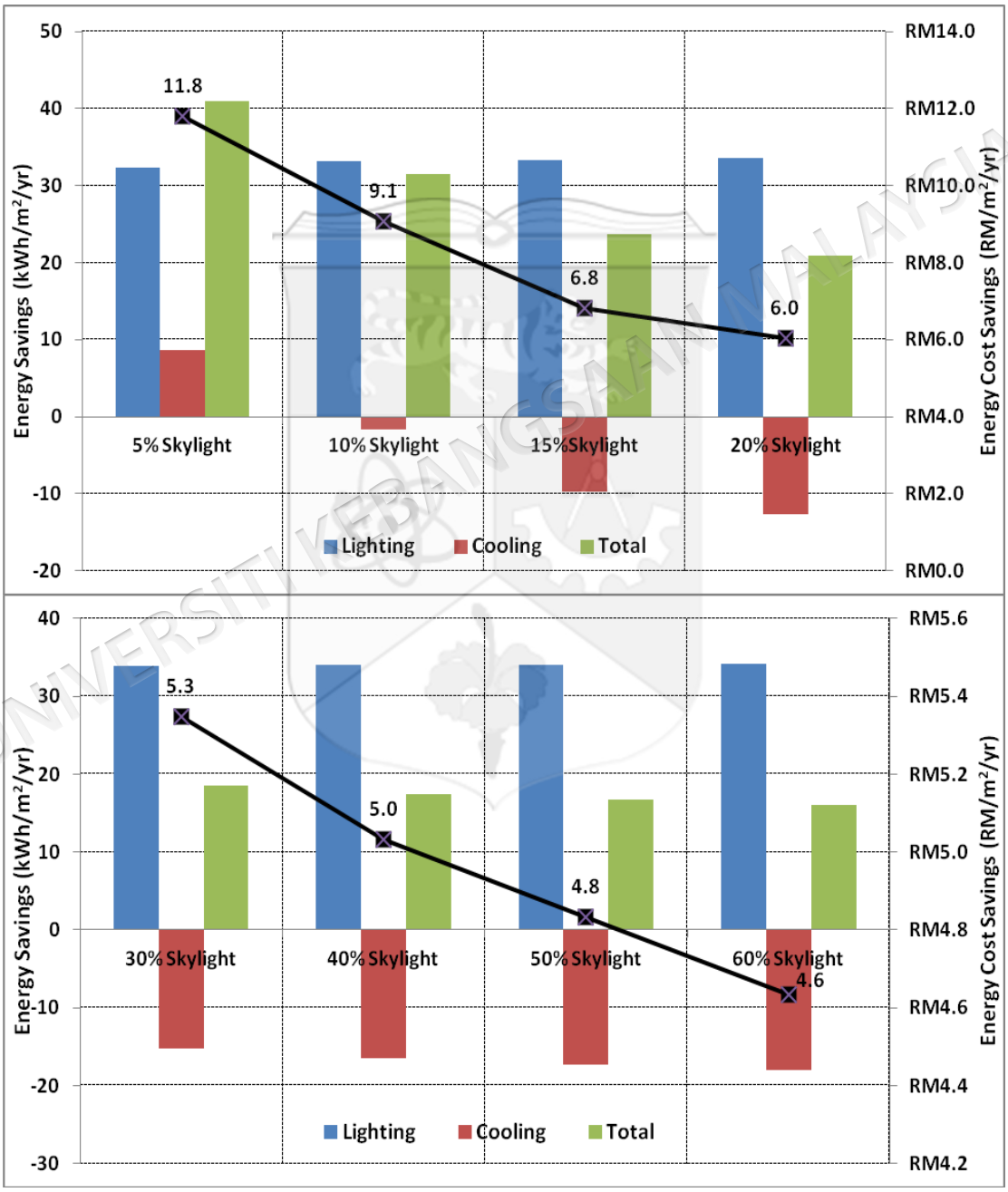

Figure 4.85 Total annual energy and energy cost savings by end use (lighting, cooling, and total) for suggested skylight cases

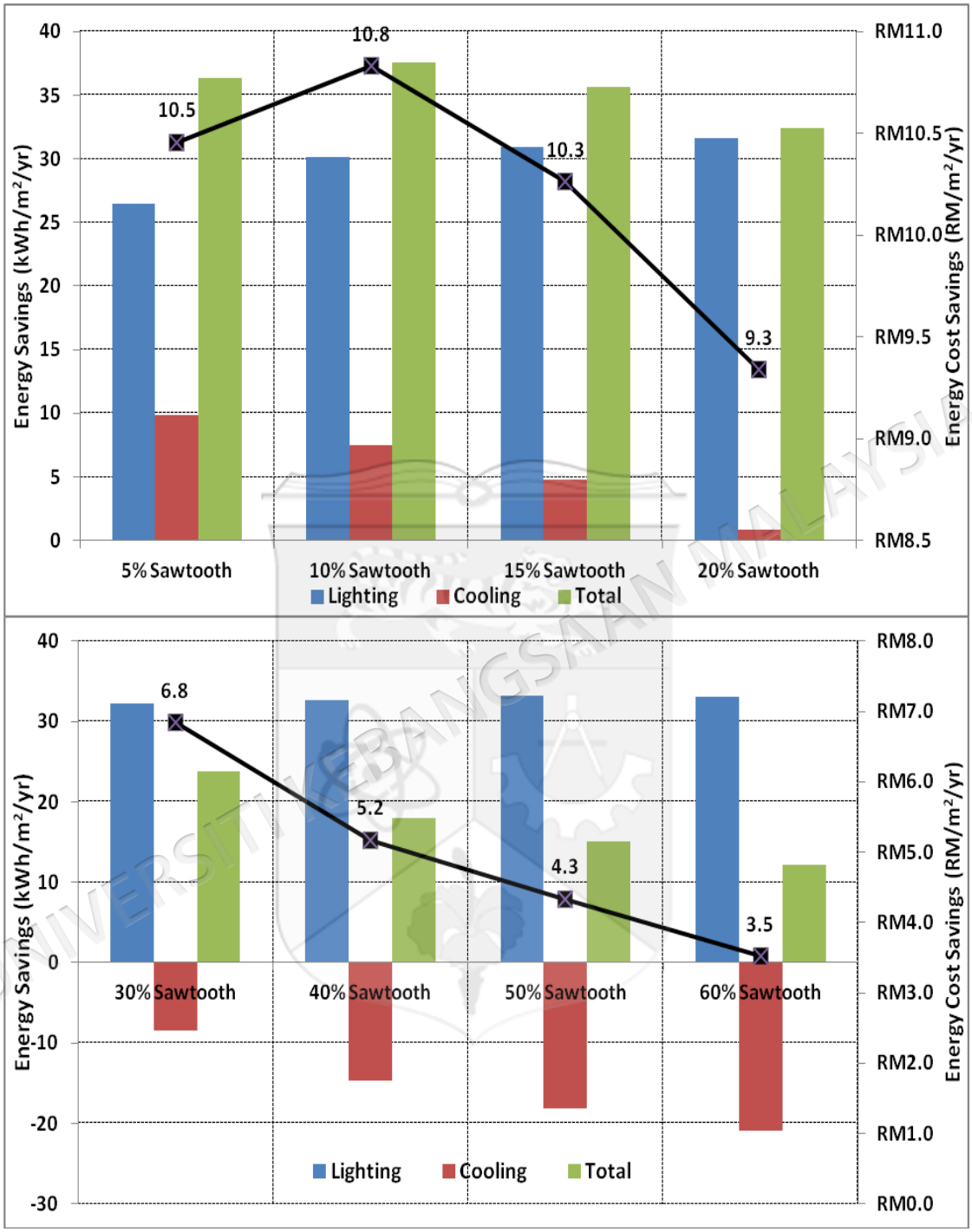

Figure 4.86 Total annual energy and energy cost savings by end use (lighting, cooling, and total) for suggested sawtooth cases

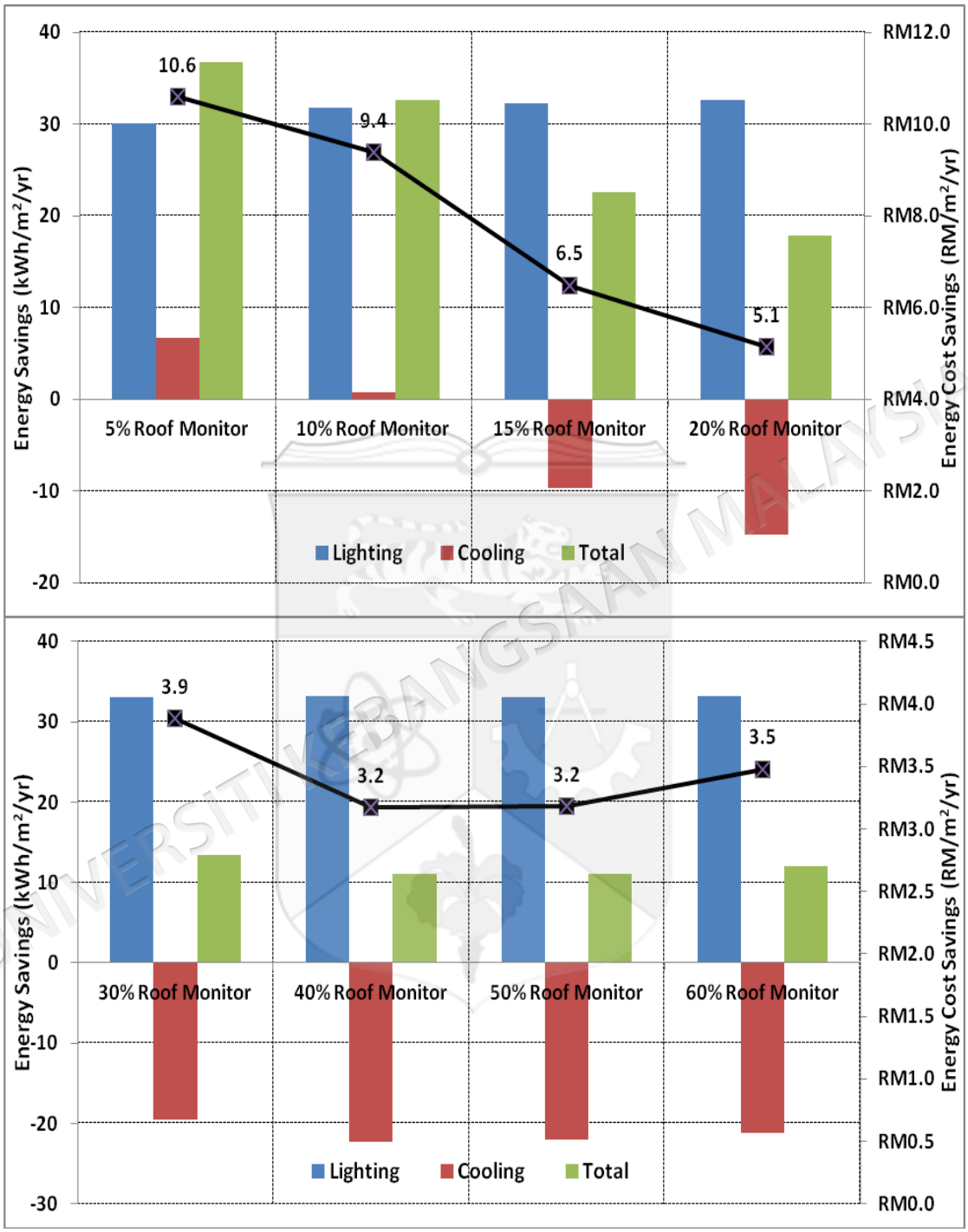

Figure 4.87 Total annual energy and energy cost savings by end use (lighting, cooling, and total) for suggested roof monitor cases

4.2.9.3 National Energy and Cost Savings Potential across Malaysia

The energy and energy cost savings of the toplighting systems differ significantly depending on the climate and toplighting design of the building. To estimate the national energy and cost saving potential and the economic benefits of using the toplighting system across Malaysia, the sawtooth toplighting design with different TFRs and with the double low-e clear glazing type of the same case study building was evaluated. To assess the possibility of applying the results of this study to other locations, the weather data files for Kuching, George Town, Kuala Lumpur, and Kota Baharu were selected for comparison as they all have a tropical climate.

Due to cost and weather data availability in EnergyPlus weather file website, this study applied simulated weather data for four Malaysian cities, namely, Kuchang, George Town, Kuala Lumpur and Kota Bharu that represent most of the climatic and daylight utilization conditions in Malaysia. The results might not accurately reflect electric energy savings within other Malaysian regions because of climate and daylight availability differences. The Malaysian energy cost of the energy consumption for all the cases calculations was counted to be RM 0.288 per kWh. This information was obtained from utility bills and official electricity rates at the Tenaga Nasional Berhad (TNB) for commercial tariffs for offices, universities, shops, restaurants and hotels.

Figure 4.88 shows Effect of different climate conditions on total energy and energy cost savings for different sawtooth glazed areas for double Low-e clear glazed in south orientation using EnergyPlus simulation software. The justification on the selection of four locations, namely, Kuchang, George Town, Kuala Lumpur and Kota Bharu is provided in Chapter III Table 3.7. The Malaysian electricity rates were used to evaluate climate condition effects. The results showed that there is a similar trend for energy savings variations with TFRs for all weather data used with noticeable difference in the amount of energy savings. This difference is almost constant as the toplighting-to-roof ratio increases. For these four climate conditions considered with a low-e double glazed sawtooth, the total energy savings increases/decreases in the same pattern. The results also showed that in all the toplighting cases, the

increases/decreases in total energy savings is less than 3 kWh/m^2 yr Therefore, concern should be taken if the toplighting glazed area increased beyond 15%. This is due to the total energy savings from daylighting remains almost constant but solar heat gain inside the space increased resulting into increase the cooling load. The results also shows that for a given toplighting glazed area, glazing type and orientation, the climate condition has big effect on the total energy savings more than 15 kWh/m^2 yr.

It can be also observed that the maximum energy and energy cost saving is achieved for Kuching weather conditions. It is followed by Kota Baharu, Kuala Lumpur, and then by George Town. This can be explained as the availability of daylight varies according to the location of the city and its longitude and latitude and also the variation of sky conditions all around the year for each city. Similar results for the other main orientations are observed. Thus, the results for Kuala Lumpur city can be used for assessing the relative energy performance of toplighting when daylighting is integrated with artificial lighting for Kuching, Kota Baharu and George Town.

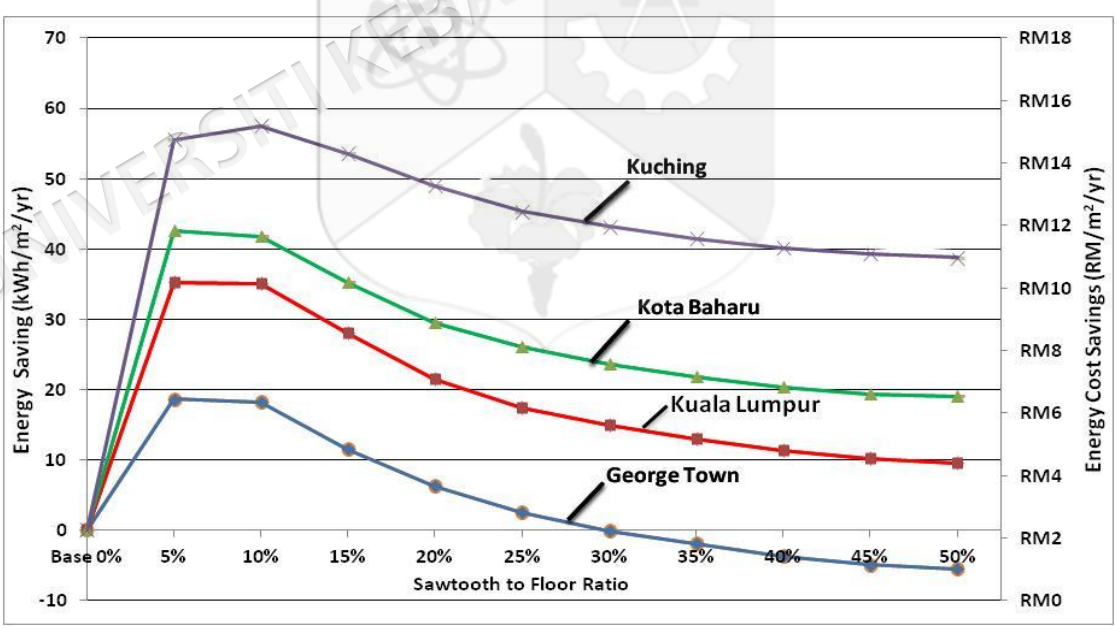

Figure 4.88 Effect of different climate conditions of four Malaysian cities on total energy and energy cost saving for the suggested sawtooth cases with better performance yielded by the glazing double low-e clear type. Orientation considered is South.

The Kuching climate city exhibit higher total energy savings than the other climate cities. This is because of increase in cooling energy required in the other climate cities climates and the lower cooling energy required in the Kuching climates. Figures 4.89 and 4.90 illustrate that even in Kuching, the climate of which was modeled for the base case model, the cooling energy savings are insignificant when a toplighting system with a large TFR is used. Figures 4.89 and 4.90 illustrate that even in Kuching, the climate of which was modeled for the base case, the cooling energy savings are insignificant when a toplighting system with a large TFR is used.

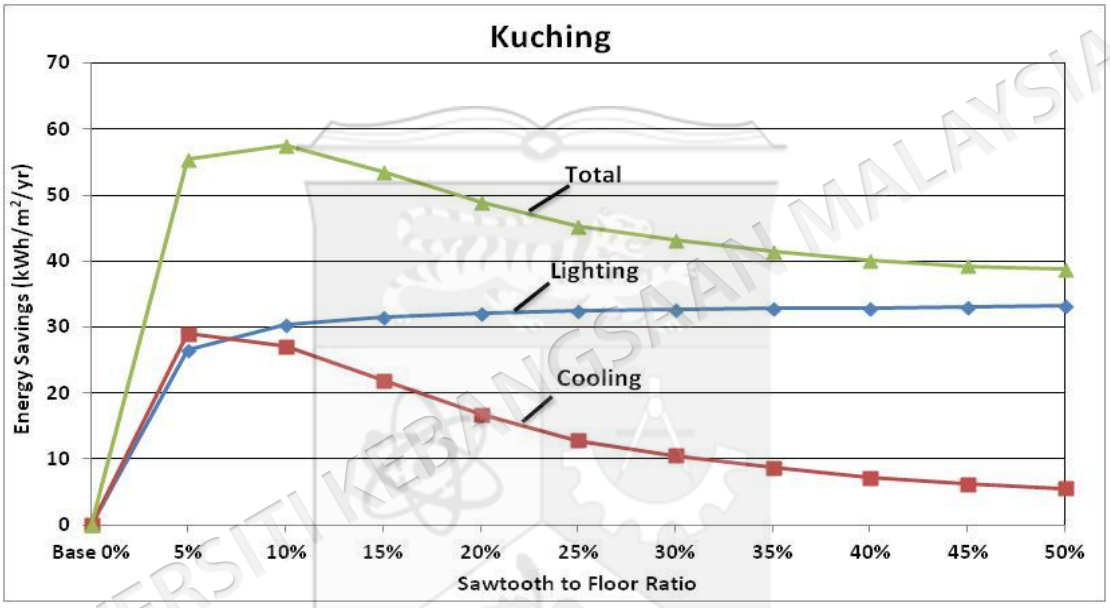

Figure 4.89 Total annual energy savings from lighting, cooling, and total for base case model simulated in Kuching

UNIVERSITI KEBANGSAAN MALAYSIA

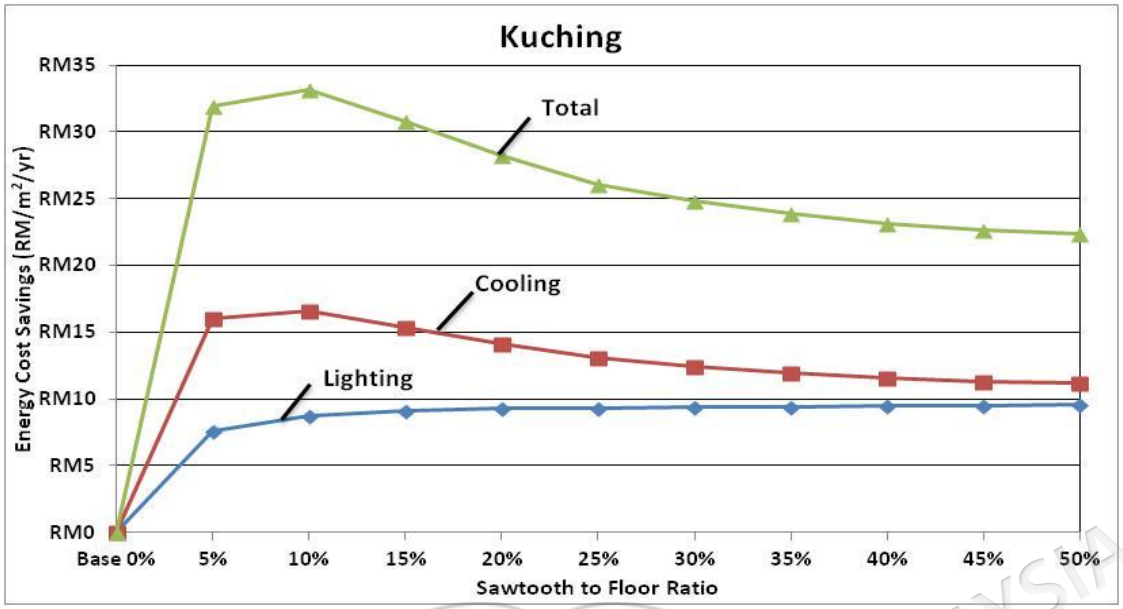

Figure 4.90 Total annual energy cost savings from lighting, cooling, and total for base case model simulated in Kuching

Figures 4.91 and 4.92 show the equivalent results in climate conditions in George Town. As the figures show, the annual cooling energy savings are insignificant when a sawtooth with a large glazing area is used. Enhancing the glazing properties of the toplighting strategy slightly increases the energy savings by decreasing the heat transfers and permitting a slight increase in the toplighting glazing areas. Lighting energy savings is the predominant type of end use controlling energy and cost savings. When the lighting energy savings begin to stabilize, no additional cost savings accrue from any additional toplighting glazing area.

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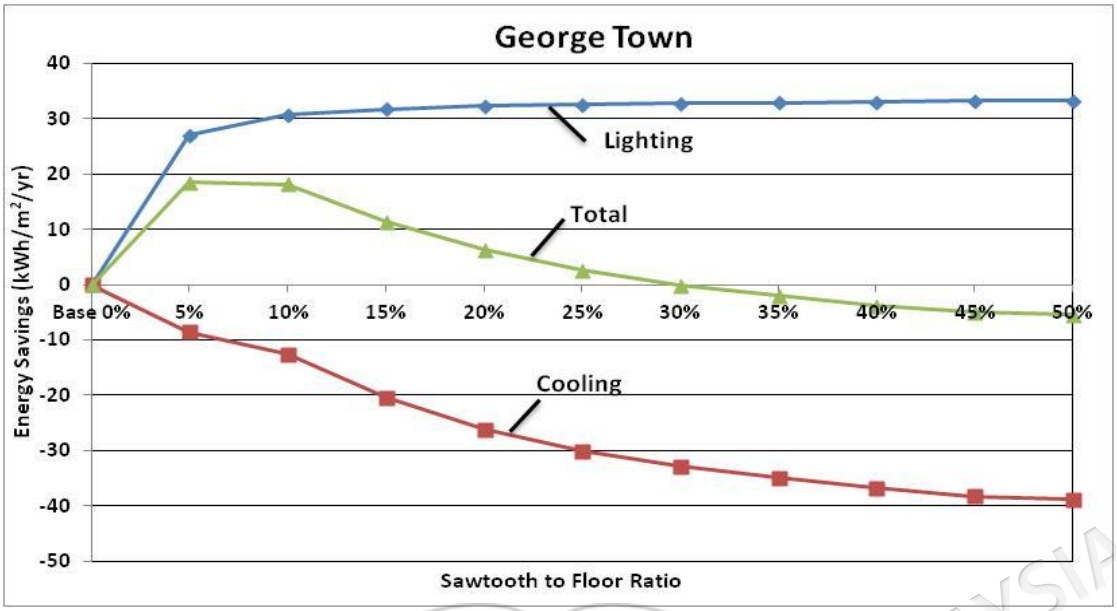

Figure 4.91 Total annual energy savings from lighting, cooling, and total for base case model simulated in George Town

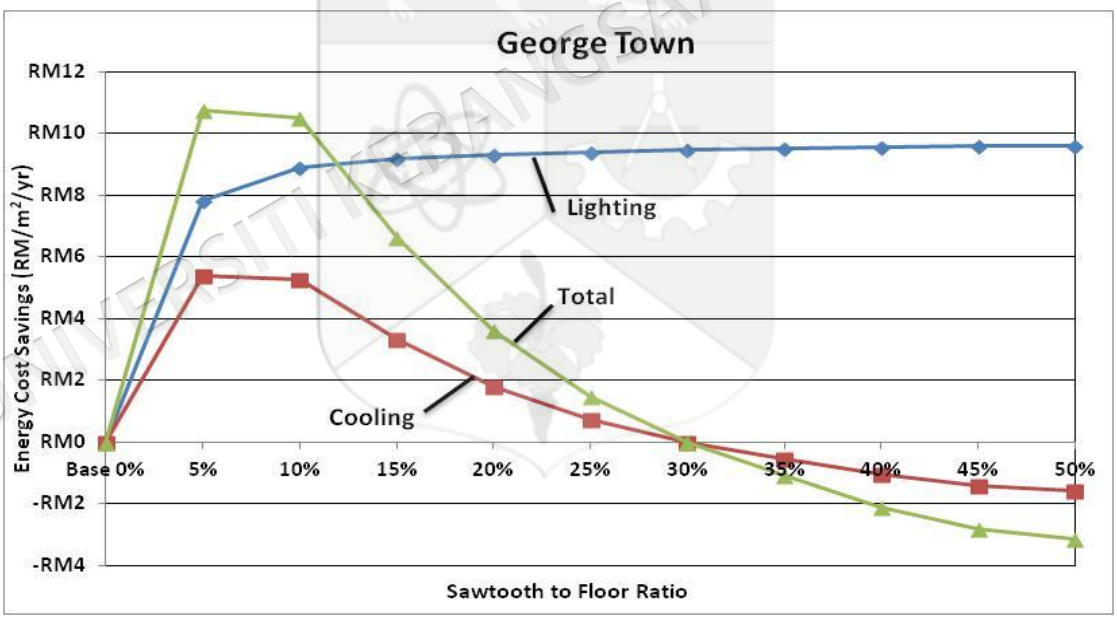

Figure 4.92 Total annual energy cost savings from lighting, cooling, and total for base case model simulated in George Town

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4.2.10 Summary

The simulation results of the lighting, cooling, and total energy use analysis indicate that applying the skylight, sawtooth, and roof monitor options in the UKM case study building space is a robust strategy in reducing not only the lighting, cooling, and total energy use but also the building energy costs.

Among all of the suggested skylight cases, the 5% skylight glazing area yields the highest total annual energy and total energy cost savings. Among all of the suggested sawtooth cases, the 10% sawtooth glazing area yields the highest annual energy cost savings. Among all of the suggested roof monitor cases, the 5% roof monitor glazing area yields the highest annual energy cost savings. This study recommends the use of the sawtooth case with a TFR between 5% and 10% as the best toplighting option for academic buildings. The 5% skylight and 5% roof monitor cases are recommended as the next best options. The 5% and 10% sawtooth cases represent the best toplighting system applications that yield the maximum energy and energy cost savings compared to roof monitor and skylight cases in terms of energy performance with illuminance levels target 500 lux. The 10% sawtooth case and the 5% roof monitor performed the best in their respective cases, while the 5% glazing area performed best in the skylight category for the total energy savings and the total energy cost savings.

The energy analysis of the building simulation results indicates that the lighting, cooling, and total annual energy consumption can be significantly reduced given the proper design of skylights, sawtooth, and roof monitors. In all skylight, sawtooth, and roof monitor cases, the cooling energy consumption remains almost as high as that of the base case model. Only small reductions occur in the 5% TFR skylight and roof monitor cases and in the 5%, 10%, 15%, and 20% TFR sawtooth cases. In general, all the suggested skylight, sawtooth, and roof monitor cases show a better performance in terms of total energy savings than does the base case model without daylighting strategy.

UNIVERSITI KEBANGSAAN MALAYSIA

The simulation results also indicate that the four orientations of the suggested toplighting options result in different total annual energy savings. The highest total annual energy savings per building area (kWh/m^2/yr) occur in the sawtooth glazing cases facing north, followed by those facing south and east. The orientations were handeled by twisted the toplighting options not the base case building (see Chapter 3 page 113 through 122). The lowest total energy savings occur in the sawtooth cases facing west. For the skylight and roof monitor cases, the highest total annual energy savings per building area occur in the skylight and roof monitor glazing facing north, followed by those facing south and east. The lowest total energy savings occur in the skylight and roof monitor glazing, with a long side, facing west.

The double Low–E clear glazed represents the recommended glazing type for Malaysia toplighting system application that yields the maximum energy savings with illuminance level target 500 lux. In addition, double low–E clear glazed shows more energy savings in Kuala Lumpur climatic condition for all toplighting alternatives, orientations, spacing-to-height ratio, and TFRs. Furthermore, the low–E clear glazed complies with the ASHRAE glazing recommendation for these climates.

The application of any of the suggested skylight, sawtooth, and roof monitor cases in the UKM academic building yield an average total annual energy cost savings of more than RM 10757, RM 9766, and RM 7432, respectively. Only a 91% area of the total UKM academic building was simulated. Thus, simulating the rest of the building may lead to more energy cost savings. The sum of the areas of all the spaces (hall and 2 coridors) under consideration is 2289m^2. This area is just 91% of the total area of the UKM case study academic hall, which is 2505m^2. The suggested toplighting alternaties have been limited to this 91% area of the UKM case study building. Assuming that daylight penetrates the entire building through skylights, sawtooth, or roof monitors, the total annual energy cost savings become considerably greater than the calculated price. If we assume that the 10% TFR sawtooth case with a double low-e clear glazed type is used to provide daylight to the building, we will observe the following total annual energy and cost savings:

UNIVERSITI KEBANGSAAN MALAYSIA

The annual lighting energy savings are approximately 56,900 kWh/yr, which is equivalent to annual cost savings of RM 16,387 per year. The annual cooling energy savings are approximately 14,167 kWh/yr, which is equivalent to annual cost savings of RM 4,080 per year. The total annual energy savings are approximately 71,067 kWh/yr, which is equivalent to annual cost savings of RM 20,467 per year.

For the sawtooth case with a 10% TFR, 56.6%, 4.3%, and 15.6% annual lighting, cooling, and total energy savings can be achieved, respectively. The total energy savings mostly come from the total lighting energy savings (56.6%). The cooling annual energy savings (4.3%) also contribute to the total annual energy savings but only to a lower extent.

The effect of climatic conditions on the total energy and energy cost savings indicate that higher energy and energy cost savings are generated in Kuching, among other Malaysian cities. Based on the results presented in figure 4.25 it can be observed that the maximum energy and energy cost saving is achieved for Kuching weather conditions followed by Kota Baharu, Kuala Lumpur, and then by George Town. This can be explained as the availability of daylight varies according to the location of the city and its longitude and latitude and also the variation of sky conditions all around the year for each city. In addition, the Kuching climate exhibits higher total energy and energy cost savings than the other climate cities. This is due to the reduction in lighting energy required in this city climate and the higher lighting energy required in the other cities climates.

These results are a significant proof that toplighting daylighting strategy can be efficiently used in academic buildings in tropical climates given proper considerations of design.

UNIVERSITI KEBANGSAAN MALAYSIA

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

5.1 INTRODUCTION

This study aims to explore the effect of various shapes and geometries of toplighting systems with integrated lighting control on both energy savings and daylight quality in UKM academic buildings in tropical climate. Currently, how toplighting systems and lighting control strategies affect on overall building energy savings and daylight quality remains unclear. Few studies have investigated the effect of toplighting shapes and geometries on building energy consumption and daylight quality. The toplighting' materials and glazing characteristics in these studies do not reflect modern toplighting options and their applications. In addition, toplighting alternatives are frequently excluded from energy research during the early stage of the design process.

Given that toplighting alternatives also affect the interior lighting surroundings in the building space, toplighting option strategies should achieve acceptable daylight quality. Daylight quality was evaluated with different daylight parameters, such as daylight factor (%), work plane illuminance level (lux), and daylight distribution and uniformity.

This study aims to improve the understanding of daylighting and toplighting alternatives to conserve energy while providing quality daylight in the building space. To achieve this objective, the study investigated the effect of toplighting shapes and geometries on lighting, cooling and total building energy consumption and savings. These effects were evaluated based on differences in toplighting parameters such as shapes, geometries, orientations, and glazing types with lighting control integration.

EnergyPlus building energy and daylight simulation program with OpenStudio user interface was used to analyze the performance of toplighting parameters. Three

UNIVERSITI KEBANGSAAN MALAYSIA

toplighting systems were considered in relation to lighting control and two spacing-to-height ratios were used in academic buildings.

The aim of this study was to evaluate the importance of daylighting application in in academic hall buildins in climate similar to that of UKM. The methodology, including data collection, on-site daylight measurements, simulation modeling in EnergyPlus, as well as evaluation of energy consumption data, is described in detail in Chapter III. This chapter presents conclusions resulting from several stages of the research. The following sections indicate the types of conclusions: 1) effect of toplighting alternatives on energy savings, 2) effect of toplighting alternatives on daylight quality, 3) economic analysis, 4) guidelines on toplighting design in tropical climate similar to that of Malaysia, and 5) recommendations for future researches.

This study was different from previous studies in this field as it included study of an existing academic hall building through two methods onsite measurements and the simulation modeling. The literature review in Chapter 2 showed that previous studies used hypothetical cases that did not include an actual building, and the examples that actual building was included, the methodology were restricted to one methodology, mainly computer simulations models. The findings of this study can be applied to the use of toplighting in one-story academic buildings in similar climates with similar building design, either in Malaysia or in other parts of the world. The findings can be also applied to industrial buildings, factories, schools, museums, art galleries, and uppermost floor contact with the roof. The approaches applied in this study include using standardized measurement tools as well as building energy and daylighting simulation programs that are highly valid and verifiable. This study is significant because it confirms that the use of toplighting for daylighting can decrease energy consumption in a building and enhance daylight quality. The following sections summarize the conclusions of this study.

5.2 THE CASE STUDY BUILDING SELECTION

The case study building is a one story academic hall in Universiti Kebangsaan Malaysia, Kuala Lumpur. The study of all the academic hall designs in Universiti

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Kebangsaan Malaysia demonstrated the fact that the case study hall was typical in the sense of size, general academic hall structure, type of construction, height, number of stories, and operation schedule. The analysis and results of the analysis for this academic hall building will apply to all similar halls in the UKM halls, thus benefiting the entire academic hall system in this university can also be applied to other academic halls in different universities that have similar building specifications, climate, operation schedules and layout. The UKM Jabatan Pengurusan Pembangunan (JPP) officers were very cooperative. The important part of this study founded the visits to the case study academic hall building and conducted the daylighting measurements. The study of the UKM actual hall building added the validity to this study and also made this study beneficial and original as regards to methods and data collection.

5.3 THE CASE STUDY BUILDING DAYLIGHT EVALUATION

The UKM case study academic hall was ideal to study the impact of daylighting. The two main problems that were visible in the academic hall were: 1) dark areas due to inaccessibility of sufficient daylight, and 2) the width of the case study building was 35meter this made daylighting from the windows in the east and west walls are inadequate. The case study hall building was served by six windows 5.6m x 3.6m, typically at east and west walls of the hall and these windows were adjoining to corridors with 3.7m width. This leads to a total dependency on artificial lighting system. Fluorescent lights provided the lighting for reading and other student activities in the academic hall space.

After an initial walk-through at the case study building, three types of design recommendations for this type of academic hall have been suggested to allow more daylight.

1) Three types of toplighting systems suggested and should be evaluated,

2) Increase the number of toplighting units throughout the roof to maximize daylight, and

UNIVERSITI KEBANGSAAN MALAYSIA

3) The case study interior space should be given priority in its admittance to daylight, and daylight entry into the hall space should not be obstructed.

The daylight factor inside the case study space was measured and found to be very low, about 0.18% for the reference point number 1 and about 0.22 % for the reference point number 2. These values are very low as compared to the IESNA recommended values between 2 to 3 % for reading areas.

Table 5.1 shows the values for average illuminance level in (lux) for the case study space at the work plane height. These daylighting measurements were taken when all the artificial lighting turns off in the case study space (Only Daylighting). It can be seen that the best time is at 12:00 pm, which has an average interior illuminance level of about 49.7 lux (4.7 footcandles). The Malaysian Standard (MS) and IESNA average recommended value for illuminance level, as mentioned earlier in the literature review is 400 to 500 lux (40-50 footcandles) for this type of building. The existing daylighting level is extremely insufficient.

Table 5.1 Average illuminance level in (lux) for the case study interior space

Time/Date	21March 09:00am	21March 12:00 pm	21March 15:00pm
Avg. illuminance level	33.5	49.7	21.6

5.4 THE ENERGYPLUS WITH OPENSTUDIO BASE CASE MODEL

A base case computer model was generated for the UKM case study hall building using the EnergyPlus with OpenStudio energy and daylighting simulation program. The existing case study building data was very beneficial in generating the LOADS part of the EnergyPlus with OpenStudio input file, while the electrical and mechanical details for the SYSTEMS part of the file were gained from the electrical and mechanical drawings obtained from the UKM Jabatan Pengurusan Dan Pembangunan (JPP). The EnergyPlus with OpenStudio Google SketchUp Plug-in software was efficient in generating the needed 3D graphical images of the base case building model. The base case model was calibrated to the utility bills (electricity) for the case

study building. Statistical and graphical analysis methods were used to realize the desired calibration. After the desired calibration was achieved, the base case model was modified to include toplighting alternatives. Lighting control type, sensors locations, minimum input power fraction for continuous dimming control, minimum light output fraction for continuous dimming control, daylighting illuminance level target (500 Lux), and maximum allowable discomfort glare index functions were determine in the LOADS part of the input file. Skylight, sawtooth and roof monitor were defined and their effect was studied on the illuminance level and daylight factor in the case study space, lighting energy and total energy savings. Two reference points were defined in the case study space, and the daylight factors at these points were compared to the actual case study space values.

The EnergyPlus base case model without daylighting was compared with the base case model with daylighting in order to analyze the effect of daylighting on energy consumption. The daylight case study model was seen to perform better than the case study model without daylighing.

5.5 EFFECT OF TOPLIGHTING OPTIONS ON ENERGY SAVINGS

EnergyPlus with user interface OpenStudio SketchUp Plug-in was used as the building energy and simulation program to study the effect of toplighting alternative designs on different types of energy use. The base case model with daylight was compared with a similar non-daylight model. Cooling energy consumption decreased, as did lighting energy for the entire year. The decreased in lighting energy use more pronounced than that in cooling energy consumption. The graphs for the total building energy consumption pointed out that the base case model with suggested toplighting options achieved a reduction in electrical energy use for the entire year. The base case model without daylighting was considered as a base case for all energy and daylighting simulation tests.

The first stage of energy evaluation involved monthly lighting energy consumption, monthly cooling energy consumption, and total building energy consumption throughout the year. Lighting, cooling, and total building energy usage

UNIVERSITI KEBANGSAAN MALAYSIA

were evaluated at the monthly level to better understand the effect of alternative toplighting designs on the results. Lighting, cooling, and total energy were evaluated for all sizes of each toplighting alternative. The 5% skylight glazing area exhibited the highest total annual energy and total energy cost savings among all of the suggested skylight cases, and the 10% sawtooth glazing area indicated the highest annual energy cost savings among all of the suggested sawtooth cases.

Analysis of cooling energy use indicated that the cooling remained almost high compared with the base case model in all skylights, sawtooth, and roof monitor cases, with small reductions in the 5% TFR skylight and roof monitor cases, whereas small decreases were observed in the 5%, 10%, 15%, and 20% TFR sawtooth cases. Cooling energy use increased with increasing toplighting alternative size because of heat gain through the additional glazing in each of the suggested toplighting alternatives cases. According to lighting and cooling energy analysis, all of the toplighting alternatives cases consistently decreased in the type of space lighting energy consumption but consistently increased in the type of space cooling energy consumption. Generally, all of the suggested skylight, sawtooth, and roof monitor cases outperformed the base case model in terms of total energy savings.

The simulation results revealed that the four orientations of the suggested toplighting alternatives showed different total annual energy savings. The highest total annual energy savings per building area ($kWh/m^2/yr$) were observed when sawtooth glazing cases were facing north, followed by south and east. The lowest total energy savings for the sawtooth cases take place in the west orientation. The skylights and roof monitors cases, the highest total annual energy savings per building area ($kWh/m^2/yr$), take place with the skylights and roof monitors glazing facing north, followed by south and east. The lowest total energy savings occur with the skylights and roof monitors glazing long side facing west.

The results also show that in tropical climates such as that in Kuala Lumpur, Malaysia, the roof monitor cases perform better than the sawtooth and skylight cases in terms of energy savings. The main contributor to total energy savings is from lighting, followed by cooling. Energy savings on lighting ranged between 30.4% to

65% for all toplighting types and sizes. The toplighting alternatives provide savings ranging from 4% to 17% for the annual total building energy without sacrificing visual comfort requirements, with higher energy savings achieved with the roof monitor toplighting strategy.

The study revealed that, of the glazing types studied, high performance glazing, such as double Low-E clear, produced the greatest lighting energy savings and total building energy savings when compared with standard single clear glaze. Optimum glazing areas were concluded to be 5% to 10% TFR for the roof monitor and sawtooth strategies, and were found to reduce cooling loads as compared to the base case. However, larger glazing areas, more than 15% TFR, increased cooling loads. The study examined the daylighting performance of the four orientations of toplighting apertures.

A north toplighting orientation showed the best overall energy savings and better illuminance distribution and uniformity. A West orientation showed the least benefit of energy savings of toplighting alternatives when compared with other orientations due to the large fraction of time during which solar radiation affects the daylighting systems, which consequently increases solar thermal load on this orientation. With regard to daylight quality, more daylight can be provided to the space within the beneficial range of 300 lux to 5000 lux compared with base case without daylighting strategies. With toplighting strategies, the daylight distribution and uniformity ratio at the work plane surface are considerably improved. With similar glazing area and glazing type, the roof monitors cases provide better daylight uniformity than the sawtooth and skylight cases, with adequate illuminance levels higher than 500 lux.

5.6 EFFECT OF TOPLIGHTING OPTIONS ON DAYLIGHT QUALITY

The base case computer model was ideal to evaluate the effect of toplighting designs on energy saving and daylight quality. Two main problems were clear in the building space: 1) large dark area of the space because of the unavailability of adequate daylight, and 2) large corridors in the east and west elevations close to the windows.

UNIVERSITI UTARA MALAYSIA

These problems obstruct the daylight entering the case study space and the building totally depending on artificial lighting to deliver lighting for reading and other student activities in the space. Illuminance level values in (lux) unit were measured inside the building space with all artificial lighting switches off (Daylighting Yes), and then Illuminance level values in (lux) unit were measured inside the building space with all artificial lighting switches on (Daylighting No). Daylight factors measured inside the building space were very extremely low, ranging from 0.18% to 0.22%. These daylight factors values were considerably low compared with the IESNA values, which ranged from 2% to 3% for reading spaces.

The roofs monitor alternative exhibited better daylight distribution than other toplighting alternatives throughout the space in all the simulated representative dates and days. Better and daylight distribution was provided compared with other toplighting alternatives regardless of a lower illuminance level value. The roof monitor option was considered the best design selection option. Although the skylight alternative provides higher illuminance values than other toplighting alternatives throughout the year, it has the worst daylighting achievement in term of daylight distribution and uniformity.

Based on the achievement of the suggested toplighting alternatives designs, the conclusions are made and can be applied only to three toplighting alternatives with similar shapes and geometries with similar building layout. Therefore, these conclusions cannot be generalized to all toplighting designs types. Different toplighting designs than these three shapes are likely to have different results.

5.7 ECONOMIC ANALYSIS

The last part of the energy evaluation using EnergyPlus with OpenStudio SketchUp Plug-in was the economic analysis, which was divided into two subsections: 1) energy savings (%) through the toplighting alternatives designs, and 2) energy cost savings (RM) through the same toplighting alternatives designs for all suggested skylights, sawtooth, and roof monitor cases. The skylight 5% TFR with double low-e clear glazing case had the best performance among the other skylight cases in terms of total

UNIVERSITI KEBANGSAAN MALAYSIA

energy savings, whereas the 10% TFR with double low-e clear glazing had the best total energy savings in the sawtooth cases. The 5% TFR case performed the best among the roof monitor cases. All of the suggested toplighting alternatives provide better total energy savings than the base case.

The individual categories of lighting energy, cooling energy, and total annual energy savings were also ranked based on their achievement. The 5% TFR sawtooth case with double low-e clear glazing had the best performance in cooling energy savings, whereas the 60% roof monitor glazing case was the least efficient. The 60% TFR skylight glazing case showed the best performance in terms of lighting energy savings, whereas the 5% TFR sawtooth case with double reflection clear glazing was the least efficient in this aspect. The 5% skylight glazing case had the best performance in total annual energy savings, whereas the 60% TFR roof monitor case with double clear glazing was the least efficient in this aspect.

The energy cost savings (RM) indicated that the 5% skylight glazing area had the highest annual energy cost savings among all of the suggested skylight cases, whereas the 10% sawtooth glazing area indicated the highest annual energy cost savings among all of the suggested sawtooth cases. The 5% roof monitor glazing area indicated the highest annual energy cost savings among all of the suggested roof monitor cases. In general, all toplighting alternatives generated savings in energy and energy cost savings. The sawtooth case with a 5% to 10% glazing area was ranked as the best among all of the suggested toplighting options, followed by the 5% skylight glazing option as the second-best and the 5% roof monitor glazing area option as the third-best. The results indicated that more than RM 10757 could be saved annually from only one academic hall building through the use of any of the proposed toplighting alternative designs. This study considers only 91% of the total building floor area in the energy and daylighting evaluation; therefore, the energy savings do not correspond to the total building floor area. The most important conclusion is that academic halls or education buildings constructed for UKM with similar layout should be provided with toplighting advantages.

UNIVERSITI KEBANGSAAN MALAYSIA

5.8 RECOMMENDATIONS FOR FUTURE RESEARCH

This study covers only a few significant parts of toplighting daylighting designs with regard to their direct effect on building energy performance and daylight quality. The study results apply only to Kuala Lumpur, however the evaluation methodology should provide guidance on application to other Malaysian states and other climates internationally. Such application is expected to increase the quantity and kind of results so that comparison between different locations can be conducted easily.

Proper design and selection of toplighting systems in academic buildings can significantly facilitate not only the reduction of building energy consumption but also the improvement of lighting quality for students. Future research should address how students respond to various toplighting designs with lighting control strategies as well as to various toplighting shades and building geometries in effort to increase the quality of energy-conservation methods and satisfy by the building users.

More studies should be conducted to test the effect of natural ventilation on space temperature since toplighting systems contribute not only to the energy and lighting of the building space but also to its thermal comfort.

Glare and its effects on the wellbeing of building occupants were not evaluated in this study. Therefore, it is recognized that further research should be conducted to evaluate the presence of glare as a function of toplighting area and building size.

Field and laboratory studies should be conducted on the actual performance of toplighting alternatives in Malaysia based on the feedback from local architects on the effect of toplighting on building energy consumption and daylight quality, as well as the possible thermal effect of toplighting designs during the day and night because these parameters have been investigated in this study based on the EnergyPlus simulation program only.

UNIVERSITI KEBANGSAAN MALAYSIA

REFERENCES

Ahmad, M. 1996. The Influence of Roof Form and Interior Cross Section on Daylighting in the Atrium Spaces in Malaysia. Tesis University of Manchester.

Ahmad, M. H. & Rasdi, M. T. H. M. 2000. *Design Principles of Atrium Buildings for the Tropics*. Penerbit UTM.

Al-Rabghi, O. M. & Hittle, D. C. 2001. Energy Simulation in Buildings: Overview and Blast Example. Energy conversion and management 42(13): 1623-1635.

Ander, G. D. 2003. Daylighting Performance and Design. Wiley. com. Amazon.com, ISBN: 978-0-471-26299-2, 336 pages

Augenbroe, G. 2002. Trends in Building Simulation. *Building and Environment* 37(8): 891-902.

ASHRAE Handbook, A. 2009. Fundamentals Atlanta: American Society of Heating, Air-Conditioning and Refrigeration Engineers, Inc.

Ayres, J. M. & Stamper, E. 1995. Historical Development of Building Energy Calculations. *ASHRAE Journal* 37(2):101(1);841-8

Baker, N. & Steemers, K. 2002. *Daylight Design for Buildings*: Earthscan.com, UK, Amazon.com

Baker, N. V., Fanchiotti, A. & Steemers, K. 2013. *Daylighting in Architecture: A European Reference Book*. Routledge.

Balcomb, J. D. 1998. Using Energy-10 to Design Low-Energy Buildings. *NREL Report: TP25740*

Bodart, M. & De Herde, A. 2002. Global Energy Savings in Offices Buildings by the Use of Daylighting. *Energy and Buildings* 34(5): 421-429.

BRE (1986). BRE Digest 309. *Estimating daylight in buildings: Part 1*. Building Research Establishment Digest, Watford, England, 8p.

Bryan, H. & Autif, S. 2002. Lighting/Daylighting Analysis: A Comparison. *Proceedings of the Solar Conference*, hlm. 521-526.

Bushweller, K. 1998. Ergonomically Correct Classrooms: Consider Students' Developmental Needs When Furnishing Your Schools. *Learning By Design* 18(20.

Cabús, R. C. & Pereira, F. O. 1996. Luminous Efficacy of Daylighting in Intertropical Region: An Analysis for Toplighting Systems. *Renewable Energy* 8(1): 210-213.

UNIVERSITI KEBANGSAAN MALAYSIA

Carmody, J., Selkowitz, S., Lee, E., Arasteh, D. & Willmert, T. 2004. *Window Systems for High-Performance Buildings*. Norton New York.

Chandran, V., Sharma, S. & Madhavan, K. 2010. Electricity Consumption–Growth Nexus: The Case of Malaysia. *Energy Policy* 38(1): 606-612.

CIBSE, C. 1994. Code for Interior Lighting. *London: The Chartered Institution of Building Services Engineers*

CIBSE, C. 2006. Code for Lighting. *London: The Chartered Institution of Building Services Engineers*

COHSR, 2009. Measurement of Lighting Levels in the Work Place. *Canada*: *Canada Occupational Health and Safety Regulations*, Part VI, October 2009

Crawley, D., Winkelmann, F., Lawrie, L. & Pedersen, C. 2001. Energyplus: A New-Generation Building Energy Simulation Program. *FORUM-PROCEEDINGS-*, hlm. 575-580
.

Crawley, D. B., Lawrie, L. K., Pedersen, C. O. & Winkelmann, F. C. 2000. Energy Plus: Energy Simulation Program. *ASHRAE Journal* 42(4): 49-56.

Cuttle, K. 1983. People and Windows in Workplaces. *Proceedings of the people and physical environment research conference*, hlm. 47-51.

Dewey, E. & Littlefair, P. 1998. Rooflight Spacing and Uniformity. *Lighting Research and Technology* 30(3): 119-125.

Degelman, L. 2002. Ener-Win 97.2000 User's Manual. *Degelman Engineering Group Inc., College Station, TX*

Djamila, H., Ming, C. C. & Kumaresan, S. 2011. Estimation of Exterior Vertical Daylight for the Humid Tropic of Kota Kinabalu City in East Malaysia. *Renewable Energy* 36(1): 9-15.

Diamond, S. & Hunn, B. 1981. Comparison of Doe-2 Computer Program Simulations to Metered Data for Seven Commercial Buildings. Los Alamos Scientific Lab., NM (USA).

Doe, U. 2010. EnergyPlus Engineering Reference. The Reference to EnergyPlus Calculations. *U.S. Department of Energy*

Doe, U. 2010b. Energyplus, Input Output Reference: The Encyclopedic Reference to Energyplus Input and Output. *USA, Department of Energy*

Doe, U. 2010c. Energyplus, Auxiliary EnergyPlus Programs: Extra programs for EnergyPlus. *USA, Department of Energy*

UNIVERSITI MALAYSIA SABAH

Doulos, L., Tsangrassoulis, A. & Topalis, F. 2005. A Critical Review of Simulation Techniques for Daylight Responsive Systems. *Proceedings of the European Conference on Dynamic Analysis, Simulation and Testing applied to the Energy and Environmental performance of buildings (DYNASTEE), Athens, Greece*, hlm. 125-139.

Dong-Hwan Ko, 2009. Fenestration Guideline for Energy and Daylight Efficiency: Evaluation and Prediction of Performance in Office Buildings. Tesis. Illinois Institute of Technology

DR Ossen, M.H. Ahmad & N.H. Madros, 2005. Impact of Solar Shading Geometry on Building Energy Use in Hot Humid Climates with Special Reference to Malaysia. NSEB2005 – SUSTAINABLE SYMBIOSIS, National Seminar on Energy in Buildings, UiTM.

DR Ossen, Mohad. Hmdan Ahmad & Nor Haliza Madros. 2005. Optimum Overhang Geometry For Building Energy Saving In Tropical Climates. Journal of Asian Architecure and Building engineering/November 2005/570

EC, 2007. Statistics of Electricity Supply in Malaysia. Malaysia: Energy Commission.

Edmonds, I. & Greenup, P. 2002. Daylighting in the Tropics. *Solar Energy* 73(2): 111-121.

Edwards, L. & Torcellini, P. A. 2002. *A Literature Review of the Effects of Natural Light on Building Occupants*. National Renewable Energy Laboratory Golden, CO.

EERE. 2003. Energy efficiency and renewable energy, U.S. Department of Energy. Retrieved December 2003, from http://www.eere.energy.gov/. EIA.

Egan, M.D & Olgay, V. W. 2002. *Architectural Lighting*. 2nd ed. Boston: McGraw-Hill Education

Ehrlich, C., Papamichael, K., Lai, J. & Revzan, K. 2002. A Method for Simulating the Performance of Photosensor-Based Lighting Controls. *Energy and Buildings* 34(9): 883-889.

EIA. 2003. *Official Energy Statistics*, Energy Information Administration, U.S. Department of Energy. Released: September, 2008, from http://www.eia.doe.gov/.

El Mohimen, M. A., Hanna, G. & Krarti, M. 2005. Analysis of Daylighting Benefits for Office Buildings in Egypt. *Journal of Solar Energy Engineering* 127(3): 366-370.

EnergyPlus. 1996-2009. *Getting Started with EnergyPlus.* U.S. Department of Energy.

Faber, O. & Littlefair, P. 1999. Daylight Linked Lighting Control in the Building Regulations. U.K. Department for Communities and Local Government. Communities.gov.uk

Fischer, J., Kirk Mescher, P., Ben Elkin, P., Mccune, S. M. & Gresham, J. 2007. High-Performance Schools. *ASHRAE Journal* 49(5): 30-46.

Franta, G. & Anstead, K. 1994. Daylighting Offers Great Opportunities. *Window & Door Specifier-Design Lab, Spring* 40-43.

Franzetti, C., Fraisse, G. & Achard, G. 2004. Influence of the Coupling between Daylight and Artificial Lighting on Thermal Loads in Office Buildings. *Energy and Buildings* 36(2): 117-126.

Galasiu, A. D. & Atif, M. R. 2002. Field-Performance of Daylight-Linked Lighting Controls and Window Blinds: A Pilot Study. *Proceedings of the Fifth European Conference on Energy-Efficient Lighting—Right Light*, hlm. 1-14.

Galasiu, A. D. & Veitch, J. A. 2006. Occupant Preferences and Satisfaction with the Luminous Environment and Control Systems in Daylit Offices: A Literature Review. *Energy and Buildings* 38(7): 728-742.

Garcia-Hansen, V., Esteves, A. & Pattini, A. 2002. Passive Solar Systems for Heating, Daylighting and Ventilation for Rooms without an Equator-Facing Facade. *Renewable Energy* 26(1): 91-111.

Ghisi, E. 2002. The Use of Fibre Optics on Energy Efficient Lighting in Buildings. Tesis University of Leeds.

Ghisi, E. & Tinker, J. A. 2005. An Ideal Window Area Concept for Energy Efficient Integration of Daylight and Artificial Light in Buildings. *Building and Environment* 40(1): 51-61.

Gratia, E. & De Herde, A. 2003. Design of Low Energy Office Buildings. *Energy and Buildings* 35(5): 473-491.

Group, S. R. 1998. Lawrence Berkley National Lab, Overview of Doe 2.2.

Haberl, J. & Bou-Saada, T. 1998. Procedures for Calibrating Hourly Simulation Models to Measured Building Energy and Environmental Data. *Journal of Solar Energy Engineering* 120(3): 193-204.

Haberl, J., O'neal, D., Bronson, J. & Hinchey, S. 1993. Graphical Tools to Help Calibrate the Doe-2 Simulation Program. ASHRAE Journal (American Society of Heating, Refrigerating and Air-Conditioning Engineers);(United States) 35(1):

Haberl, J. & Claridge, D. 1985. Retrofit Energy Studies of a Recreation Center. *ASHRAE Trans.;(United States)* 91(CONF-850606-):

Haberl, J. S. & Thamilseran, S. 1996. The Great Energy Predictor Shootout Ii: Measuring Retrofit Savings-Overview and Discussion of Results. *TRANSACTIONS-AMERICAN SOCIETY OF HEATING REFRIGERATING AND AIR CONDITIONING ENGINEERS* 102(419-438.

Hale, O. 2002. Improving performance. *American School and University*, *75*(2), 32-35.

Handbook, A. 1987. Hvac Systems and Applications. *American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Atlanta, GA*

Hastings, S. R. 1994. *Passive Solar Commercial and Institutional Buildings: A Sourcebook of Examples and Design Insights*. J. Wiley.

Hastings, S. R. 1989. Computer Design Tools for Climate-Responsive Architecture. *Solar & Wind Technology* 6(4): 357-363.

Heath, G. & Mendell, M. J. 2002. Do Indoor Environments in Schools Influence Student Performance? A Review of the Literature. *Proceedings of the 9th International Conference on Indoor Air Quality and Climate, Indoor Air 2002*, hlm.

Heerwagen, D. & Connolly, B. 2004. *Passive and Active Environmental Controls: Informing the Schematic Designing of Buildings*: McGraw-Hill Higher Education.

Heschong, L. 1999. Re-Analysis Report: Daylighting in Schools, Additional Analysis, New Buildings Institute, Feb.

Heschong, L. 2002. Daylighting and Human Performance. *ASHRAE journal* 44(6): 65-67.

Heschong, L. 2003. *Windows and Offices: A Study of Office Worker Performance and the Indoor Environment: Technical Report*. California: Energy Commission.

Hong, T., Chou, S. & Bong, T. 2000. Building Simulation: An Overview of Developments and Information Sources. *Building and Environment* 35(4): 347-361.

Hopkinson, R. G., Petherbridge, P. & Longmore, J. 1966. *Daylighting*: Heinemann.

Husaini, D. H. & Lean, H. H. 2012. Electricity Consumption, Export and Production: Evidence from Malaysian Manufacturing Sector. *Proceedings of USM-AUT International Conference 2012 Sustainable Economic Development: Policies and Strategies*, hlm. 701.

UNIVERSITI KEBANGSAAN MALAYSIA

Hunn, B., Jones, J., Grasso, M. & Hitzfelder, J. 1993. Effectiveness of Shading Devices on Buildings in Heating-Dominated Climates. *ASHRAE, ATLANTA, GA(USA).* 07-222):

Ibrahim, N. & Zain-Ahmed, A. 2007. Daylight Availability in an Office Interior Due to Various Fenestration Options. *2nd PALENC Conference and 28th AIVC Conference on Building Low Energy Cooling and Advanced Ventilation Technologies in the 21st Century, Crete island, Greece,* hlm.

IEA SHC Task 21. 2000. Task 21: Daylight in Buildings. International Energy Agency (IEA) Solar Heating and Cooling Programme. Rerieved September 2003, from http://www.iea-shc.org/task21/

IESNA, L. H. 2000. Reference and Application Volume. *New York: Illuminating Engineering Society of North America*

Johnsen, K. 1998. Daylight in Buildings, Collaborative Research in the International Energy Agency (Iea Task 21). *Renewable Energy* 15(1): 142-150.

Johnsen, K., Dubois, M.-C. & Sørensen, K. G. 2006. *Assessment of Daylight Quality in Simple Rooms: Impact of Three Window Configurations on Daylight Conditions, Phase 2*. SBI forlag.

J O'connor, J., Lee, E., Rubinstein, F. & Selkowitz, S. 1997. Tips for Daylighting with Windows: The Integrated Approach. LBNL Publication 790

Kaplan, M., J Mcferran, J Jansen, R Pratt. 1992. Reconciliation of a DOE2.1c Model with Monitored End-use Data from a Small Office Building. ASHRAE Trasactions(American Society of Heating, Refrigerating and Air-Conditioning Engineers);(United States). Vol. 96.Pt.1,pp, 981-993

Kim, K., Boyer, L. & Degelman, L. 1985. Daylighting Analysis through Scale Model, Full Scale Measurements and Computer Analysis for a Texas a&M University Campus Building.

Kreider, J. and J. Haberl. 1994. Predicting Hourly Building Energy Usage: The Great Energy Predictor Shootout: Overview and Discussion of Results. ASHRAE Transactions Technical Paper, Vol. 100, pt. 2

Kreider, J. and J. Haberl, 1994 .Predicting Hourly Building Energy Usage: The Results of the 1993 Great Energy Predictor Shootout to Identify the Most Accurate Method for Making Hourly Energy Use Predictions. ASHRAE Journal, pp. 72-81

Krarti, M., Erickson, P. M. & Hillman, T. C. 2005. A Simplified Method to Estimate Energy Savings of Artificial Lighting Use from Daylighting. *Building and environment* 40(6): 747-754.

Lam, J. C. & Li, D. H. 1998. Daylighting and Energy Analysis for Air-Conditioned Office Buildings. *Energy* 23(2): 79-89.

Lam, W. M. 1985. Sunlighting as Formgiver for Architecture. U.S. Osti.gov.

Laouadi, A. 2004. Design with Skyvision: A Computer Tool to Predict Daylighting Performance of Skylights. National Research Councial Canada (NRC), CA.

Lawrence, T. & Roth, K. 2008. Commercial Building Toplighting: Energy Saving Potential and Potential Paths Forward. *Prepared by TIAX LLC for US Department of Energy, Building Technologies Program*

LBNL. 2002. Building energy analysis: Simulation research group. Lawrence BerkeleyNational Laboratory, Berkeley, CA.

LBNL. 2003. Windows and daylighting group. Building technologies program, Lawrence Berkeley National Laboratory, Berkeley, CA.

LBNL. 2003. The RADIANCE lighting simulation and rendering system. Building Technologies Program, Lawrence Berkeley National Laboratory, Berkeley, CA.

LBNL. 2003. SUPERLITE 2.0. Windows and daylighting group. Building technologiesprogram, Lawrence Berkeley National Laboratory, Berkeley, CA.

Lee, E. S. & Selkowitz, S. E. 2006. The New York Times Headquarters Daylighting Mockup: Monitored Performance of the Daylighting Control System. *Energy and Buildings* 38(7): 914-929.

Li, D. & Lam, J. 2001. Predicting Vertical Luminous Efficacy Using Horizontal Solar Data. *Lighting Research and Technology* 33(1): 25-42.

Li, D., Lam, J. & Wong, S. 2005. Daylighting and Its Effects on Peak Load Determination. *Energy* 30(10): 1817-1831.

Li, D. H. & Lam, J. C. 2003. An Investigation of Daylighting Performance and Energy Saving in a Daylit Corridor. *Energy and Buildings* 35(4): 365-373.

Li, D. H., Lam, T. N. & Wong, S. 2006. Lighting and Energy Performance for an Office Using High Frequency Dimming Controls. *Energy Conversion and Management* 47(9): 1133-1145.

Li, D. H. W. & Lam, J. C. 2003. An Investigation of Daylighting Performance and Energy Saving in a Daylit Corridor. *Energy and Buildings* 35(4): 365-373.

Lim, Y.-W., Kandar, M. Z., Ahmad, M. H., Ossen, D. R. & Abdullah, A. M. 2012. Building Façade Design for Daylighting Quality in Typical Government Office Building. *Building and Environment* 57(194-204.

Lim, Y.-W., Ahmad, M. H. & Ossen, D. R. 2013. Internal Shading for Efficient Tropical Daylighting in Malaysian Contemporary High-Rise Open Plan Office. *Indoor and Built Environment* 22(6): 932-951.

Loutzenhiser, P., Manz, H., Felsmann, C., Strachan, P. & Maxwell, G. 2007. An Empirical Validation of Modeling Solar Gain through a Glazing Unit with External and Internal Shading Screens. *Applied Thermal Engineering* 27(2): 528-538.

Mahdavi, A., Rao, S. P. & Inangda, N. 2013. Parametric Studies on Window-to-Wall Ratio for Day Lighting Optimisation in High-Rise Office Buildings in Kuala Lumpur, Malaysia. *Journal of Design and Built Environment* 12(1):

Mclain, H., Leigh, S. & Macdonald, J. 1994. Analysis of Savings Due to Multiple Energy Retrofits in a Large Office Building. Oak Ridge National Lab., TN (United States).

Mendell, M. J. & Heath, G. A. 2005. Do Indoor Pollutants and Thermal Conditions in Schools Influence Student Performance? A Critical Review of the Literature. *Indoor air* 15(1): 27-52.

Millet, M. S. & Bedrick, J. R. 1980. Graphic Daylighting Design Method. *Depepartment of Architecture, University of Washington, Seattle, Washington*

Miyazaki, T., Akisawa, A. & Kashiwagi, T. 2005. Energy Savings of Office Buildings by the Use of Semi-Transparent Solar Cells for Windows. *Renewable Energy* 30(3): 281-304.

MMD, 2001. Malaysian Meteorological Department. Available from: http://www.met.gov.my/.

MMD, 2010. Malaysian Meteorological Department. Available from: http://www.met.gov.my/.

Moore, G. T. & Lackney, J. A. 1993. School Design: Crisis, Educational Performance and Design Applications. *Children's Environments* 99-112.

MOSTI. 2008. Ministry of Science, Technology and Innovation. Malaysia Meteorological Department (MMID). Available at www.met.gov.my

Muneer, T. 2007. *Solar Radiation and Daylight Models*. Routledge.Com, Books.googl.com

Nicklas, M. & Bailey, G. 1996. Energy Performance of Daylit Schools in North Carolina. Institute of Education Sciences (ERIC), North Carolina.

Onaygıl, S. & Güler, Ö. 2003. Determination of the Energy Saving by Daylight Responsive Lighting Control Systems with an Example from Istanbul. *Building and environment* 38(7): 973-977.

UNIVERSITI KEBANGSAAN MALAYSIA

Ong, H., Mahlia, T. & Masjuki, H. 2011. A Review on Energy Scenario and Sustainable Energy in Malaysia. *Renewable and Sustainable Energy Reviews* 15(1): 639-647.

OpenStudio Software. 2012. National Renewable Energy Laboratory. OpenStudio User Documentation. (online) http://openstudio.nrel.gov/

Parker, D. S., Fairey Iii, P. W. & Mcilvaine, J. E. 1997. Energy-Efficient Office Building Design for Floridas Hot and Humid Climate. *ASHRAE journal* 39(4):

Perez-Lombard, L., Ortiz, J. & Pout, C. 2008. A Review on Buildings Energy Consumption Information. *Energy and Buildings* 40(3): 394-398.

Place, W., Fontoynont, M., Conner, C., Kammerud, R. C., Anderson, B., Bauman, F., Carroll, W., Howard, T., Mertol, A. & Webster, T. 1984. The Predicted Impact of Roof Aperture Design on the Energy Performance of Office Buildings. *Energy and Buildings* 6(4): 361-373.

Plympton, P., Conway, S. & Epstein, K. 2000. Daylighting in Schools: Improving Student Performance and Health at a Price Schools Can Afford. *Proceedings of the Solar Conference*, hlm. 487-492.

Rea, M. S. 2000. The IESNA Lighting Handbook: Reference & Application.

Reinhart, C. F. & Jones, C. 2004. Electric Lighting Energy Savings for an on/Off Photocell Control–a Comparative Simulation Study Using Doe2. 1 and Daysim. *Proc. eSim* 183-189.

Robbins, C. L. 1985. Daylighting. Design and Analysis: Van Nostrand Reinhold, New York.

Rodgers, P. 1998. An Elementary School That Saves Energy and Is Visually Comfortable-Case Study (Project for the Mary-Mcleod-Bethune-Elementary-School, Rochester, New-York, Swbr-Architects, Architect, Lighting Design by Tom Ritzenthaler and David Kaye). *Architectural Record* 186(8): 159.

Rouk, U. 1997. Probe—Developing Education Policy Issues, Washington, DC: National Education Knowledge Industry Association Communications.

Ruck, N. C. 1986. Letting in the Daylight. *Building Research and Practice* 14(5): 294-300.

Ruck, N. C. 1989. Building Design and Human Performance: U.S.Osti.gov

Rumana, R. 2009. Mohd. Hamdan Bin Ahmed "Thermal Performance of Rooftop Greenery System at the Tropical Climate of Malaysia, a Case Study of a 10 Storied Building Rcc Flat Rooftop". *Journal of Architecture and Built Environment* 37(1): 41-50.

Sammaljärvi, E. 1991. Impact of Certain Indoor Parameters on Children: A Questionnaire Study. *Environment International* 17(4): 311-316.

Santamouris, M., Argiriou, A., Dascalaki, E., Balaras, C. & Gaglia, A. 1994. Energy Characteristics and Savings Potential in Office Buildings. *Solar Energy* 52(1): 59-66.

Schrum, L. & Parker, D. 2003. Doe-2 Validation: Daylighting Dimming and Energy Savings: The Effects of Window Orientation and Blinds. *DOE-2 Articles from the Building Energy Simulation User News* 43.

Secondary School Energy Efficiency Action Project (SSEEAP), 2009, http://cetdem.org.my/wordpress/?page_id=2422 [4 March 2014].

Slade, Y. 2010. 2013 Commercial and Industrial Standard Offer Program. Measurement and Verification Guidelines for Retrofit Projects. CenterPoint Energy. Program Manual v 13.1

Slater, A., Bordass, W. & Heasman, T. 1996. *People and Lighting Controls*. Construction Research Communications Limited. Opengrey.eu

Standard, M. 2007. Ms 1525: 2007–Code of Practice on Energy Efficiency and Use of Renewable Energy for Non-Residential Buildings. *Cyberjaya Selangor, Department of Standards Malaysia*

Steemers, K., Baker, N. V. & Fanchiotti, A. 1993. *Daylighting in Architecture: A European Reference Book*. Commission.

Steffy, G. 2002. *Architectural Lighting Design*: John Wiley & Sons.

Sullivan, R., Lee, E. & Selkowitz, S. 1992. A Method of Optimizing Solar Control and Daylighting Performance in Commercial Office Buildings. *LBL-32931, Lawrence Berkeley Laboratory, Berkeley, CA*

Suruhanjaya Tenaga 2005 'Building energy performance in Malaysia', EE Seminar - How to take advantage of it, Kuala Lumpur.

Tools, G. D. 2001. Visualdoe 3.0 Program Documentation. *Eley Associates, San Francisco*

Treado, S., Gillette, G. & Kusuda, T. 1984. Daylighting with Windows, Skylights, and Clerestories. *Energy and Buildings* 6(4): 319-330.

Visual, D. 2003. 3.1 DOE Visual Manual. *Department of Energy, USA*

Winkelmann, F., Birdsall, B., Buhl, W., Ellington, K., Erdem, A., Hirsch, J. & Gates, S. 1993a. Doe-2 Supplement: Version 2.1 E. Lawrence Berkeley Lab., CA (United States); Hirsch (James J.) and Associates, Camarillo, CA (United States).

UNIVERSITI PENDIDIKAN SULTAN IDRIS

Winkelmann, F., Birdsall, B., Buhl, W., Ellington, K., Erdem, A., Hirsch, J. & Gates, S. 1993b. Doe-2, Bdl Summary. Version 2.1 E. Lawrence Berkeley Lab., CA (United States).

Winkelmann, F. 1998. Underground Surfaces: How to Get a Better Underground Surface Heat Transfer Calculation in Doe-2.1 E. *DOE-2 USER News* 19(1): 6-13.

Witte, M. J., Henninger, R. H., Glazer, J. & Crawley, D. B. 2001. Testing and Validation of a New Building Energy Simulation Program. *Proceedings of Building Simulation 2001* 353-360.

Wong, N. H. & Jan, W. L. S. 2003. Total Building Performance Evaluation of Academic Institution in Singapore. *Building and Environment* 38(1): 161-176.

Zain-Ahmed, A. 2000. Daylighting and Shading for Thermal Comfort in Malaysian Buildings. Tesis University of Herfordshire.

Zain-Ahmed, A., Sopian, K., Zainol Abidin, Z. & Othman, M. 2002. The Availability of Daylight from Tropical Skies—a Case Study of Malaysia. *Renewable energy* 25(1): 21-30.

Zain-Ahmed, A., Sopian, K., Othman, M., Sayigh, A. & Surendran, P. 2002. Daylighting as a Passive Solar Design Strategy in Tropical Buildings: A Case Study of Malaysia. *Energy conversion and management* 43(13): 1725-1736.

Zmeureanu, R., Pasqualetto, L. & Bilas, F. 1995. Comparison of Cost and Energy Savings in an Existing Large Building as Predicted by Three Simulation Programs. *Fourth International Conference Proceedings. Madison, USA*, hlm. 14-16.

UNIVERSITI KEBANGSAAN MALAYSIA

LIST OF PUBLICATIONS

Alrubaih, M., Zain, M., Alghoul, M., Ibrahim, N., Shameri, M. & Elayeb, O. 2013. Research and Development on Aspects of Daylighting Fundamentals. *Renewable and Sustainable Energy Reviews* 21(494-505.

Alrubaih, M., Zain, M., Ibrahim, N., Alghoul, M. & Sauod, K. B. 2012. The Energy Impacts of Using Top-Light Daylighting Systems for Academic Buildings in Tropical Climate. *Proceedings of World Academy of Science, Engineering and Technology*, hlm.

Alrubaih, M., Zain, M., Ibrahim, N. 2011. A Review Of Impact Of Daylighting On Energy Savings And Building Thermal Loads. *Proceedings of Regional Engineering Postgraduate Conference (EPC).*

Shameri, M., Alghoul, M., Elayeb, O., Zain, M. F. M., Alrubaih, M., Amir, H. & Sopian, K. 2013. Daylighting Characterstics of Existing Double-Skin Façade Office Buildings. *Energy and Buildings.*

Salem. M. Sharif, M. F. M. Zain, M. S. Alrubaih, M. Surat. 2010 Consensus of Environment and Socio-Culture in the Traditional Arab House-Tripoli. *ICBEDC 2010: 4th Int'l Conference on Built Environment in Developing Countries.*

Salem. M. Sharif, M. F. M. Zain, M. S. Alrubaih, Mastor. S. 2010 Abstracting Contemporary Design Guidelines from Traditional Arab Houses. *ICBEDC 2010: 4th Int'l Conference on Built Environment in Developing Countries.*

UNIVERSITI KEBANGSAAN MALAYSIA

APPENDIX A: DETAILED RESULTS FOR ENERGY ANALYSIS

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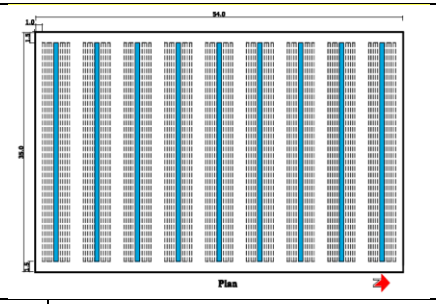
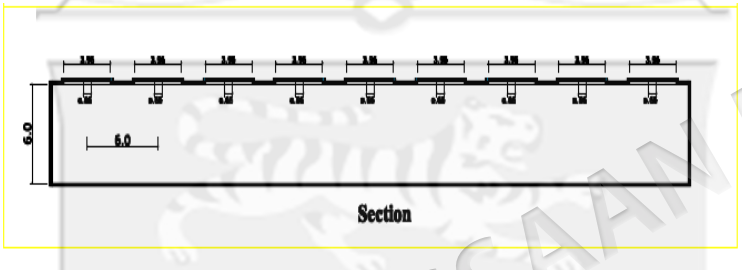
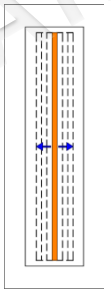
Table A-1: Total energy savings (%) for different skylight cases with different glazing types across all orientations as compared to the base case model without daylighting. Skylights 1 to 1 Spacing-to-Ceiling Height Ratio







TFR (%)	North				South				East				West			
	Sgl Clr	Dbl Clr	Dbl LoE	Dbl Ref	Sgl Clr	Dbl Clr	Dbl LoE	Dbl Ref	Sgl Clr	Dbl Clr	Dbl LoE	Dbl Ref	Sgl Clr	Dbl Clr	Dbl LoE	Dbl Ref
5%	13.3%	14.9%	17%	15.7%	13.3%	14.9%	17 %	15.7%	13.1%	15%	16.6%	15.2%	13.1%	15%	16.6%	15.2%
10%	8.8%	9.4%	13.1%	12.4%	8.8%	9.4%	13.1%	12.4%	8.7%	9.3%	13.3%	12.3%	8.7%	9.3%	13.3%	12.3%
15%	7.7%	7.9%	9.8%	9.4%	7.7%	7.9%	9.8%	9.4%	7.7%	7.9%	10%	9.4%	7.7%	7.9%	10%	9.4%
20%	7.4%	7.3%	8.7%	8.5%	7.4%	7.3%	8.7%	8.5%	7.2%	7.2%	8.7%	8.5%	7.2%	7.2%	8.7%	8.5%
25%	7.1%	7.0%	8.1%	8.1%	7.1%	7.0%	8.1%	8.1%	7.0%	6.8%	8.0%	8.0%	7.0%	6.8%	8.0%	8.0%
30%	6.9%	6.7%	7.7%	7.7%	6.9%	6.7%	7.7%	7.7%	6.9%	6.6%	7.7%	7.7%	6.9%	6.6%	7.7%	7.7%
35%	6.8%	6.4%	7.5%	7.5%	6.8%	6.4%	7.5%	7.5%	6.8%	6.4%	7.5%	7.5%	6.8%	6.4%	7.5%	7.5%
40%	6.7%	6.3%	7.3%	7.4%	6.7%	6.3%	7.3%	7.4%	6.7%	6.3%	7.3%	7.3%	6.7%	6.3%	7.3%	7.3%
45%	6.8%	6.3%	7.1%	7.3%	6.8%	6.3%	7.1%	7.3%	6.7%	6.3%	7.1%	7.3%	6.7%	6.3%	7.1%	7.3%
50%	6.8%	6.2%	7.0%	7.3%	6.8%	6.2%	7.0%	7.3%	6.8%	6.3%	7.0%	7.2%	6.8%	6.3%	7.0%	7.2%
55%	6.8%	6.2%	6.8%	7.1%	6.8%	6.2%	6.8%	7.1%	6.8%	6.2%	6.8%	7.1%	6.8%	6.2%	6.8%	7.1%
60%	6.9%	6.2%	6.7%	7.1%	6.9%	6.2%	6.7%	7.1%	6.9%	6.2%	6.7%	7.1%	6.9%	6.2%	6.7%	7.1%

*** *Sgl Clr***: Single clear 6 mm
Dbl Clr: Double clear 6mm-13mm air
***Dbl LoE*:** Double Low-e clear 6mm-13mm air
Dbl Ref: Double reflect clear 6mm-13mm air

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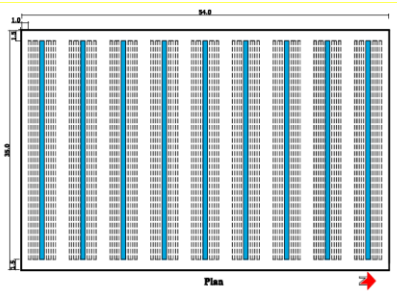
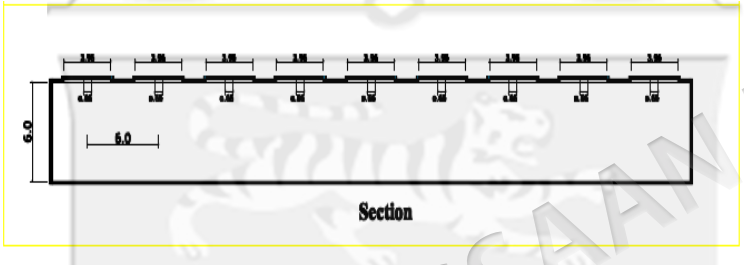
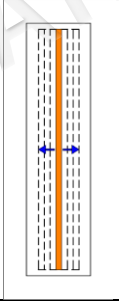
Table A-2: Lighting energy savings (%) for different skylight cases with different glazing types across all orientations as compared to the base case model without daylighting. Skylights 1 to 1 Spacing-to-Ceiling Height Ratio







TFR (%)	North				South				East				West			
	Sgl Clr	Dbl Clr	Dbl LoE	Dbl Ref	Sgl Clr	Dbl Clr	Dbl LoE	Dbl Ref	Sgl Clr	Dbl Clr	Dbl LoE	Dbl Ref	Sgl Clr	Dbl Clr	Dbl LoE	Dbl Ref
5%	61.7%	61.3%	60.8%	57.5%	61.7%	61.3%	60.8%	57.5%	60.5%	59.9%	59.4%	54.8%	60.5%	59.9%	59.4%	54.8%
10%	62.9%	62.7%	62.5%	60.5%	62.9%	62.7%	62.5%	60.5%	62.3%	62.0%	61.6%	58.8%	62.3%	62.0%	61.6%	58.8%
15%	63.2%	63.0%	62.8%	61.1%	63.2%	63.0%	62.8%	61.1%	62.9%	62.6%	62.4%	60.4%	62.9%	62.6%	62.4%	60.4%
20%	63.7%	63.4%	63.2%	61.9%	63.7%	63.4%	63.2%	61.9%	63.3%	63.1%	62.9%	61.3%	63.3%	63.1%	62.9%	61.3%
25%	63.8%	63.6%	63.4%	62.2%	63.8%	63.6%	63.4%	62.2%	63.6%	63.4%	63.2%	61.9%	63.6%	63.4%	63.2%	61.9%
30%	64.0%	63.8%	63.7%	62.5%	64.0%	63.8%	63.7%	62.5%	63.8%	63.7%	63.5%	62.2%	63.8%	63.7%	63.5%	62.2%
35%	64.1%	63.9%	63.8%	62.6%	64.1%	63.9%	63.8%	62.6%	64.0%	63.8%	63.7%	62.5%	64.0%	63.8%	63.7%	62.5%
40%	64.2%	64.0%	63.9%	62.8%	64.2%	64.0%	63.9%	62.8%	64.1%	63.9%	63.8%	62.6%	64.1%	63.9%	63.8%	62.6%
45%	64.3%	64.1%	64.0%	63.0%	64.3%	64.1%	64.0%	63.0%	64.2%	64.1%	63.9%	62.9%	64.2%	64.1%	63.9%	62.9%
50%	64.4%	64.2%	64.1%	63.1%	64.4%	64.2%	64.1%	63.1%	64.3%	64.2%	64.0%	63.0%	64.3%	64.2%	64.0%	63.0%
55%	64.4%	64.3%	64.2%	63.3%	64.4%	64.3%	64.2%	63.3%	64.4%	64.2%	64.1%	63.2%	64.4%	64.2%	64.1%	63.2%
60%	64.5%	64.4%	64.2%	63.4%	64.5%	64.4%	64.2%	63.4%	64.5%	64.3%	64.2%	63.3%	64.5%	64.3%	64.2%	63.3%

*** *Sgl Clr***: Single clear 6 mm
Dbl Clr: Double clear 6mm-13mm air
***Dbl LoE*:** Double Low-e clear 6mm-13mm air
Dbl Ref: Double reflect clear 6mm-13mm air

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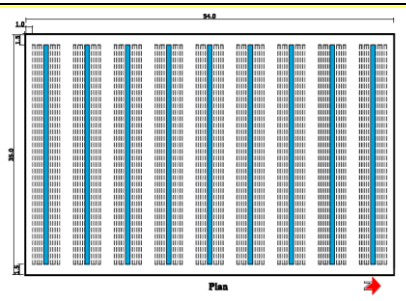
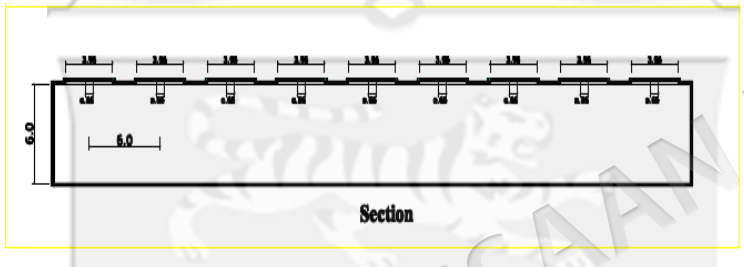
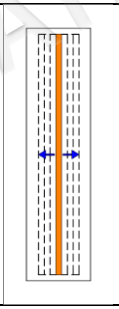
Table A-3: Cooling energy savings (%) for different skylight cases with different glazing types across all orientations as compared to the base case model without daylighting. Skylights 1 to 1 Spacing-to-Ceiling Height Ratio







TFR (%)	North				South				East				West			
	Sgl Clr	Dbl Clr	Dbl LoE	Dbl Ref	Sgl Clr	Dbl Clr	Dbl LoE	Dbl Ref	Sgl Clr	Dbl Clr	Dbl LoE	Dbl Ref	Sgl Clr	Dbl Clr	Dbl LoE	Dbl Ref
5%	0%	2%	5%	4%	0%	2%	5%	4%	0%	2%	5%	4%	0%	2%	5%	4%
10%	-7%	-6%	-1%	-1%	-7%	-6%	-1%	-1%	-7%	-6%	0%	-1%	-7%	-6%	0%	-1%
15%	-9%	-8%	-6%	-6%	-9%	-8%	-6%	-6%	-9%	-8%	-5%	-5%	-9%	-8%	-5%	-5%
20%	-9%	-9%	-7%	-7%	-9%	-9%	-7%	-7%	-9%	-9%	-7%	-7%	-9%	-9%	-7%	-7%
25%	-10%	-10%	-8%	-8%	-10%	-10%	-8%	-8%	-10%	-10%	-8%	-8%	-10%	-10%	-8%	-8%
30%	-10%	-10%	-9%	-8%	-10%	-10%	-9%	-8%	-10%	-10%	-9%	-8%	-10%	-10%	-9%	-8%
35%	-10%	-11%	-9%	-9%	-10%	-11%	-9%	-9%	-10%	-11%	-9%	-9%	-10%	-11%	-9%	-9%
40%	-10%	-11%	-9%	-9%	-10%	-11%	-9%	-9%	-10%	-11%	-9%	-9%	-10%	-11%	-9%	-9%
45%	-10%	-11%	-10%	-9%	-10%	-11%	-10%	-9%	-10%	-11%	-10%	-9%	-10%	-11%	-10%	-9%
50%	-10%	-11%	-10%	-9%	-10%	-11%	-10%	-9%	-10%	-11%	-10%	-9%	-10%	-11%	-10%	-9%
55%	-10%	-11%	-10%	-9%	-10%	-11%	-10%	-9%	-10%	-11%	-10%	-9%	-10%	-11%	-10%	-9%
60%	-10%	-11%	-10%	-10%	-10%	-11%	-10%	-10%	-10%	-11%	-10%	-9%	-10%	-11%	-10%	-9%

**** Sgl Clr***: Single clear 6 mm
Dbl Clr: Double clear 6mm-13mm air
***Dbl LoE*:** Double Low-e clear 6mm-13mm air
Dbl Ref: Double reflect clear 6mm-13mm air

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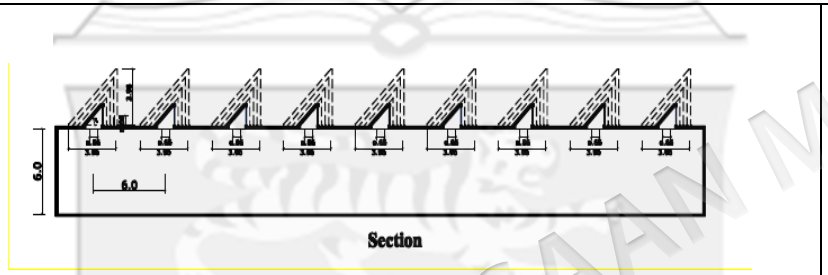
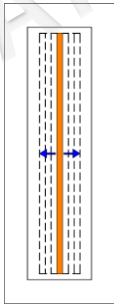
Table A-4: Total energy savings (%) for different sawtooth cases with different glazing types across all orientations as compared to the base case model without daylighting. Sawtooth 1 to 1 Spacing-to-Ceiling Height Ratio





TFR (%)	North				South				East				West			
	Sgl Clr	Dbl Clr	Dbl LoE	Dbl Ref	Sgl Clr	Dbl Clr	Dbl LoE	Dbl Ref	Sgl Clr	Dbl Clr	Dbl LoE	Dbl Ref	Sgl Clr	Dbl Clr	Dbl LoE	Dbl Ref
5%	14.1%	14.3%	14.5%	6.9%	14.6%	14.4%	15.1%	7.3%	13.6%	13.2%	14.2%	7.7%	13.8%	12.8%	13.6%	7.3%
10%	12.5%	13.5%	15.0%	12.1%	12.7%	14.2%	15.6%	11.6%	13.3%	13.7%	14.7%	11.7%	12.2%	13.5%	15.1%	10.7%
15%	8.9%	10.6%	14.3%	11.9%	9.0%	10.8%	14.8%	11.9%	7.7%	9.7%	14.2%	12.2%	9.1%	10.2%	14.4%	10.7%
20%	7.1%	8.3%	13.2%	10.6%	7.3%	8.6%	13.5%	10.9%	6.0%	6.7%	12.9%	10.2%	6.9%	8.3%	12.0%	9.2%
25%	6.1%	6.9%	11.6%	8.9%	6.4%	7.1%	11.6%	9.1%	5.1%	5.6%	9.7%	7.3%	5.8%	6.5%	10.3%	8.1%
30%	5.2%	5.8%	9.6%	7.3%	5.5%	6.2%	9.9%	7.7%	4.7%	5.1%	7.6%	6.3%	5.2%	5.7%	9.2%	7.3%
35%	4.8%	5.1%	8.2%	6.2%	5.0%	5.5%	8.4%	6.5%	4.3%	4.5%	6.7%	5.4%	4.6%	5.0%	8.2%	6.5%
40%	4.3%	4.7%	7.1%	5.6%	4.5%	4.9%	7.5%	5.9%	3.9%	4.2%	5.9%	4.8%	4.2%	4.6%	7.1%	5.7%
45%	4.1%	4.3%	6.4%	5.4%	4.3%	4.5%	6.8%	5.6%	3.4%	3.6%	5.3%	4.2%	3.8%	4.0%	6.2%	4.9%
50%	3.9%	4.1%	5.9%	5.0%	4.0%	4.2%	6.3%	5.3%	3.3%	3.3%	4.9%	3.9%	3.6%	3.7%	5.6%	4.5%
55%	3.5%	3.6%	5.2%	4.4%	3.7%	3.8%	5.6%	4.6%	3.2%	3.2%	4.7%	3.8%	3.5%	3.5%	5.1%	4.5%
60%	3.4%	3.4%	4.8%	4.1%	3.6%	3.6%	5.1%	4.2%	3.0%	3.0%	4.2%	3.5%	3.2%	3.3%	4.7%	4.1%

**** Sgl Clr***: Single clear 6 mm
Dbl Clr: Double clear 6mm-13mm air
***Dbl LoE*:** Double Low-e clear 6mm-13mm air
Dbl Ref: Double reflect clear 6mm-13mm air

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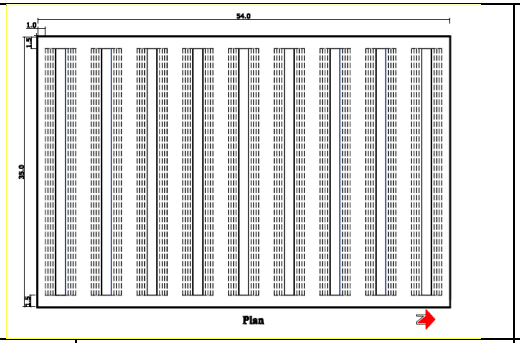
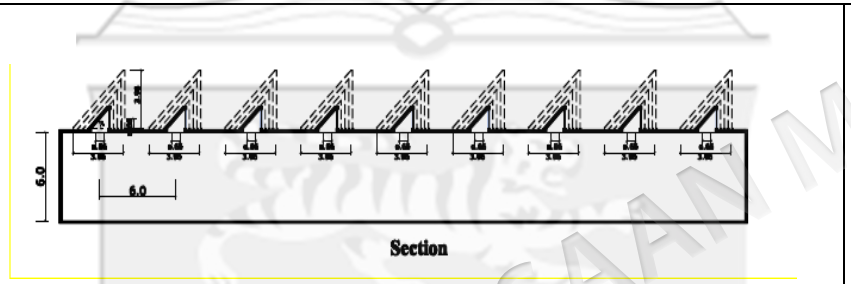
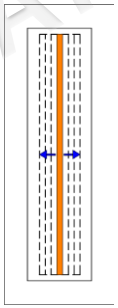
Table A-5: Lighting energy savings (%) for different sawtooth cases with different glazing types across all orientations as compared to the base case model without daylighting. Sawtooth 1 to 1 Spacing-to-Ceiling Height Ratio







TFR (%)	North				South				East				West			
	Sgl Clr	Dbl Clr	Dbl LoE	Dbl Ref	Sgl Clr	Dbl Clr	Dbl LoE	Dbl Ref	Sgl Clr	Dbl Clr	Dbl LoE	Dbl Ref	Sgl Clr	Dbl Clr	Dbl LoE	Dbl Ref
5%	53.6%	51.8%	49.4%	27.3%	53.8%	52.0%	49.8%	30.4%	52.1%	49.4%	46.8%	29.1%	51.7%	49.1%	46.6%	29.5%
10%	58.4%	57.4%	56.6%	47.2%	58.4%	57.5%	56.6%	47.9%	58.1%	57.1%	56.1%	46.3%	58.1%	56.9%	55.8%	46.1%
15%	59.6%	58.8%	58.1%	52.3%	59.6%	58.8%	58.1%	52.6%	60.1%	59.4%	58.8%	53.6%	60.4%	59.6%	58.9%	53.1%
20%	60.6%	60.0%	59.5%	55.1%	60.6%	60.0%	59.5%	55.1%	61.2%	60.7%	60.1%	56.3%	61.4%	60.9%	60.4%	56.0%
25%	61.1%	60.5%	60.0%	56.2%	61.1%	60.5%	60.0%	56.2%	61.7%	61.3%	60.9%	57.6%	61.8%	61.4%	61.0%	57.5%
30%	61.6%	61.0%	60.6%	57.2%	61.6%	61.0%	60.6%	57.3%	62.1%	61.7%	61.3%	58.4%	62.2%	61.8%	61.4%	58.4%
35%	61.9%	61.4%	61.0%	57.9%	61.9%	61.4%	61.0%	57.9%	62.3%	62.0%	61.6%	59.0%	62.4%	62.1%	61.8%	59.1%
40%	62.2%	61.8%	61.4%	58.6%	62.2%	61.8%	61.4%	58.6%	62.5%	62.2%	61.9%	59.4%	62.6%	62.3%	62.0%	59.6%
45%	62.7%	62.4%	62.2%	60.1%	62.8%	62.5%	62.2%	60.1%	62.4%	62.0%	61.7%	59.1%	62.4%	62.1%	61.8%	59.2%
50%	62.9%	62.6%	62.3%	60.4%	62.9%	62.6%	62.4%	60.4%	62.5%	62.2%	61.9%	59.4%	62.6%	62.2%	62.0%	59.6%
55%	62.7%	62.3%	62.1%	59.9%	62.7%	62.4%	62.1%	59.9%	62.9%	62.7%	62.4%	60.5%	63.0%	62.8%	62.5%	60.7%
60%	62.8%	62.5%	62.2%	60.2%	62.8%	62.5%	62.3%	60.1%	63.0%	62.8%	62.5%	60.7%	63.1%	62.8%	62.6%	60.9%

*** *Sgl Clr***: Single clear 6 mm
Dbl Clr: Double clear 6mm-13mm air
***Dbl LoE*:** Double Low-e clear 6mm-13mm air
Dbl Ref: Double reflect clear 6mm-13mm air

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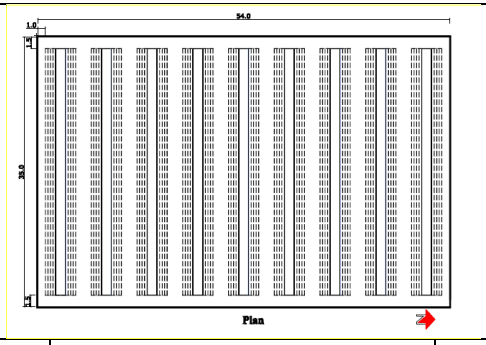
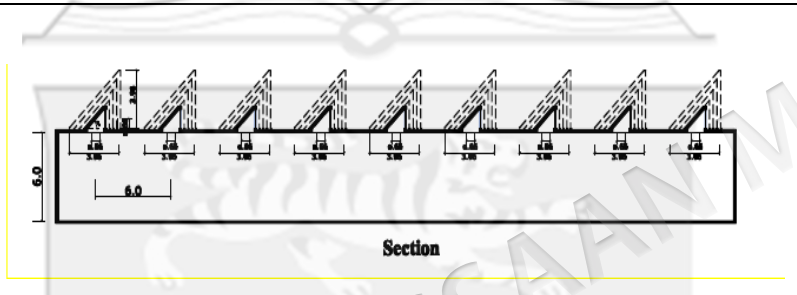
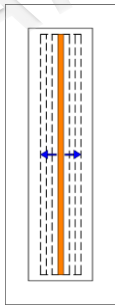
Table A-6: Cooling energy savings (%) for different sawtooth cases with different glazing types across all orientations as compared to the base case model without daylighting. Sawtooth 1 to 1 Spacing-to-Ceiling Height Ratio







TFR (%)	North				South				East				West			
	Sgl Clr	Dbl Clr	Dbl LoE	Dbl Ref	Sgl Clr	Dbl Clr	Dbl LoE	Dbl Ref	Sgl Clr	Dbl Clr	Dbl LoE	Dbl Ref	Sgl Clr	Dbl Clr	Dbl LoE	Dbl Ref
5%	3%	4%	5%	1%	4%	4%	6%	1%	3%	3%	5%	2%	3%	3%	4%	1%
10%	-1%	1%	3%	2%	0%	2%	4%	1%	1%	1%	3%	2%	-1%	1%	4%	1%
15%	-6%	-3%	2%	0%	-6%	-3%	3%	0%	-8%	-5%	2%	1%	-6%	-4%	2%	-1%
20%	-9%	-7%	0%	-2%	-8%	-6%	0%	-2%	-10%	-9%	-1%	-3%	-9%	-7%	-2%	-4%
25%	-10%	-9%	-2%	-5%	-10%	-9%	-2%	-4%	-12%	-11%	-5%	-8%	-11%	-10%	-4%	-6%
30%	-12%	-10%	-5%	-7%	-11%	-10%	-5%	-7%	-12%	-12%	-8%	-9%	-12%	-11%	-6%	-8%
35%	-12%	-12%	-7%	-9%	-12%	-11%	-7%	-9%	-13%	-13%	-10%	-10%	-13%	-12%	-7%	-9%
40%	-13%	-12%	-9%	-10%	-13%	-12%	-8%	-10%	-14%	-13%	-11%	-11%	-13%	-13%	-9%	-10%
45%	-13%	-13%	-10%	-11%	-13%	-13%	-10%	-10%	-14%	-14%	-11%	-12%	-14%	-13%	-10%	-11%
50%	-14%	-13%	-11%	-11%	-14%	-13%	-10%	-11%	-14%	-14%	-12%	-13%	-14%	-14%	-11%	-12%
55%	-14%	-14%	-12%	-12%	-14%	-14%	-11%	-12%	-15%	-15%	-13%	-13%	-14%	-14%	-12%	-12%
60%	-14%	-14%	-12%	-13%	-14%	-14%	-12%	-12%	-15%	-15%	-13%	-14%	-15%	-15%	-13%	-13%

*** *Sgl Clr***: Single clear 6 mm
Dbl Clr: Double clear 6mm-13mm air
***Dbl LoE*:** Double Low-e clear 6mm-13mm air
Dbl Ref: Double reflect clear 6mm-13mm air

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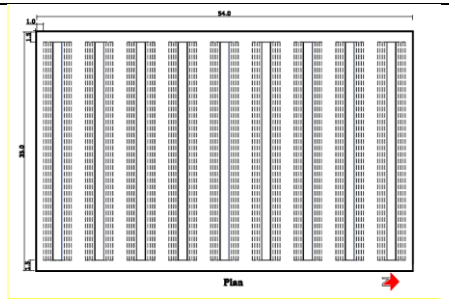
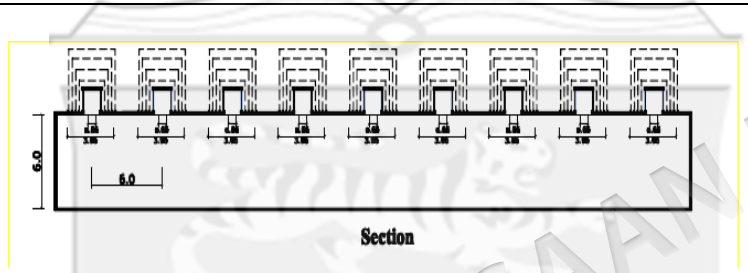
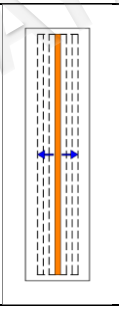
Table A-7: Total energy savings (%) for different roof monitor cases with different glazing types across all orientations as compared to the base case model without daylighting. Roof Monitor 1 to 1 Spacing-to-Ceiling Height Ratio







TFR (%)	North				South				East				West			
	Sgl Clr	Dbl Clr	Dbl LoE	Dbl Ref	Sgl Clr	Dbl Clr	Dbl LoE	Dbl Ref	Sgl Clr	Dbl Clr	Dbl LoE	Dbl Ref	Sgl Clr	Dbl Clr	Dbl LoE	Dbl Ref
5%	12.4%	13.9%	15.3%	12.3%	12.4%	13.9%	15.3%	12.3%	13.7%	14.2%	15.1%	12.4%	13.7%	14.2%	15.1%	12.4%
10%	7.3%	8.4%	13.5%	10.9%	7.3%	8.4%	13.5%	10.9%	6.2%	6.8%	12.3%	9.6%	6.2%	6.8%	12.3%	9.6%
15%	5.7%	6.2%	9.4%	7.4%	5.7%	6.2%	9.4%	7.4%	4.2%	4.9%	9.1%	7.0%	4.2%	4.9%	9.1%	7.0%
20%	4.9%	5.3%	7.4%	5.9%	4.9%	5.3%	7.4%	5.9%	3.9%	4.2%	6.8%	5.5%	3.9%	4.2%	6.8%	5.5%
25%	4.4%	4.6%	6.4%	5.2%	4.4%	4.6%	6.4%	5.2%	3.8%	3.9%	5.3%	4.6%	3.8%	3.9%	5.3%	4.6%
30%	4.0%	4.1%	5.6%	4.7%	4.0%	4.1%	5.6%	4.7%	3.5%	3.5%	4.6%	4.1%	3.5%	3.5%	4.6%	4.1%
35%	3.7%	3.7%	4.9%	4.3%	3.7%	3.7%	4.9%	4.3%	3.5%	3.4%	4.4%	4.0%	3.5%	3.4%	4.4%	4.0%
40%	3.5%	3.5%	4.6%	4.1%	3.5%	3.5%	4.6%	4.1%	3.3%	3.2%	4.1%	3.8%	3.3%	3.2%	4.1%	3.8%
45%	3.4%	3.3%	4.2%	3.8%	3.4%	3.3%	4.2%	3.8%	3.2%	3.1%	3.9%	3.7%	3.2%	3.1%	3.9%	3.7%
50%	3.2%	3.1%	4.0%	3.8%	3.2%	3.1%	4.0%	3.8%	3.1%	3.1%	3.9%	3.5%	3.1%	3.1%	3.9%	3.5%
55%	3.1%	2.9%	3.9%	3.7%	3.1%	2.9%	3.9%	3.7%	3.0%	3.0%	3.7%	3.4%	3.0%	3.0%	3.7%	3.4%
60%	2.9%	2.7%	3.8%	3.5%	2.9%	2.7%	3.8%	3.5%	2.9%	2.9%	3.7%	3.4%	2.9%	2.9%	3.7%	3.4%

*** *Sgl Clr***: Single clear 6 mm
Dbl Clr: Double clear 6mm-13mm ai
***Dbl LoE*:** Double Low-e clear 6mm-13mm air
Dbl Ref: Double reflect clear 6mm-13mm air

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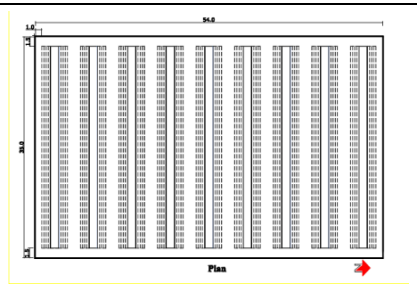
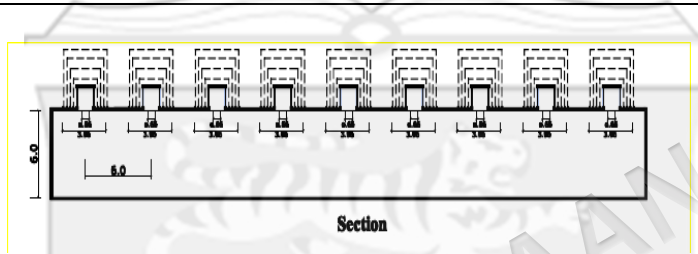
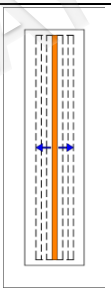
Table A-8: Lighting energy savings (%) for different roof monitor cases with different glazing types across all orientations as compared to the base case model without daylighting. Roof Monitor 1 to 1 Spacing-to-Ceiling Height Ratio







TFR (%)	North				South				East				West			
	Sgl Clr	Dbl Clr	Dbl LoE	Dbl Ref	Sgl Clr	Dbl Clr	Dbl LoE	Dbl Ref	Sgl Clr	Dbl Clr	Dbl LoE	Dbl Ref	Sgl Clr	Dbl Clr	Dbl LoE	Dbl Ref
5%	58.2%	57.4%	56.6%	49.1%	58.2%	57.4%	56.6%	49.1%	58.0%	57.1%	56.2%	49.5%	58.0%	57.1%	56.2%	49.5%
10%	60.8%	60.3%	59.8%	55.9%	60.8%	60.3%	59.8%	55.9%	61.3%	60.8%	60.3%	56.9%	61.3%	60.8%	60.3%	56.9%
15%	61.6%	61.1%	60.6%	57.5%	61.6%	61.1%	60.6%	57.5%	61.8%	61.3%	60.8%	57.8%	61.8%	61.3%	60.8%	57.8%
20%	62.2%	61.8%	61.4%	58.7%	62.2%	61.8%	61.4%	58.7%	62.5%	62.2%	61.9%	59.5%	62.5%	62.2%	61.9%	59.5%
25%	62.4%	62.1%	61.7%	59.3%	62.4%	62.1%	61.7%	59.3%	62.9%	62.6%	62.4%	60.5%	62.9%	62.6%	62.4%	60.5%
30%	62.7%	62.4%	62.2%	60.1%	62.7%	62.4%	62.2%	60.1%	63.1%	62.9%	62.6%	61.0%	63.1%	62.9%	62.6%	61.0%
35%	62.9%	62.6%	62.4%	60.5%	62.9%	62.6%	62.4%	60.5%	63.4%	63.1%	62.9%	61.5%	63.4%	63.1%	62.9%	61.5%
40%	63.1%	62.8%	62.6%	60.9%	63.1%	62.8%	62.6%	60.9%	63.5%	63.3%	63.0%	61.7%	63.5%	63.3%	63.0%	61.7%
45%	62.8%	62.4%	62.1%	60.0%	62.8%	62.4%	62.1%	60.0%	63.0%	62.7%	62.4%	60.7%	63.0%	62.7%	62.4%	60.7%
50%	62.9%	62.5%	62.3%	60.3%	62.9%	62.5%	62.3%	60.3%	63.0%	62.8%	62.5%	60.8%	63.0%	62.8%	62.5%	60.8%
55%	63.0%	62.6%	62.4%	60.5%	63.0%	62.6%	62.4%	60.5%	63.1%	62.8%	62.6%	61.0%	63.1%	62.8%	62.6%	61.0%
60%	63.2%	62.8%	62.5%	60.8%	63.2%	62.8%	62.5%	60.8%	63.3%	63.0%	62.8%	61.4%	63.3%	63.0%	62.8%	61.4%

*** *Sgl Clr***: Single clear 6 mm
Dbl Clr: Double clear 6mm-13mm air
Dbl LoE**:** Double Low-e clear 6mm-13mm air
Dbl Ref: Double reflect clear 6mm-13mm air

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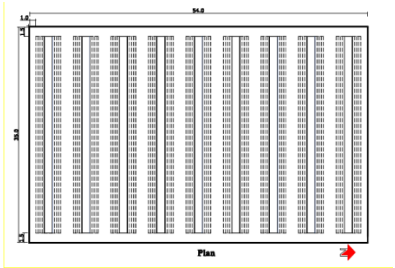
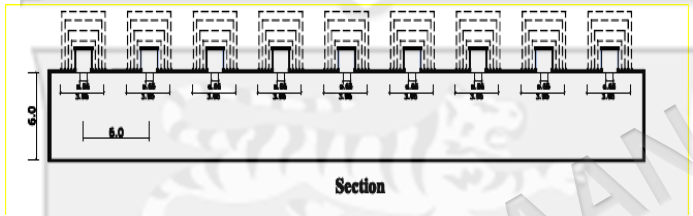
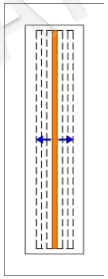
Table A-9: Cooling energy savings (%) for different roof monitor cases with different glazing types across all orientations as compared to the base case model without daylighting. Roof Monitor 1 to 1 Spacing-to-Ceiling Height Ratio







TFR (%)	North				South				East				West			
	Sgl Clr	Dbl Clr	Dbl LoE	Dbl Ref	Sgl Clr	Dbl Clr	Dbl LoE	Dbl Ref	Sgl Clr	Dbl Clr	Dbl LoE	Dbl Ref	Sgl Clr	Dbl Clr	Dbl LoE	Dbl Ref
5%	-1%	2%	4%	2%	-1%	2%	4%	2%	1%	2%	4%	2%	1%	2%	4%	2%
10%	-8%	-7%	0%	-2%	-8%	-7%	0%	-2%	-7%	-6%	-1%	-3%	-7%	-6%	-1%	-3%
15%	-11%	-10%	-6%	-7%	-11%	-10%	-6%	-7%	-11%	-10%	-6%	-8%	-11%	-10%	-6%	-8%
20%	-12%	-12%	-8%	-10%	-12%	-12%	-8%	-10%	-13%	-12%	-9%	-10%	-13%	-12%	-9%	-10%
25%	-13%	-13%	-10%	-11%	-13%	-13%	-10%	-11%	-14%	-14%	-12%	-12%	-14%	-14%	-12%	-12%
30%	-14%	-13%	-11%	-12%	-14%	-13%	-11%	-12%	-14%	-14%	-13%	-13%	-14%	-14%	-13%	-13%
35%	-14%	-14%	-12%	-12%	-14%	-14%	-12%	-12%	-14%	-14%	-13%	-13%	-14%	-14%	-13%	-13%
40%	-14%	-14%	-13%	-13%	-14%	-14%	-13%	-13%	-15%	-15%	-13%	-14%	-15%	-15%	-13%	-14%
45%	-14%	-14%	-13%	-13%	-14%	-14%	-13%	-13%	-15%	-15%	-14%	-14%	-15%	-15%	-14%	-14%
50%	-14%	-14%	-13%	-13%	-14%	-14%	-13%	-13%	-15%	-15%	-14%	-14%	-15%	-15%	-14%	-14%
55%	-14%	-15%	-13%	-13%	-14%	-15%	-13%	-13%	-15%	-15%	-14%	-14%	-15%	-15%	-14%	-14%
60%	-14%	-15%	-13%	-14%	-14%	-15%	-13%	-14%	-15%	-15%	-15%	-15%	-15%	-15%	-15%	-15%

**** Sgl Clr***: Single clear 6 mm
Dbl Clr: Double clear 6mm-13mm air
***Dbl LoE*:** Double Low-e clear 6mm-13mm air
Dbl Ref: Double reflect clear 6mm-13mm air

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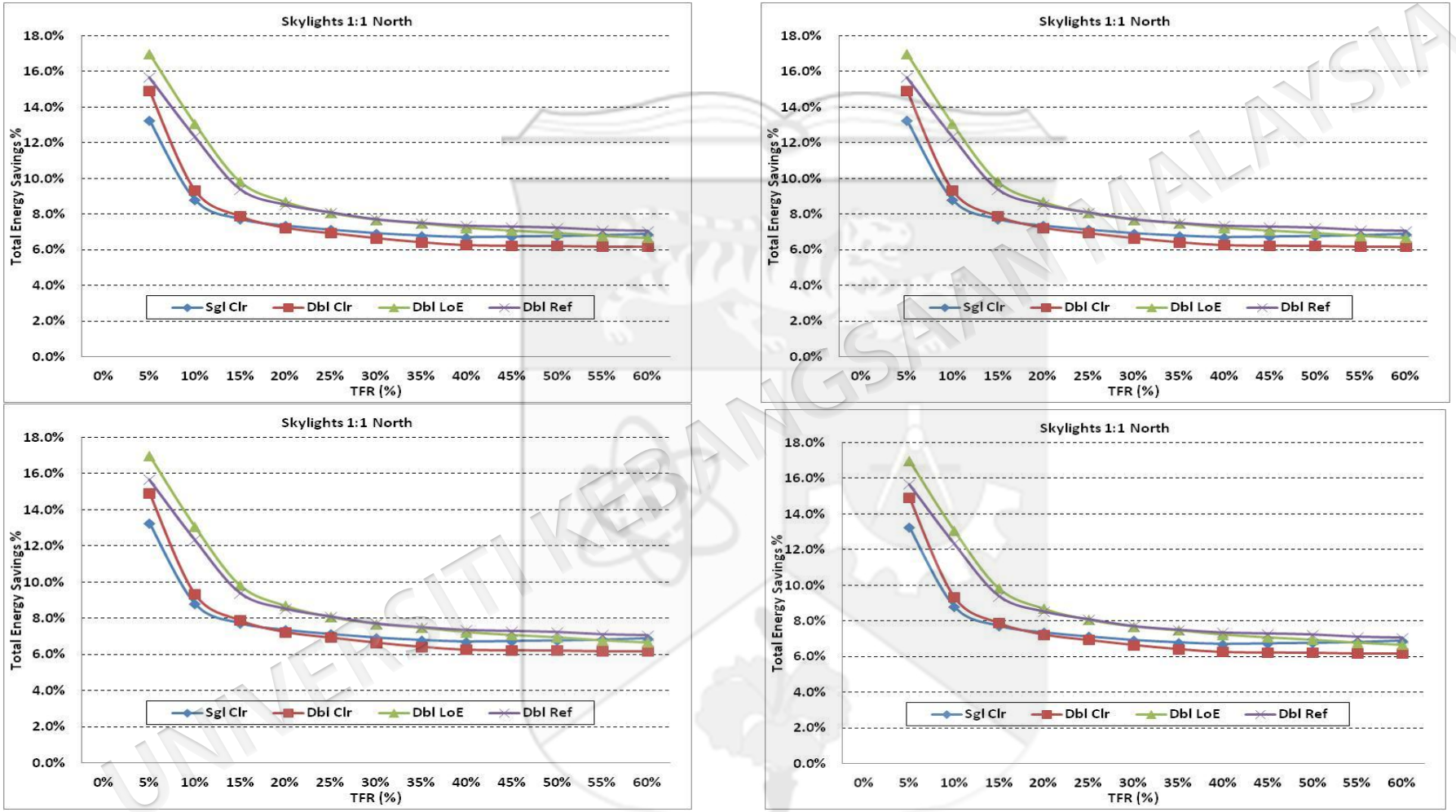

Figure A-1 Total energy savings (%) for different skylight cases with different glazing types across all orientations as compared to the base case model without daylighting. 1 to 1 Spacing-to-Height Ratio

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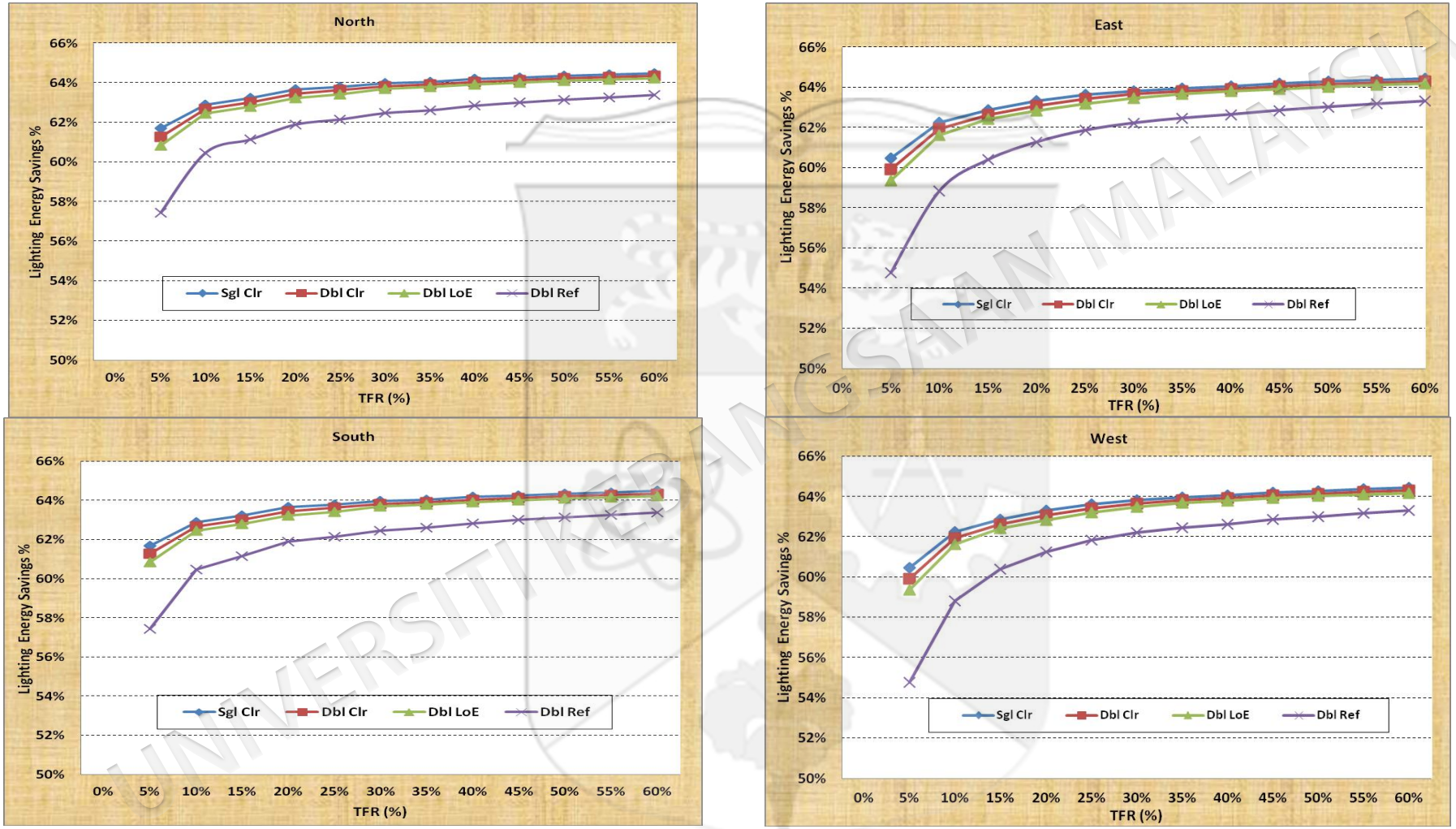

Figure A-2 Lighting energy savings (%) for different skylight cases with different glazing types across all orientations as compared to the base case model without daylighting. 1 to 1 Spacing-to-Height Ratio

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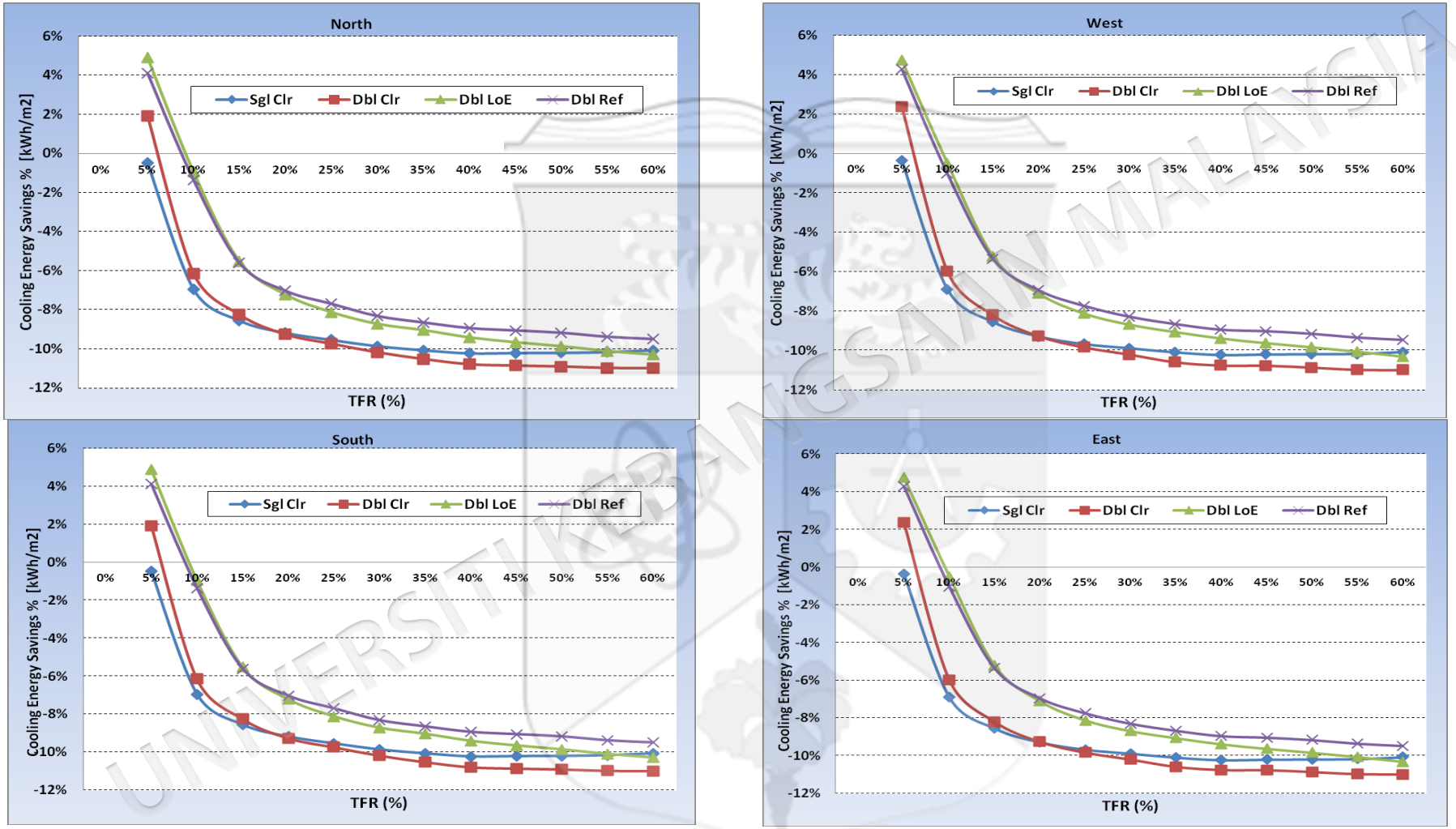

Figure A-3 Cooling energy savings (%) for different skylight cases with different glazing types across all orientations as compared to the base case model without daylighting. 1 to 1 Spacing-to-Height Ratio

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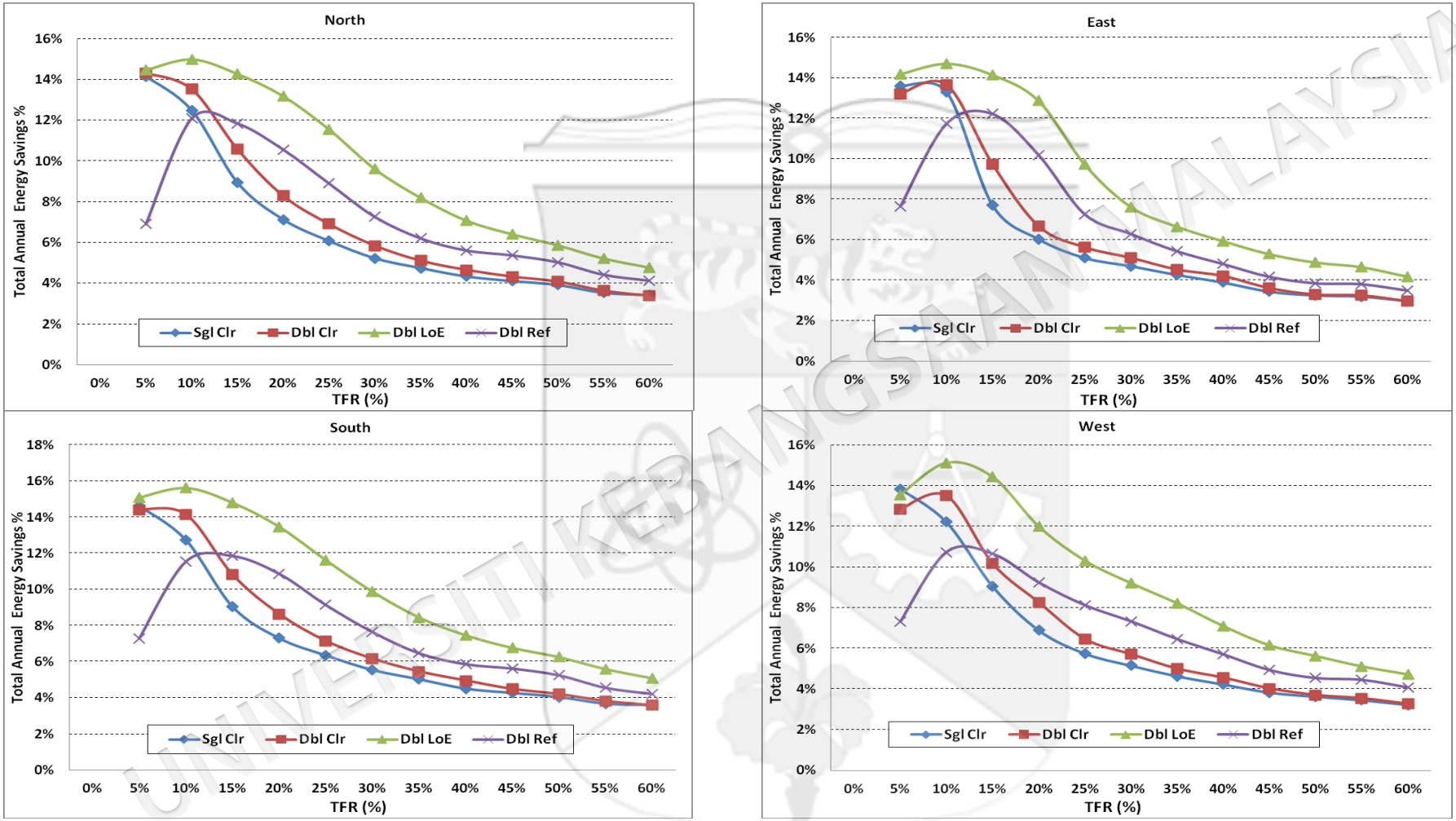

Figure A-4 Total energy savings (%) for different sawtooth cases with different glazing types across all orientations as compared to the base case model without daylighting. 1 to 1 Spacing-to-Height Ratio

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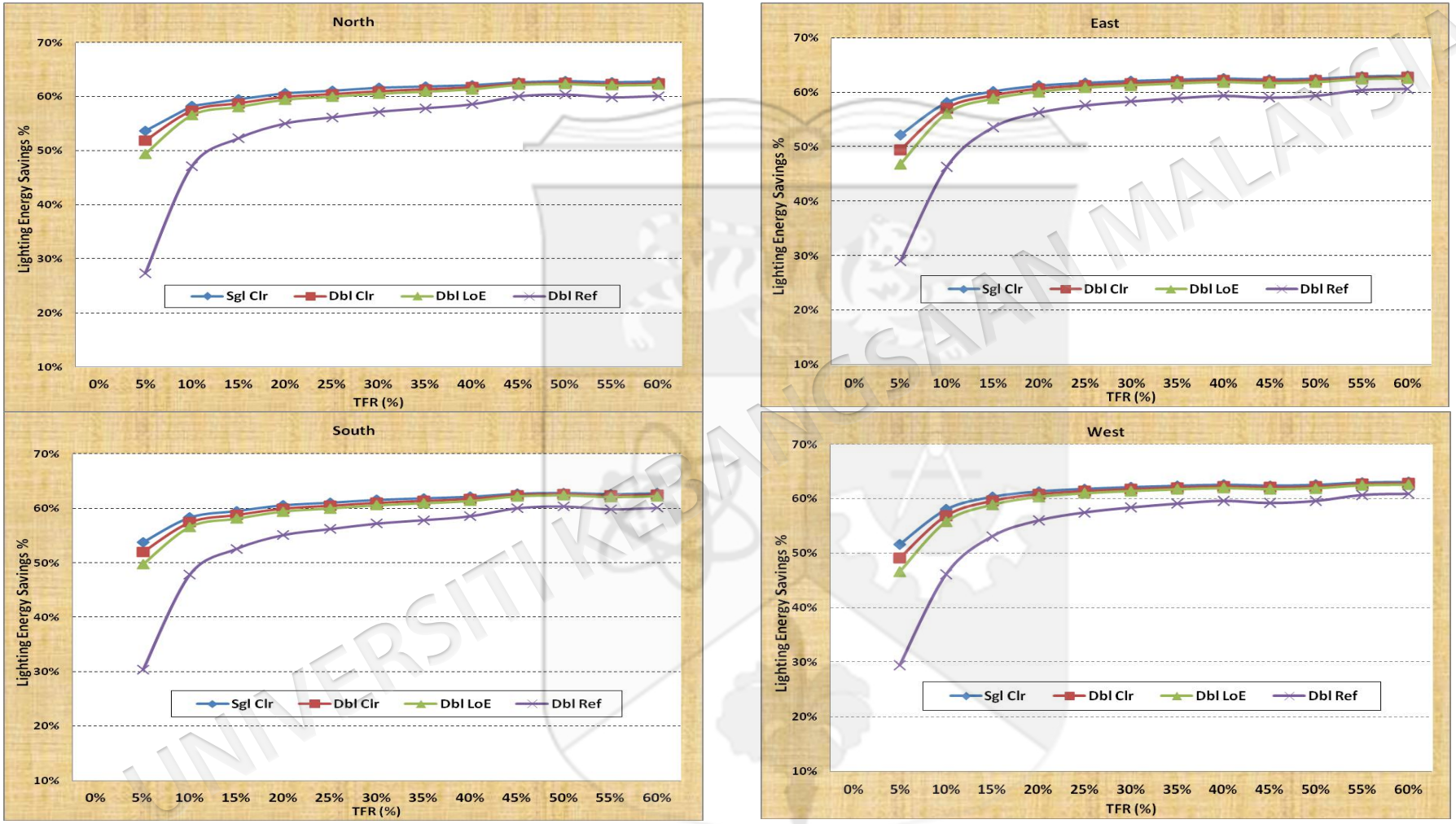

Figure A-5 Lighting energy savings (%) for different sawtooth cases with different glazing types across all orientations as compared to the base case model without daylighting. 1 to 1 Spacing-to-Height Ratio

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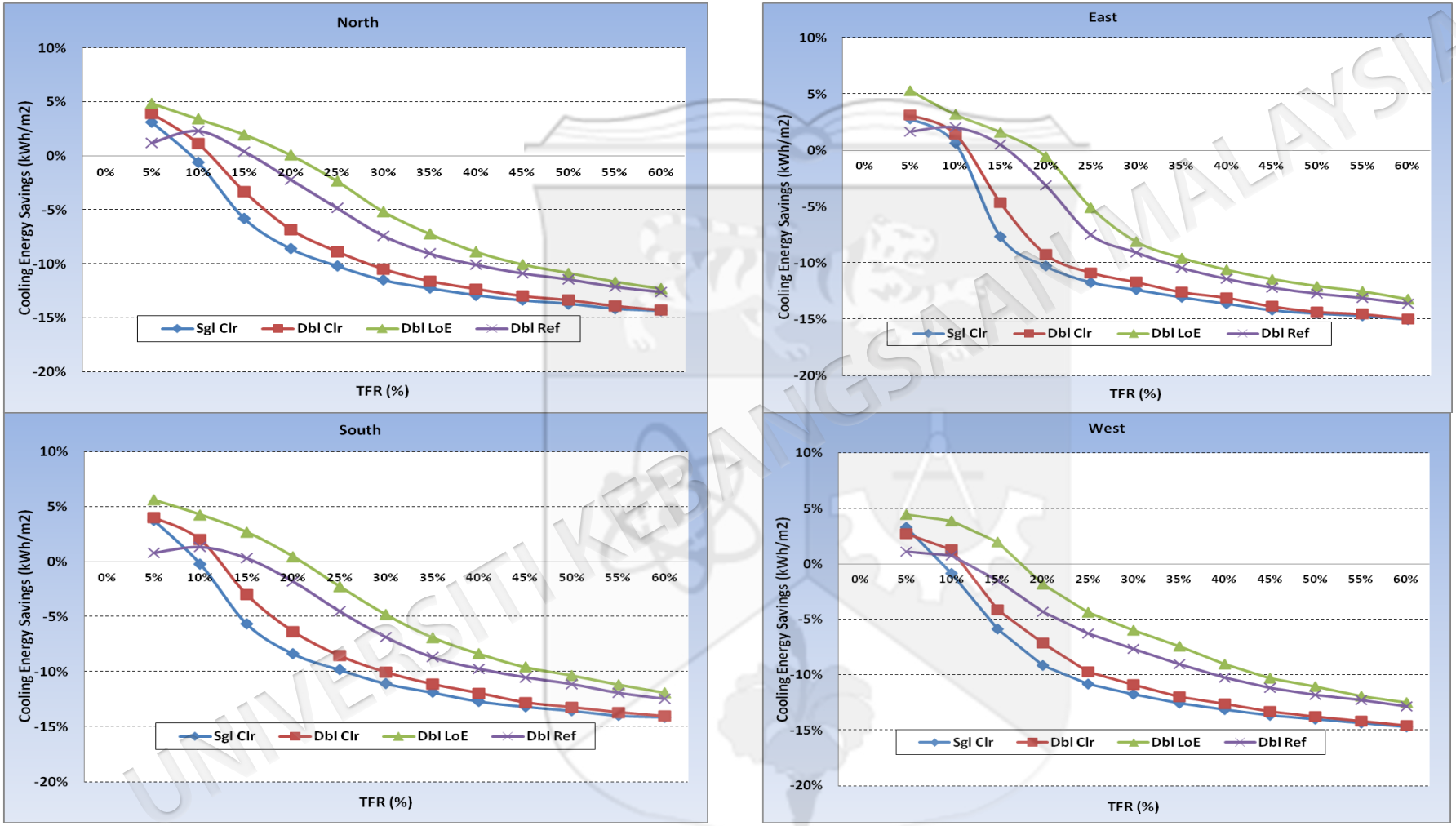

Figure A-6: Cooling energy savings (%) for different sawtooth cases with different glazing types across all orientations as compared to the base case model without daylighting. 1 to 1 Spacing-to-Height Ratio

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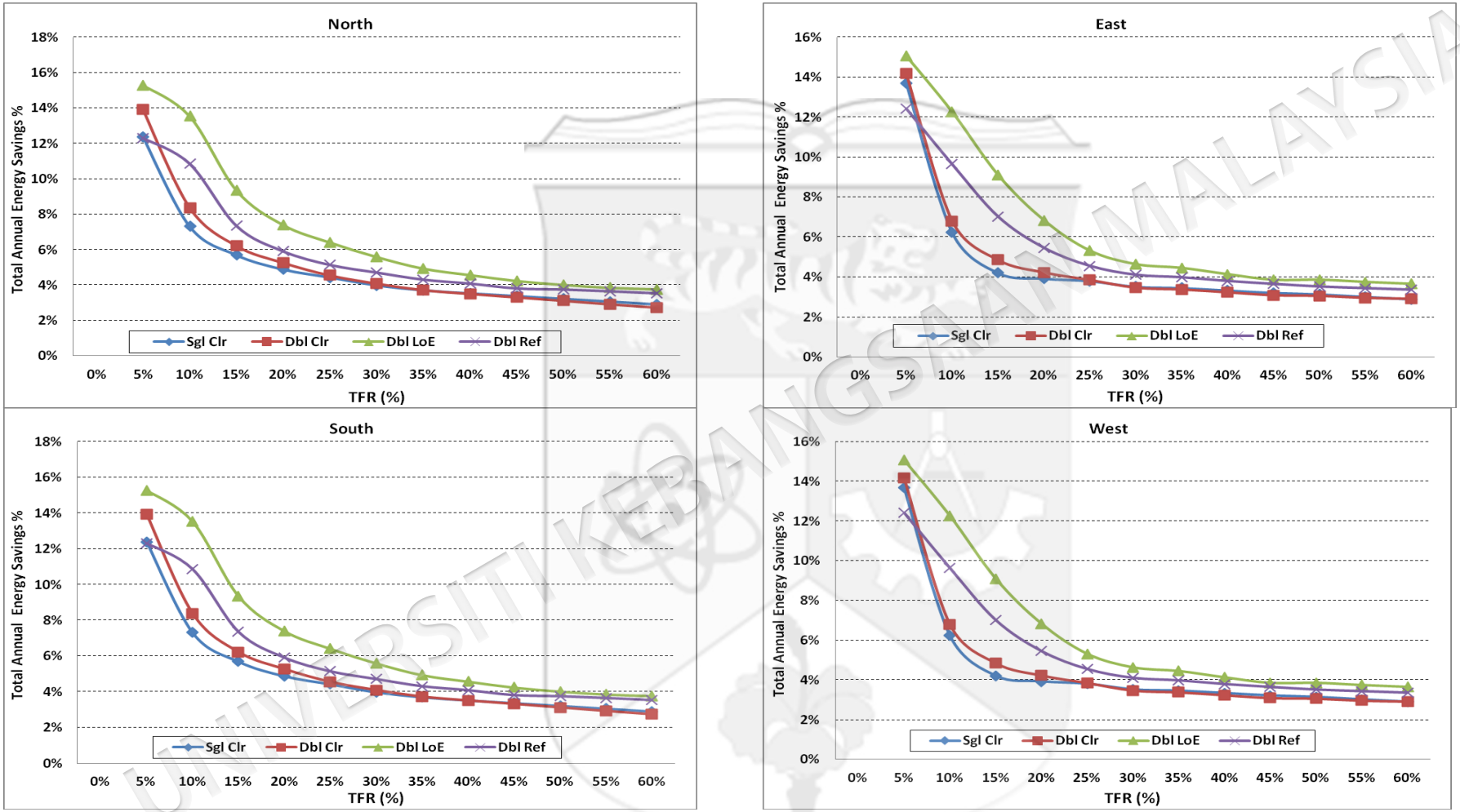

Figure A-7 Total energy savings (%) for different roof monitor cases with different glazing types across all orientations as compared to the base case model without daylighting. 1 to 1 Spacing-to-Height Ratio

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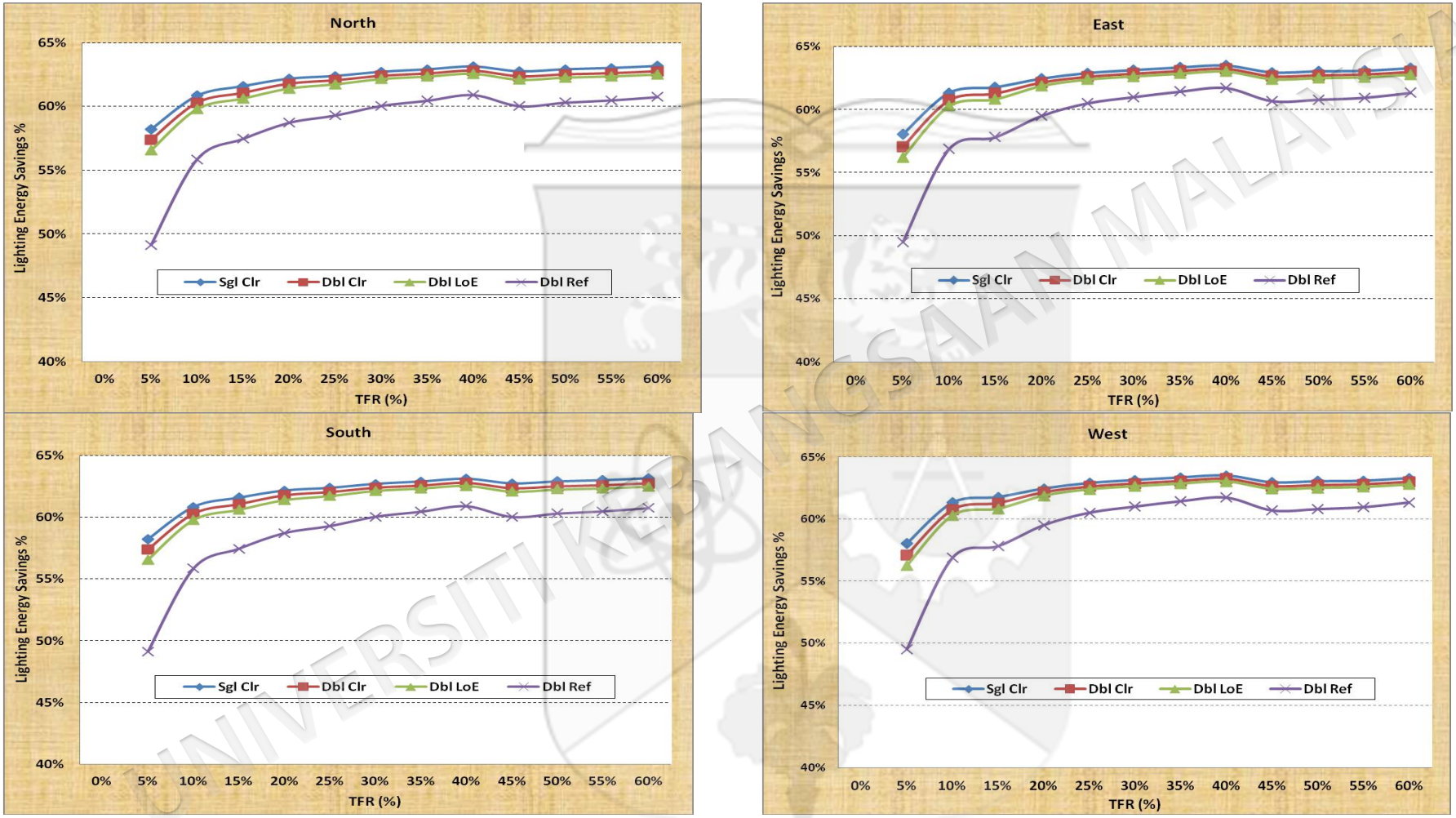

Figure A-8 Lighting energy savings (%) for different roof monitor cases with different glazing types across all orientations as compared to the base case model without daylighting. 1 to 1 Spacing-to-Height Ratio

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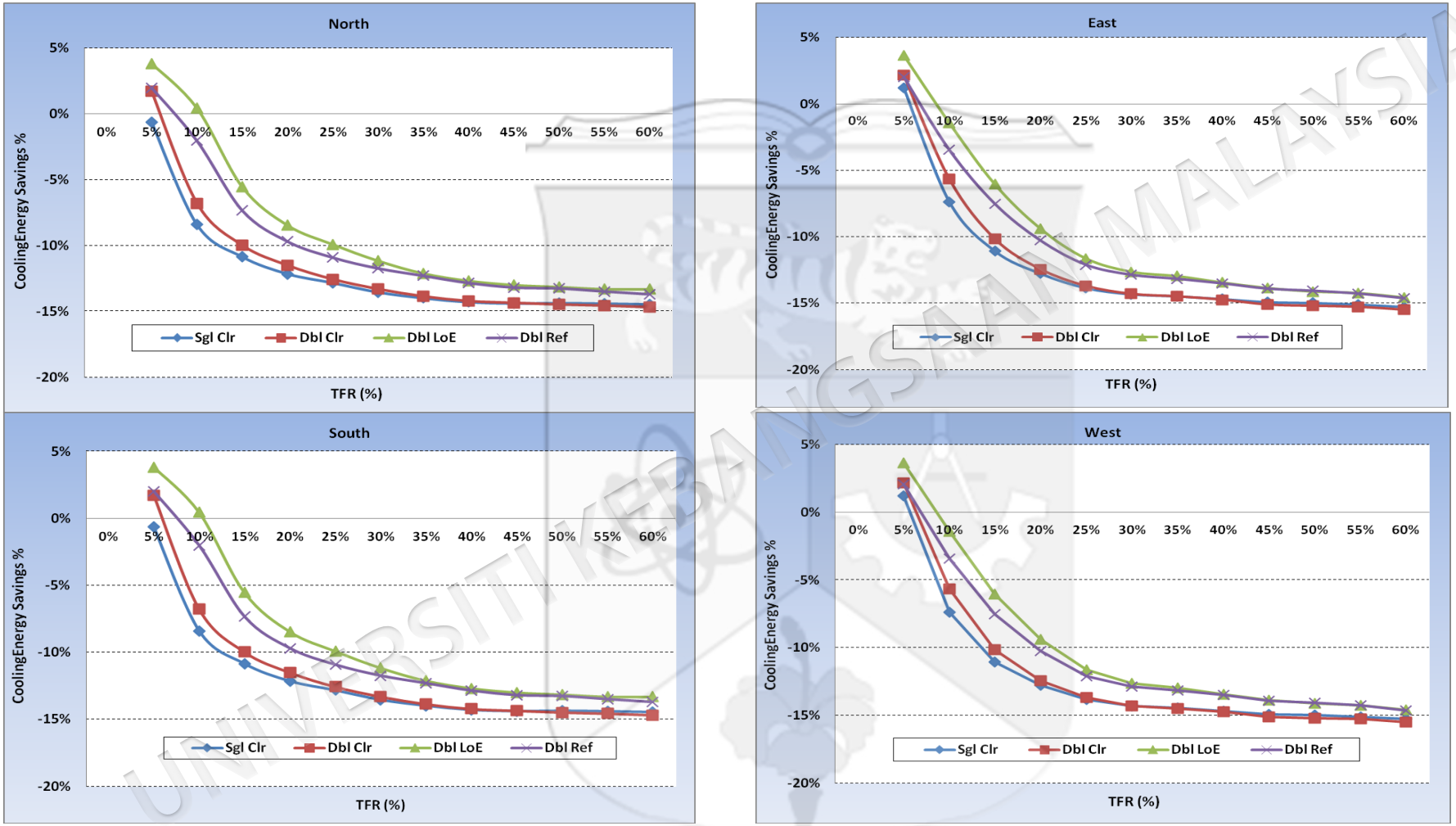

Figure A-9 Cooling energy savings (%) for different roof monitor cases with different glazing types across all orientations as compared to the base case model without daylighting. 1 to 1 Spacing-to-Height Ratio

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Table A-10 Total energy savings (%) comparison for the different toplighting options with different glazing types, in all orientations and TFR of 15% as compared to the base case model. A negative value represents an increase in the energy consumed.

TFR 15%		North				South				East				West			
		Sgl	Dbl	LoE	Ref	Sgl	Dbl	LoE	Ref	Sgl	Dbl	LoE	Ref	Sgl	Dbl	LoE	Ref
Skylight	Light	63%	63%	63%	61%	63%	63%	63%	61%	63%	63%	62%	60%	63%	63%	62%	60%
	Cool	-8.6%	-8.3%	-5.5%	-5.6%	-8.6%	-8.3%	-5.5%	-5.6%	-8.5%	-8.2%	-5.2%	-5.4%	-8.5%	-8.2%	-5.2%	-5.4%
	Total	**7.7%**	**7.9%**	**9.8%**	**9.4%**	**7.7%**	**7.9%**	**9.8%**	**9.4%**	**7.7%**	**7.9%**	**10%**	**9.4%**	**7.7%**	**7.9%**	**10%**	**9.4%**
Sawtooth	Light	60%	59%	58%	52%	60%	59%	58%	53%	60%	59%	59%	54%	60%	60%	59%	53%
	Cool	-5.8%	-3.3%	2.0%	0.4%	-5.6%	-3.0%	2.7%	0.3%	-7.7%	-4.7%	1.6%	0.5%	-5.9%	-4.1%	2.0%	-1.5%
	Total	**8.9%**	**11%**	**14%**	**12%**	**9.0%**	**11%**	**15%**	**12%**	**7.7%**	**9.7%**	**14%**	**12%**	**9.1%**	**10%**	**14%**	**11%**
Roof Monitor	Light	62%	61%	61%	57%	62%	61%	61%	57%	62%	61%	61%	58%	62%	61%	61%	58%
	Cool	-11%	-10%	-5.5%	-7.3%	-11%	-10%	-5.5%	-7.3%	-11%	-10%	-6.0%	-7.5%	-11%	-10%	-6.0%	-7.5%
	Total	**5.7%**	**6.2%**	**9.4%**	**7.4%**	**5.7%**	**6.2%**	**9.4%**	**7.4%**	**4.2%**	**4.9%**	**9.1%**	**7.0%**	**4.2%**	**4.9%**	**9.1%**	**7.0%**

**** Sgl Clr***: Single clear 6 mm
Dbl Clr: Double clear 6mm-13mm air
***Dbl LoE*:** Double Low-e clear 6mm-13mm air
Dbl Ref: Double reflect clear 6mm-13mm air

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Table A-11 Total energy savings (%) comparison for the different toplighting options with different glazing types, in all orientations and TFR of 20% as compared to the base case model. A negative value represents an increase in the energy consumed.

TFR **20%**		**North**				**South**				**East**				**West**			
		Sgl	Dbl	LoE	Ref	Sgl	Dbl	LoE	Ref	Sgl	Dbl	LoE	Ref	Sgl	Dbl	LoE	Ref
Skylight	Light	64%	63%	63%	62%	**64%**	**63%**	**63%**	**62%**	**63%**	**63%**	**63%**	61%	63%	63%	63%	61%
	Cool	-9.2%	-9.3%	-7.2%	-7.0%	**-9.2%**	**-9.3%**	**-7.2%**	**-7.0%**	**-9.3%**	**-9.3%**	**-7.1%**	-6.9%	-9.3%	-9.3%	-7.1%	-6.9%
	Total	7.4%	7.3%	8.7%	8.5%	**7.4%**	**7.3%**	**8.7%**	**8.5%**	**7.2%**	**7.2%**	**8.7%**	8.5%	7.2%	7.2%	8.7%	8.5%
Sawtooth	Light	61%	60%	59%	55%	**61%**	**60%**	**59%**	**55%**	**61%**	**61%**	**60%**	56%	61%	61%	60%	56%
	Cool	-9%	-7%	0%	-2%	-8%	-6%	0%	-2%	-10%	-9%	-1%	-3%	-9%	-7%	-2%	-4%
	Total	7.1%	8.3%	13%	11%	**7.3%**	**8.6%**	**13%**	**11%**	**6.0%**	**6.7%**	**13%**	10%	6.9%	8.3%	12%	9.2%
Roof Monitor	Light	**62%**	**62%**	**61%**	**59%**	**62%**	**62%**	**61%**	**59%**	**62%**	**62%**	**62%**	60%	62%	62%	62%	60%
	Cool	-12%	-12%	-8%	-10%	-12%	-12%	-8%	-10%	-13%	-12%	-9%	-10%	-13%	-12%	-9%	-10%
	Total	**4.9%**	**5.3%**	**7.4%**	**5.9%**	**4.9%**	**5.3%**	**7.4%**	**5.9%**	**3.9%**	**4.2%**	**6.8%**	5.5%	3.9%	4.2%	6.8%	5.5%

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Table A-12 Total energy savings (%) comparison for the different toplighting options with different glazing types, all orientations, and TFR of 25% as compared to the base case model. A negative value represents an increase in the energy consumed.

TFR **25%**		**North**				**South**				**East**				**West**			
		Sgl	Dbl	LoE	Ref	Sgl	Dbl	LoE	Ref	Sgl	Dbl	LoE	Ref	Sgl	Dbl	LoE	Ref
Skylight	Light	64%	64%	63%	62%	**64%**	**64%**	**63%**	**62%**	**64%**	**63%**	**63%**	62%	64%	63%	63%	62%
	Cool	-9.5%	-9.7%	-8.1%	-7.7%	**-9.5%**	**-9.7%**	**-8.1%**	**-7.7%**	**-9.7%**	**-9.8%**	**-8.1%**	-7.7%	-9.7%	-9.8%	-8.1%	-7.7%
	Total	7.1%	7.0%	8.1%	8.1%	**7.1%**	**7.0%**	**8.1%**	**8.1%**	**7.0%**	**6.8%**	**8.0%**	8.0%	7.0%	6.8%	8.0%	8.0%
Sawtooth	Light	61%	60%	60%	56%	**61%**	**61%**	**60%**	**56%**	**62%**	**61%**	**61%**	58%	62%	61%	61%	57%
	Cool	-10%	-9%	-2%	-5%	-10%	-9%	-2%	-4%	-12%	-11%	-5%	-8%	-11%	-10%	-4%	-6%
	Total	6.1%	6.9%	12%	8.9%	**6.4%**	**7.1%**	**12%**	**9.1%**	**5.1%**	**5.6%**	**9.7%**	7.3%	5.8%	6.5%	10%	8.1%
Roof Monitor	Light	**62%**	**62%**	**62%**	**59%**	**62%**	**62%**	**62%**	**59%**	**63%**	**63%**	**62%**	61%	63%	63%	62%	61%
	Cool	-13%	-13%	-10%	-11%	-13%	-13%	-10%	-11%	-14%	-14%	-12%	-12%	-14%	-14%	-12%	-12%
	Total	**4.4%**	**4.6%**	**6.4%**	**5.2%**	**4.4%**	**4.6%**	**6.4%**	**5.2%**	**3.8%**	**3.9%**	**5.3%**	4.6%	3.8%	3.9%	5.3%	4.6%

UNIVERSITI KEBANGSAAN MALAYSIA

Table A-13 Total energy savings (%) comparison for the different toplighting options with different glazing types, in all orientations and TFR of 30% as compared to the base case model. A negative value represents an increase in the energy consumed.

TFR **30%**		**North**				**South**				**East**				**West**			
		Sgl	Dbl	LoE	Ref	Sgl	Dbl	LoE	Ref	Sgl	Dbl	LoE	Ref	Sgl	Dbl	LoE	Ref
Skylight	Light	64%	64%	64%	62%	**64%**	**64%**	**64%**	**62%**	**64%**	**64%**	**63%**	62%	64%	64%	63%	62%
	Cool	-9.9%	-10%	-8.7%	-8.3%	**-9.9%**	**-10%**	**-8.7%**	**-8.3%**	**-9.9%**	**-10%**	**-8.7%**	-8.3%	-9.9%	-10%	-8.7%	-8.3%
	Total	6.9%	6.7%	7.7%	7.7%	**6.9%**	**6.7%**	**7.7%**	**7.7%**	**6.9%**	**6.6%**	**7.7%**	7.7%	6.9%	6.6%	7.7%	7.7%
Sawtooth	Light	62%	61%	61%	57%	**62%**	**61%**	**61%**	**57%**	**62%**	**62%**	**61%**	58%	62%	62%	61%	58%
	Cool	-12%	-10%	-5%	-7%	-11%	-10%	-5%	-7%	-12%	-12%	-8%	-9%	-12%	-11%	-6%	-8%
	Total	5.2%	5.8%	9.6%	7.3%	**5.5%**	**6.2%**	**9.9%**	**7.7%**	**4.7%**	**5.1%**	**7.6%**	6.3%	5.2%	5.7%	9.2%	7.3%
Roof Monitor	Light	**63%**	**62%**	**62%**	**60%**	**63%**	**62%**	**62%**	**60%**	**63%**	**63%**	**63%**	61%	63%	63%	63%	61%
	Cool	-14%	-13%	-11%	-12%	-14%	-13%	-11%	-12%	-14%	-14%	-13%	-13%	-14%	-14%	-13%	-13%
	Total	**4.0%**	**4.1%**	**5.6%**	**4.7%**	**4.0%**	**4.1%**	**5.6%**	**4.7%**	**3.5%**	**3.5%**	**4.6%**	4.1%	3.5%	3.5%	4.6%	4.1%

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Table A-14 Total energy savings (%) comparison for the different toplighting options with different glazing types, all orientations, and TFR of 40% as compared to the base case model. A negative value represents an increase in the energy consumed.

TFR **40%**		**North**				**South**				**East**				**West**			
		Sgl	Dbl	LoE	Ref	Sgl	Dbl	LoE	Ref	Sgl	Dbl	LoE	Ref	Sgl	Dbl	LoE	Ref
Skylight	Light	64%	64%	64%	63%	**64%**	**64%**	**64%**	**63%**	**64%**	**64%**	**64%**	63%	64%	64%	64%	63%
	Cool	-10%	-11%	-9.4%	-8.9%	**-10%**	**-11%**	**-9.4%**	**-8.9%**	**-10%**	**-11%**	**-9.4%**	-9.0%	-10%	-11%	-9.4%	-9.0%
	Total	6.7%	6.3%	7.3%	7.4%	**6.7%**	**6.3%**	**7.3%**	**7.4%**	**6.7%**	**6.3%**	**7.3%**	7.3%	6.7%	6.3%	7.3%	7.3%
Sawtooth	Light	62%	62%	61%	59%	**62%**	**62%**	**61%**	**59%**	**63%**	**62%**	**62%**	59%	63%	62%	62%	60%
	Cool	-13%	-12%	-9%	-10%	-13%	-12%	-8%	-10%	-14%	-13%	-11%	-11%	-13%	-13%	-9%	-10%
	Total	4.3%	4.7%	7.1%	5.6%	**4.5%**	**4.9%**	**7.5%**	**5.9%**	**3.9%**	**4.2%**	**5.9%**	4.8%	4.2%	4.6%	7.1%	5.7%
Roof Monitor	Light	**63%**	**63%**	**63%**	**61%**	**63%**	**63%**	**63%**	**61%**	**64%**	**63%**	**63%**	62%	64%	63%	63%	62%
	Cool	-14%	-14%	-13%	-13%	-14%	-14%	-13%	-13%	-15%	-15%	-13%	-14%	-15%	-15%	-13%	-14%
	Total	**3.5%**	**3.5%**	**4.6%**	**4.1%**	**3.5%**	**3.5%**	**4.6%**	**4.1%**	**3.3%**	**3.2%**	**4.1%**	3.8%	3.3%	3.2%	4.1%	3.8%

UNIVERSITI KEBANGSAAN MALAYSIA

Table A-15 Total energy savings (%) comparison for the different toplighting options with different glazing types, in all orientations and TFR of 50% as compared to the base case model. A negative value represents an increase in the energy consumed.

TFR **50%**		**North**				**South**				**East**				**West**			
		Sgl	Dbl	LoE	Ref	Sgl	Dbl	LoE	Ref	Sgl	Dbl	LoE	Ref	Sgl	Dbl	LoE	Ref
Skylight	Light	64%	64%	64%	63%	**64%**	**64%**	**64%**	**63%**	**64%**	**64%**	**64%**	63%	64%	64%	64%	63%
	Cool	-10%	-11%	-9.9%	-9.2%	**-10%**	**-11%**	**-9.9%**	**-9.2%**	**-10%**	**-11%**	**-9.8%**	-9.2%	-10%	-11%	-9.8%	-9.2%
	Total	6.8%	6.2%	7.0%	7.3%	**6.8%**	**6.2%**	**7.0%**	**7.3%**	**6.8%**	**6.3%**	**7.0%**	7.2%	6.8%	6.3%	7.0%	7.2%
Sawtooth	Light	63%	63%	62%	60%	**63%**	**63%**	**62%**	**60%**	**63%**	**62%**	**62%**	59%	63%	62%	62%	60%
	Cool	-14%	-13%	-11%	-11%	-14%	-13%	-10%	-11%	-14%	-14%	-12%	-13%	-14%	-14%	-11%	-12%
	Total	3.9%	4.1%	5.9%	5.0%	**4.0%**	**4.2%**	**6.3%**	**5.3%**	**3.3%**	**3.3%**	**4.9%**	3.9%	3.6%	3.7%	5.6%	4.5%
Roof Monitor	Light	**63%**	**63%**	**62%**	**60%**	**63%**	**63%**	**62%**	**60%**	**63%**	**63%**	**63%**	61%	63%	63%	63%	61%
	Cool	-14%	-14%	-13%	-13%	-14%	-14%	-13%	-13%	-15%	-15%	-14%	-14%	-15%	-15%	-14%	-14%
	Total	**3.2%**	**3.1%**	**4.0%**	**3.8%**	**3.2%**	**3.1%**	**4.0%**	**3.8%**	**3.1%**	**3.1%**	**3.9%**	3.5%	3.1%	3.1%	3.9%	3.5%

UNIVERSITI KEBANGSAAN MALAYSIA

Table A-16 Total energy savings (%) comparison for the different toplighting options with different glazing types, all orientations, and TFR of 60% as compared to the base case model. A negative value represents an increase in the energy consumed.

TFR **60%**		**North**				**South**				**East**				**West**			
		Sgl	Dbl	LoE	Ref	Sgl	Dbl	LoE	Ref	Sgl	Dbl	LoE	Ref	Sgl	Dbl	LoE	Ref
Skylight	Light	64%	64%	64%	63%	**64%**	**64%**	**64%**	**63%**	**64%**	**64%**	**64%**	63%	64%	64%	64%	63%
	Cool	-10%	-11%	-10%	-9.5%	**-10%**	**-11%**	**-10%**	**-9.5%**	**-10%**	**-11%**	**-10%**	-9.5%	-10%	-11%	-10%	-9.5%
	Total	6.9%	6.2%	6.7%	7.1%	**6.9%**	**6.2%**	**6.7%**	**7.1%**	**6.9%**	**6.2%**	**6.7%**	7.1%	6.9%	6.2%	6.7%	7.1%
Sawtooth	Light	63%	62%	62%	60%	**63%**	**63%**	**62%**	**60%**	**63%**	**63%**	**63%**	61%	63%	63%	63%	61%
	Cool	-14%	-14%	-12%	-13%	-14%	-14%	-12%	-12%	-15%	-15%	-13%	-14%	-15%	-15%	-13%	-13%
	Total	3.4%	3.4%	4.8%	4.1%	**3.6%**	**3.6%**	**5.1%**	**4.2%**	**3.0%**	**3.0%**	**4.2%**	3.5%	3.2%	3.3%	4.7%	4.1%
Roof Monitor	Light	**63%**	**63%**	**63%**	**61%**	**63%**	**63%**	**63%**	**61%**	**63%**	**63%**	**63%**	61%	63%	63%	63%	61%
	Cool	-14%	-15%	-13%	-14%	-14%	-15%	-13%	-14%	-15%	-15%	-15%	-15%	-15%	-15%	-15%	-15%
	Total	**2.9%**	**2.7%**	**3.8%**	**3.5%**	**2.9%**	**2.7%**	**3.8%**	**3.5%**	**2.9%**	**2.9%**	**3.7%**	3.4%	2.9%	2.9%	3.7%	3.4%

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Table A.17 Total lighting energy savings (%) comparison for toplighting alternatives with different glazing types, different orientations and different glazed area TFR. 1 to 1.5 spacing-to-height Ratio

TFR		North				South				East				West			
		Sgl Clr	Dbl Clr	Dbl LoE	Dbl Ref	Sgl Clr	Dbl Clr	Dbl LoE	Dbl Ref	Sgl Clr	Dbl Clr	Dbl LoE	Dbl Ref	Sgl Clr	Dbl Clr	Dbl LoE	Dbl Ref
Skylight	**5%**	60.0	59.4	58.8	54.0	60.0	59.4	58.8	54.0	60.1	59.5	58.9	54.0	60.1	59.5	58.9	54.0
	10%	62.0	61.7	61.2	58.2	62.0	61.7	61.2	58.2	62.1	61.7	61.3	58.3	62.1	61.7	61.3	58.3
	15%	62.7	62.4	62.2	59.9	62.7	62.4	62.2	59.9	62.7	62.5	62.2	60.0	62.7	62.5	62.2	60.0
	20%	63.1	62.9	62.7	60.9	63.1	62.9	62.7	60.9	63.2	62.9	62.7	60.9	63.2	62.9	62.7	60.9
	30%	63.7	63.5	63.3	62.0	63.7	63.5	63.3	62.0	63.7	63.5	63.3	62.0	63.7	63.5	63.3	62.0
	40%	64.0	63.9	63.7	62.5	64.0	63.9	63.7	62.5	64.0	63.9	63.7	62.5	64.0	63.9	63.7	62.5
	50%	64.2	64.1	63.9	62.9	64.2	64.1	63.9	62.9	64.2	64.1	64.0	62.9	64.2	64.1	64.0	62.9
	60%	64.4	64.3	64.1	63.2	64.4	64.3	64.1	63.2	64.4	64.3	64.1	63.2	64.4	64.3	64.1	63.2
Sawtooth	**5%**	52.9	50.7	48.0	26.3	53.0	51.0	48.5	29.2	51.5	48.7	46.0	28.2	51.0	48.3	45.6	28.3
	10%	58.3	57.3	56.5	47.3	58.3	57.4	56.5	48.0	56.9	55.7	54.5	41.7	56.6	55.2	54.0	41.2
	15%	60.0	59.4	58.7	53.5	60.0	59.4	58.7	53.7	59.8	59.1	58.5	52.8	60.0	59.2	58.5	52.2
	20%	60.9	60.4	59.9	55.8	60.9	60.4	59.9	55.8	60.8	60.2	59.7	55.4	61.0	60.4	59.9	55.0
	30%	61.8	61.4	61.0	57.9	61.8	61.4	61.0	57.9	61.8	61.4	60.9	57.8	61.9	61.5	61.1	57.7
	40%	62.2	61.9	61.6	58.9	62.3	61.9	61.6	58.9	62.2	61.9	61.5	58.8	62.3	62.0	61.6	58.9
	50%	62.7	62.4	62.2	60.1	62.7	62.5	62.2	60.1	62.7	62.5	62.2	60.1	62.8	62.6	62.3	60.3
	60%	62.7	62.4	62.2	60.1	62.7	62.5	62.2	60.1	62.9	62.7	62.5	60.6	63.0	62.8	62.6	60.8
Roof Monitor	**5%**	57.8	56.9	56.1	48.6	57.8	56.9	56.1	48.6	57.8	56.9	56.0	48.6	57.8	56.9	56.0	48.6
	10%	60.8	60.3	59.8	55.8	60.8	60.3	59.8	55.8	60.2	59.6	59.1	54.7	60.2	59.6	59.1	54.7
	15%	61.9	61.5	61.1	58.1	61.9	61.5	61.1	58.1	61.9	61.6	61.1	58.3	61.9	61.6	61.1	58.3
	20%	62.4	62.1	61.8	59.4	62.4	62.1	61.8	59.4	62.4	62.1	61.8	59.5	62.4	62.1	61.8	59.5
	30%	62.9	62.6	62.4	60.5	62.9	62.6	62.4	60.5	62.9	62.6	62.4	60.6	62.9	62.6	62.4	60.6
	40%	63.2	62.9	62.7	61.2	63.2	62.9	62.7	61.2	63.2	63.0	62.8	61.3	63.2	63.0	62.8	61.3
	50%	62.8	62.6	62.3	60.5	62.8	62.6	62.3	60.5	63.2	63.0	62.7	61.3	63.2	63.0	62.7	61.3
	60%	62.6	62.3	62.1	60.0	62.6	62.3	62.1	60.0	63.0	62.8	62.6	61.0	63.0	62.8	62.6	61.0

* *Sgl Clr*: Single clear 6 mm
Dbl Clr: Double clear 6mm-13mm air
Dbl LoE: Double Low-e clear 6mm-13mm air
Dbl Ref: Double reflect clear 6mm-13mm air

Table A.18 Total cooling energy savings (%) comparison for toplighting alternatives with different glazing types, different orientations and different glazed area TFR. 1 to 1.5 spacing-to-height ratio. A negative percentage represents an increase in energy consumed.

TFR		North				South				East				West			
		Sgl Clr	Dbl Clr	Dbl LoE	Dbl Ref	Sgl Clr	Dbl Clr	Dbl LoE	Dbl Ref	Sgl Clr	Dbl Clr	Dbl LoE	Dbl Ref	Sgl Clr	Dbl Clr	Dbl LoE	Dbl Ref
Skylight	**5%**	-1%	2%	5%	4%	-1%	2%	5%	4%	0%	2%	5%	4%	0%	2%	5%	4%
	10%	-7%	-6%	-1%	-2%	-7%	-6%	-1%	-2%	-7%	-6%	0%	-1%	-7%	-6%	0%	-1%
	15%	-9%	-8%	-6%	-6%	-9%	-8%	-6%	-6%	-9%	-8%	-5%	-5%	-9%	-8%	-5%	-5%
	20%	-9%	-9%	-7%	-7%	-9%	-9%	-7%	-7%	-9%	-9%	-7%	-7%	-9%	-9%	-7%	-7%
	30%	-10%	-10%	-9%	-8%	-10%	-10%	-9%	-8%	-10%	-10%	-9%	-8%	-10%	-10%	-9%	-8%
	40%	-10%	-11%	-9%	-9%	-10%	-11%	-9%	-9%	-10%	-11%	-9%	-9%	-10%	-11%	-9%	-9%
	50%	-10%	-11%	-10%	-9%	-10%	-11%	-10%	-9%	-10%	-11%	-10%	-9%	-10%	-11%	-10%	-9%
	60%	-10%	-11%	-10%	-10%	-10%	-11%	-10%	-10%	-10%	-11%	-10%	-9%	-10%	-11%	-10%	-9%
Sawtooth	**5%**	4.0%	3.9%	5.5%	1.8%	4.3%	4.6%	5.6%	0.9%	2.8%	3.0%	5.2%	1.9%	3.1%	2.6%	4.1%	1.1%
	10%	0.5%	1.9%	3.7%	2.6%	1.2%	2.6%	4.5%	1.6%	1.4%	2.0%	3.4%	2.0%	1.1%	2.6%	4.2%	0.9%
	15%	-5%	-2%	2%	1%	-5%	-2%	3%	1%	-8%	-4%	2%	0%	-6%	-4%	2%	-1%
	20%	-8%	-6%	0%	-1%	-8%	-6%	1%	-1%	-10%	-9%	0%	-2%	-9%	-7%	-1%	-4%
	30%	-11%	-10%	-5%	-7%	-11%	-10%	-5%	-7%	-13%	-12%	-8%	-9%	-12%	-11%	-6%	-8%
	40%	-13%	-13%	-9%	-10%	-13%	-12%	-9%	-10%	-14%	-14%	-11%	-12%	-13%	-13%	-9%	-10%
	50%	-14%	-14%	-11%	-12%	-14%	-14%	-11%	-12%	-15%	-15%	-12%	-13%	-14%	-14%	-12%	-12%
	60%	-13%	-13%	-11%	-11%	-13%	-13%	-10%	-11%	-15%	-15%	-13%	-13%	-14%	-15%	-12%	-13%
Roof Monitor	**5%**	2%	3%	4%	3%	2%	3%	4%	3%	1%	2%	3%	2%	1%	2%	3%	2%
	10%	-8%	-6%	2%	-1%	-8%	-6%	2%	-1%	-7%	-5%	2%	0%	-7%	-5%	2%	0%
	15%	-10%	-10%	-5%	-7%	-10%	-10%	-5%	-7%	-12%	-11%	-7%	-8%	-12%	-11%	-7%	-8%
	20%	-12%	-11%	-8%	-9%	-12%	-11%	-8%	-9%	-13%	-13%	-10%	-11%	-13%	-13%	-10%	-11%
	30%	-14%	-13%	-11%	-12%	-14%	-13%	-11%	-12%	-14%	-14%	-13%	-13%	-14%	-14%	-13%	-13%
	40%	-14%	-14%	-13%	-13%	-14%	-14%	-13%	-13%	-15%	-15%	-14%	-14%	-15%	-15%	-14%	-14%
	50%	-14%	-13%	-12%	-12%	-14%	-13%	-12%	-12%	-14%	-14%	-12%	-13%	-14%	-14%	-12%	-13%
	60%	-14%	-14%	-13%	-13%	-14%	-14%	-13%	-13%	-15%	-14%	-13%	-14%	-15%	-14%	-13%	-14%

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Table A.19 Total energy savings (%) comparison for toplighting alternatives with different glazing types, different orientations and different glazed area TFR. 1 to 1.5 spacing-to-height ratio.

	TFR	North				South				East				West			
		Sgl Clr	Dbl Clr	Dbl LoE	Dbl Ref	Sgl Clr	Dbl Clr	Dbl LoE	Dbl Ref	Sgl Clr	Dbl Clr	Dbl LoE	Dbl Ref	Sgl Clr	Dbl Clr	Dbl LoE	Dbl Ref
Skylights	**5%**	12.8	14.5	16.4	14.5	12.8	14.5	16.4	14.5	13.1	14.9	16.4	14.9	13.1	14.9	16.4	14.9
	10%	8.6	9.1	12.8	11.5	8.6	9.1	12.8	11.5	8.7	9.3	13.2	12.0	8.7	9.3	13.2	12.0
	15%	7.6	7.8	9.7	9.1	7.6	7.8	9.7	9.1	7.6	7.8	9.9	9.3	7.6	7.8	9.9	9.3
	20%	7.2	7.1	8.6	8.2	7.2	7.1	8.6	8.2	7.2	7.1	8.7	8.4	7.2	7.1	8.7	8.4
	30%	6.8	6.5	7.6	7.6	6.8	6.5	7.6	7.6	6.8	6.6	7.6	7.6	6.8	6.6	7.6	7.6
	40%	6.7	6.2	7.2	7.3	6.7	6.2	7.2	7.3	6.7	6.3	7.2	7.3	6.7	6.3	7.2	7.3
	50%	6.8	6.2	6.9	7.2	6.8	6.2	6.9	7.2	6.8	6.2	6.9	7.2	6.8	6.2	6.9	7.2
	60%	6.9	6.2	6.7	7.0	6.9	6.2	6.7	7.0	6.9	6.2	6.6	7.1	6.9	6.2	6.6	7.1
Sawtooth	**5%**	14.6	14.0	14.6	7.1	14.8	14.6	14.8	7.1	13.4	12.9	13.9	7.6	13.5	12.5	13.0	7.1
	10%	13.2	14.0	15.2	12.3	13.7	14.6	15.7	11.8	13.6	13.8	14.5	10.6	13.3	14.1	14.9	9.7
	15%	9.6	11.4	14.6	12.5	9.8	11.7	15.3	12.9	7.7	9.9	14.1	12.0	9.1	10.2	14.4	10.5
	20%	7.4	8.7	13.5	11.2	7.6	8.9	13.8	11.4	6.1	6.8	13.4	10.7	7.1	8.4	12.2	9.2
	30%	5.3	6.0	9.7	7.7	5.6	6.2	10.0	7.8	4.5	4.9	8.0	6.3	5.0	5.6	9.3	7.1
	40%	4.2	4.5	7.0	5.5	4.4	4.7	7.4	5.9	3.6	3.8	5.6	4.5	4.0	4.3	6.8	5.4
	50%	3.6	3.8	5.5	4.7	3.7	3.9	6.0	4.9	3.2	3.2	4.7	3.9	3.5	3.6	5.4	4.6
	60%	3.5	3.7	5.1	4.3	3.5	3.7	5.4	4.4	3.1	3.0	4.2	3.6	3.4	3.3	4.8	4.2
Roof Monitor	**5%**	14.3	14.8	15.5	13.1	14.3	14.8	15.5	13.1	13.5	14.1	14.9	12.1	13.5	14.1	14.9	12.1
	10%	7.9	9.0	14.3	11.7	7.9	9.0	14.3	11.7	8.0	9.8	14.4	12.2	8.0	9.8	14.4	12.2
	15%	6.1	6.7	10.0	8.0	6.1	6.7	10.0	8.0	5.1	5.5	8.7	6.8	5.1	5.5	8.7	6.8
	20%	5.1	5.5	7.7	6.4	5.1	5.5	7.7	6.4	4.3	4.5	6.6	5.3	4.3	4.5	6.6	5.3
	30%	4.0	4.1	5.5	4.8	4.0	4.1	5.5	4.8	3.4	3.3	4.5	4.0	3.4	3.3	4.5	4.0
	40%	3.5	3.5	4.5	4.1	3.5	3.5	4.5	4.1	3.1	2.9	3.9	3.5	3.1	2.9	3.9	3.5
	50%	3.3	3.3	4.3	3.9	3.3	3.3	4.3	3.9	2.8	2.7	3.8	3.3	2.8	2.7	3.8	3.3
	60%	2.9	3.0	4.0	3.6	2.9	3.0	4.0	3.6	2.5	2.3	3.6	3.1	2.5	2.3	3.6	3.1

* *Sgl Clr*: Single clear 6 mm
Dbl Clr: Double clear 6mm-13mm air
Dbl LoE: Double Low-e clear 6mm-13mm air
Dbl Ref: Double reflect clear 6mm-13mm air

Table A.20 Total annual building energy and energy cost savings for all the suggested skylight cases. The energy and energy cost savings are addressed into lighting, cooling, and total energy savings.

Skylights: Savings from Skylight designs systems									
Savings	**Base Case**	5% Skylight	10% Skylight	15% Skylight	20% Skylight	30% Skylight	40% Skylight	50% Skylight	60% Skylight
Lighting Energy Use (kWh/yr)	100458	39331	37717	37381	36939	36475	36242	36069	35933
Annual Energy Savings (kWh/yr)		61128	62742	63078	63519	63983	64217	64389	64525
Annual Energy Cost (RM)	28932	11327	10862	10766	10638	10505	10438	10388	10349
Annual Cost Savings (RM/yr)		17605	18070	18166	18294	18427	18494	18544	18583
	Base Case	5% Skylight	10% Skylight	15% Skylight	20% Skylight	30% Skylight	40% Skylight	50% Skylight	60% Skylight
Cooling Energy Use (kWh/yr)	331442	315172	334594	349744	355350	360333	362631	364117	365550
Annual Energy Savings (kWh/yr)		16269	-3153	-18303	-23908	-28892	-31189	-32675	-34108
Annual Energy Cost (RM)	95455	90770	96363	100726	102341	103776	104438	104866	105278
Annual Cost Savings (RM /yr)		4686	-908	-5271	-6886	-8321	-8982	-9410	-9823
	Base Case	5% Skylight	10% Skylight	15% Skylight	20% Skylight	30% Skylight	40% Skylight	50% Skylight	60% Skylight
Total Energy Use (kWh/yr)	454903	377506	395314	410131	415292	419814	421875	423192	424489
Annual Energy Savings (kWh/yr)		77397	59589	44772	39611	35089	33028	31711	30414
Annual Energy Cost (RM)	131012	108721.6	113850.4	118117.6	119604	120906.4	121500	121879.2	122252.8
Annual Cost Savings (RM/yr)		22290.4	17161.6	12894.4	11408	10106	9512	9133	8759

**** Energy Cost** :Peak period from 7am-7pm = 0.288 sen/kWh*
Off Peak period from 7pm-7am = 0.177 sen/kWh
Maximum Demand during the peak =35.6 RM/kWh

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Table A.21 Total annual energy and energy cost savings for all the suggested sawtooth cases. The energy and energy cost savings are addressed into lighting, cooling, and total energy savings.

Sawtooth: Savings from Sawtooth designs systems									
Savings	**Base Case**	5% Sawtooth	10% Sawtooth	15% Sawtooth	20% Sawtooth	30% Sawtooth	40% Sawtooth	50% Sawtooth	60% Sawtooth
Lighting Energy Use (kWh/yr)	100458	50439	43558	42056	40731	39586	38789	37772	37919
Annual Energy Savings (kWh/yr)		50019	56900	58403	59728	60872	61669	62686	62539
Annual Energy Cost (RM)	28932	14526	12545	12112	11730	11401	11171	10878	10921
Annual Cost Savings (RM/yr)		14406	16387	16820	17202	17531	17761	18054	18011
	Base Case	5% Sawtooth	10% Sawtooth	15% Sawtooth	20% Sawtooth	30% Sawtooth	40% Sawtooth	50% Sawtooth	60% Sawtooth
Cooling Energy Use (kWh/yr)	331442	312833	317275	322492	329878	347361	359150	365672	370858
Annual Energy Savings (kWh/yr)		18608	14167	8950	1564	-15919	-27708	-34231	-39417
Annual Energy Cost (RM)	95455	90096	91375	92878	95005	100040	103435	105314	106807
Annual Cost Savings (RM/yr)		5359	4080	2578	450	-4585	-7980	-9858	-11352
	Base Case	5% Sawtooth	10% Sawtooth	15% Sawtooth	20% Sawtooth	30% Sawtooth	40% Sawtooth	50% Sawtooth	60% Sawtooth
Total Energy Use (kWh/yr)	454903	386278	383836	387550	393611	409953	420944	426450	431781
Annual Energy Savings (kWh/yr)		68625	71067	67353	61292	44950	33958	28453	23122
Annual Energy Cost (RM)	131012	111248	110545	111614	113360	118066	121232	122818	124353
Annual Cost Savings (RM/yr)		19764	20467.2	19397.6	17652	12946	9780	8194	6659

**** Energy Cost** :Peak period from 7am-7pm = 0.288 sen/kWh*
Off Peak period from 7pm-7am = 0.177 sen/kWh
Maximum Demand during the peak =35.6 RM/kWh

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Table A.22 Total annual energy and energy cost savings for all the suggested roof monitor cases. The energy and energy cost savings are addressed into lighting, cooling, and total energy savings.

Roof Monitor: Savings from Roof Monitor designs systems									
Savings	**Base Case**	5% Roof Monitor	10% Roof Monitor	15% Roof Monitor	20% Roof Monitor	30% Roof Monitor	40% Roof Monitor	50% Roof Monitor	60% Roof Monitor
Lighting Energy Use (kWh/yr)	100458	43608	40369	39542	38756	38011	37600	37894	37653
Annual Energy Savings (kWh/yr)		56850	60089	60917	61703	62447	62858	62564	62806
Annual Energy Cost (RM)	28932	12559	11626	11388	11162	10947	10829	10914	10844
Annual Cost Savings (RM/yr)		16373	17306	17544	17770	17985	18103	18018	18088
	Base Case	5% Roof Monitor	10% Roof Monitor	15% Roof Monitor	20% Roof Monitor	30% Roof Monitor	40% Roof Monitor	50% Roof Monitor	60% Roof Monitor
Cooling Energy Use (kWh/yr)	331442	318766.7	329955.6	349788.9	359463.9	368416.7	373469.4	373125.0	371408.3
Annual Energy Savings (kWh/yr)		12675	1486	-18347	-28022	-36975	-42028	-41683	-39967
Annual Energy Cost (RM)	95455	91805	95027	100739	103526	106104	107559	107460	106966
Annual Cost Savings (RM/yr)		3650	428	-5284	-8070	-10649	-12104	-12005	-11510
	Base Case	5% Roof Monitor	10% Roof Monitor	15% Roof Monitor	20% Roof Monitor	30% Roof Monitor	40% Roof Monitor	50% Roof Monitor	60% Roof Monitor
Total Energy Use (kWh/yr)	454903	385377.8	393327.8	412333.3	421225.0	429430.6	434072.2	434022.2	432063.9
Annual Energy Savings (kWh/yr)		69525	61575	42569	33678	25472	20831	20881	22839
Annual Energy Cost (RM)	131012	110989	113278	118752	121313	123676	125013	124998	124434
Annual Cost Savings (RM/yr)		20023	17734	12260	9699	7336	5999	6014	6578

**** Energy Cost** :Peak period from 7am-7pm = 0.288 sen/kWh*
Off Peak period from 7pm-7am = 0.177 sen/kWh
Maximum Demand during the peak =35.6 RM/kWh

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APPENDIX B: DETAILED RESULTS FOR DAYLIGHTING ANALYSIS

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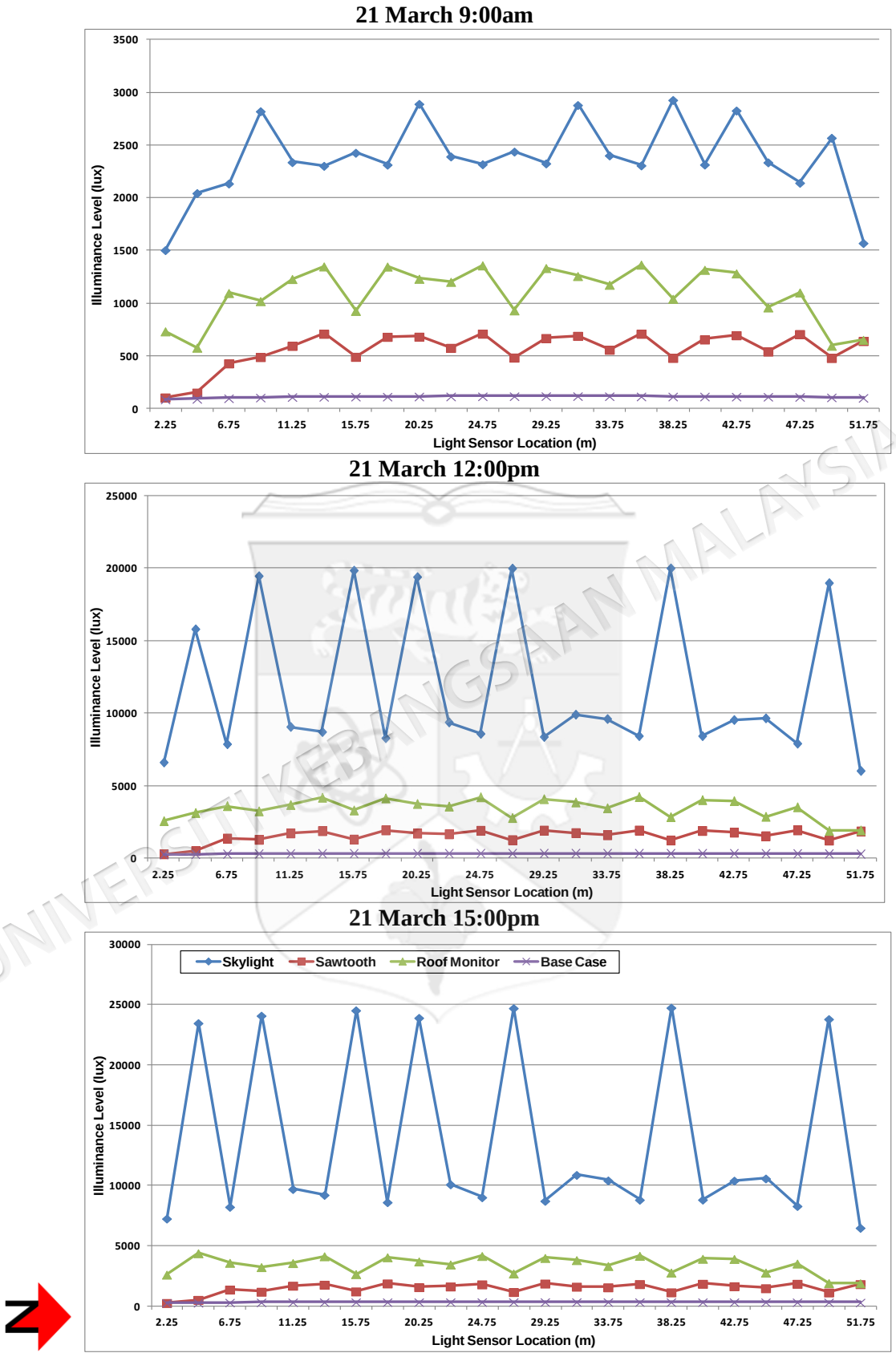

Figure B-1: Illuminance Level comparison: 1 to 1 spacing-to-ceiling height ratio, 20% TFR, double Low-e clear, 21 of March

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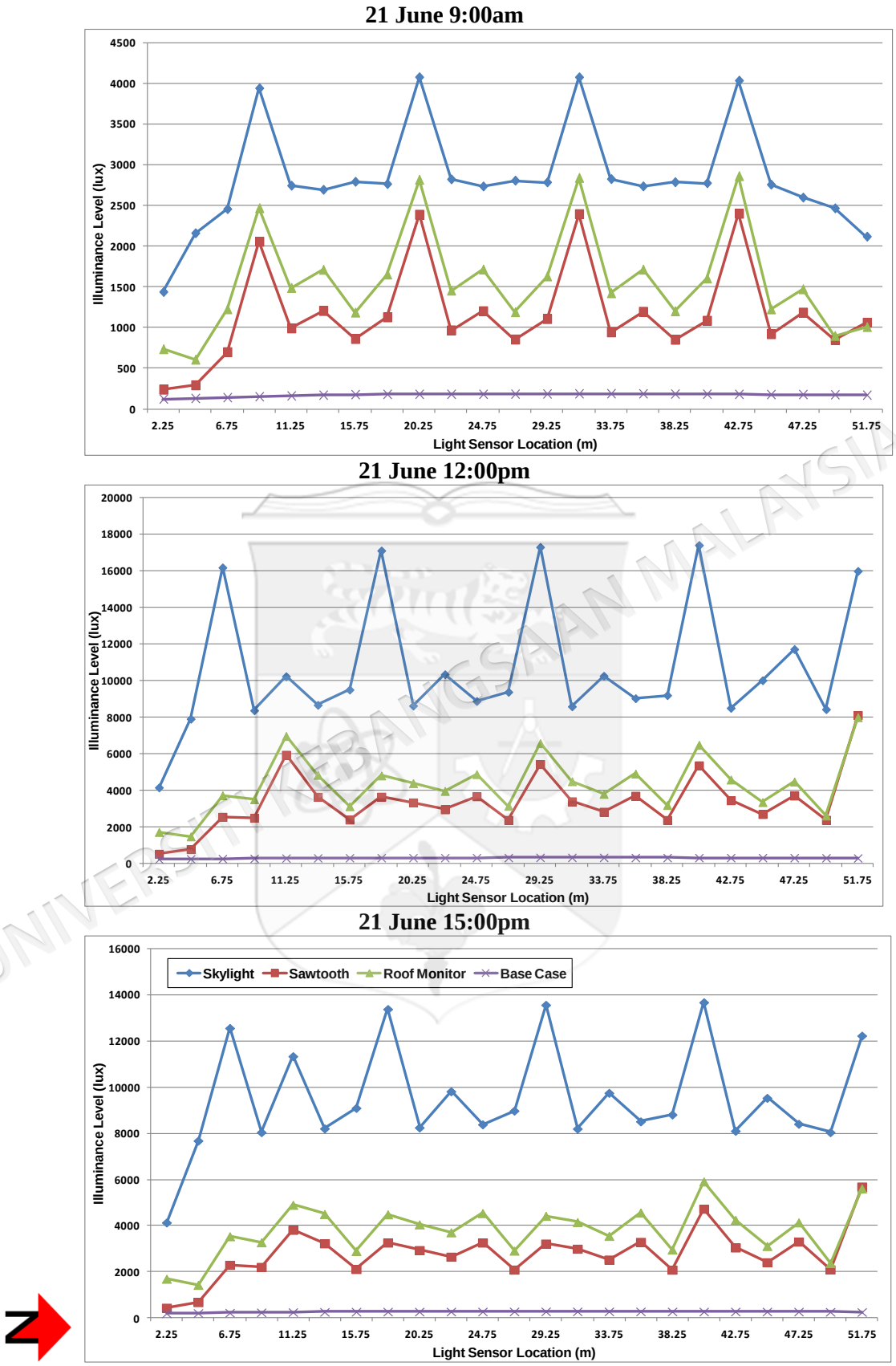

Figure B-2 Illuminance Level comparison: 1 to 1 spacing-to-ceiling height ratio, 20% TFR, double Low-e clear, 21 of June

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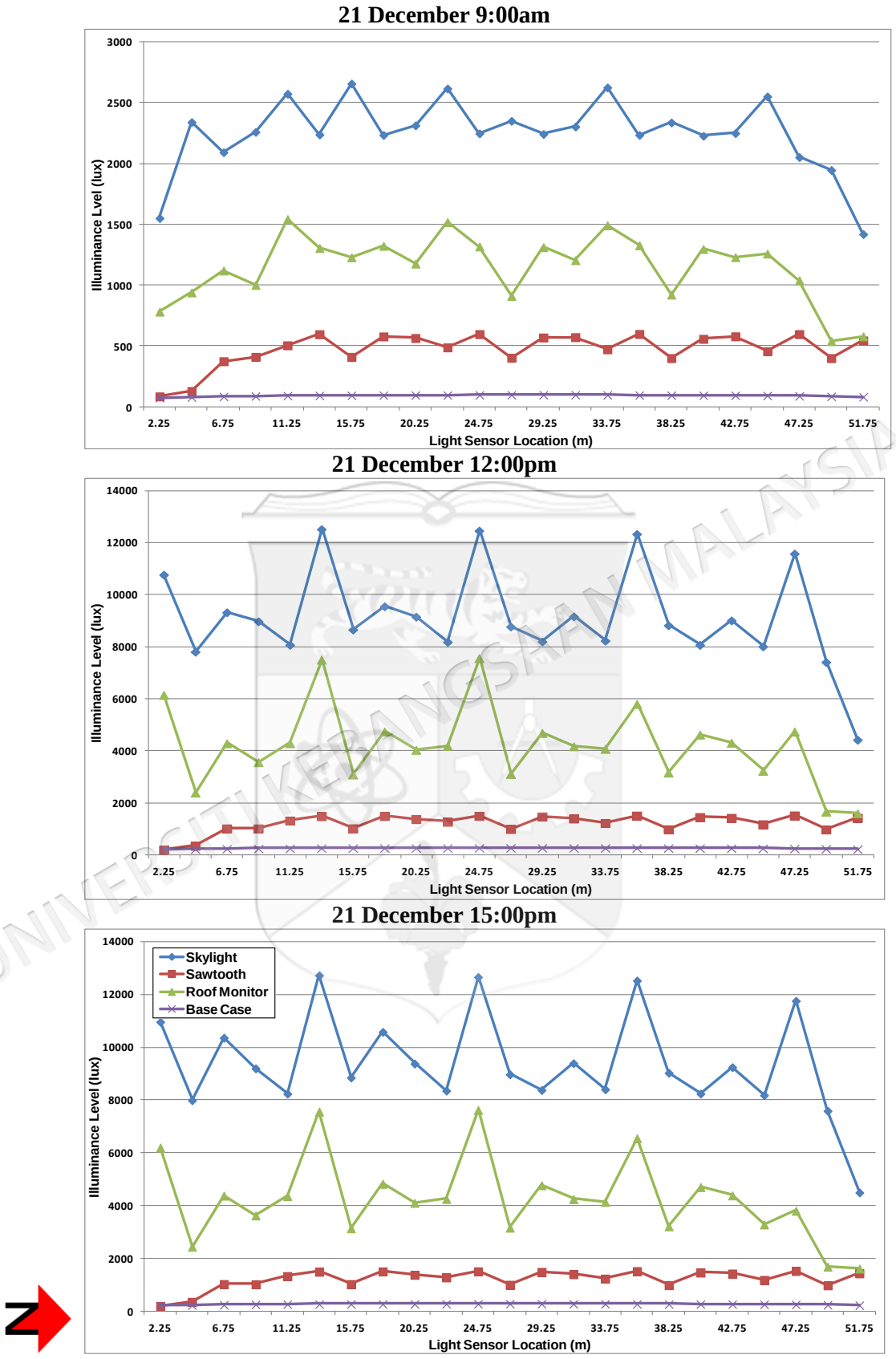

Figure B-3 Illuminance Level comparison: 1 to 1 spacing-to-ceiling height ratio, 20% TFR, double Low-e clear, 21 of December

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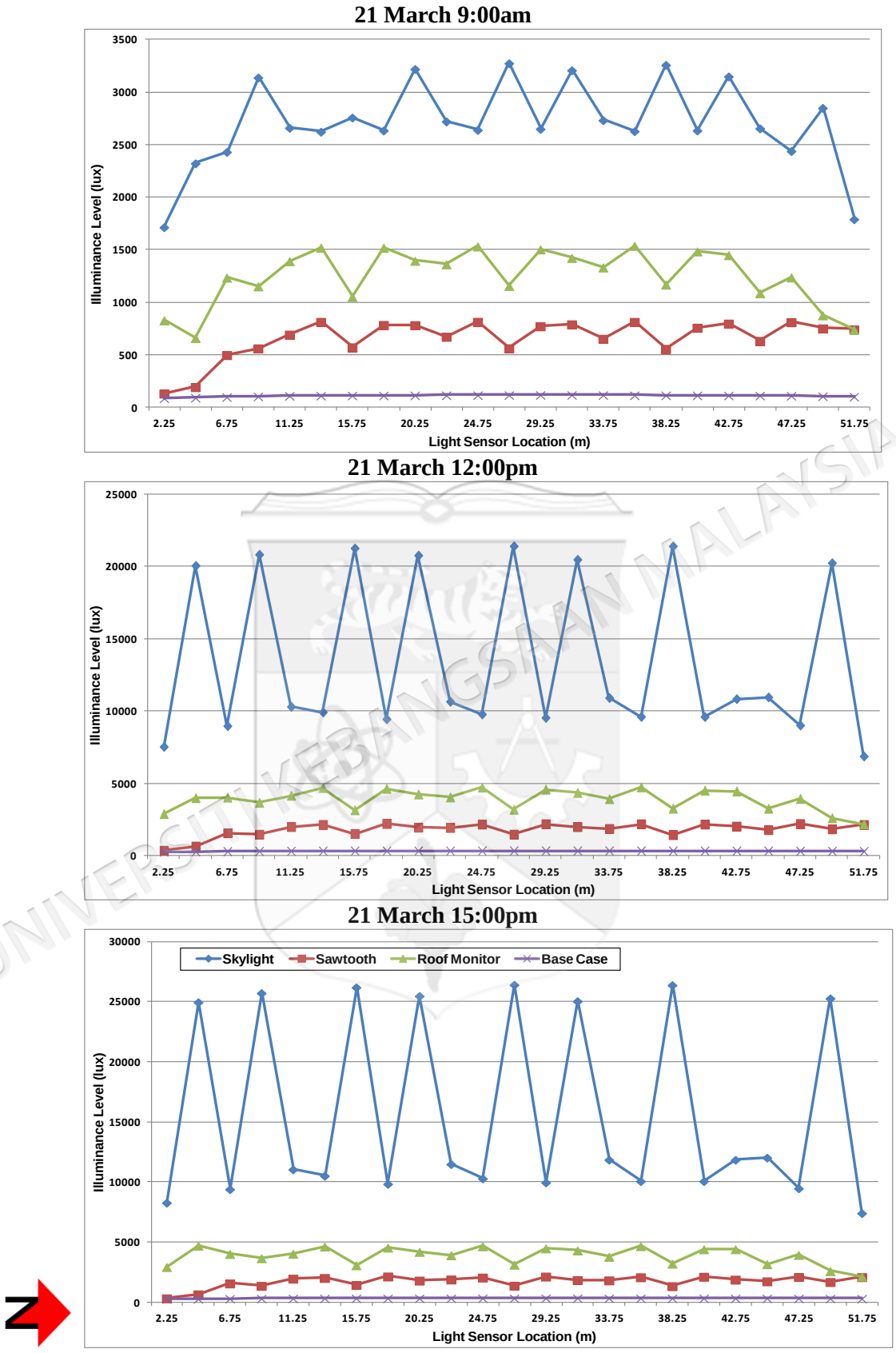

Figure B-4 Illuminance Level comparison: 1 to 1 spacing-to-ceiling height ratio, 25% TFR, double Low-e clear, 21 of March

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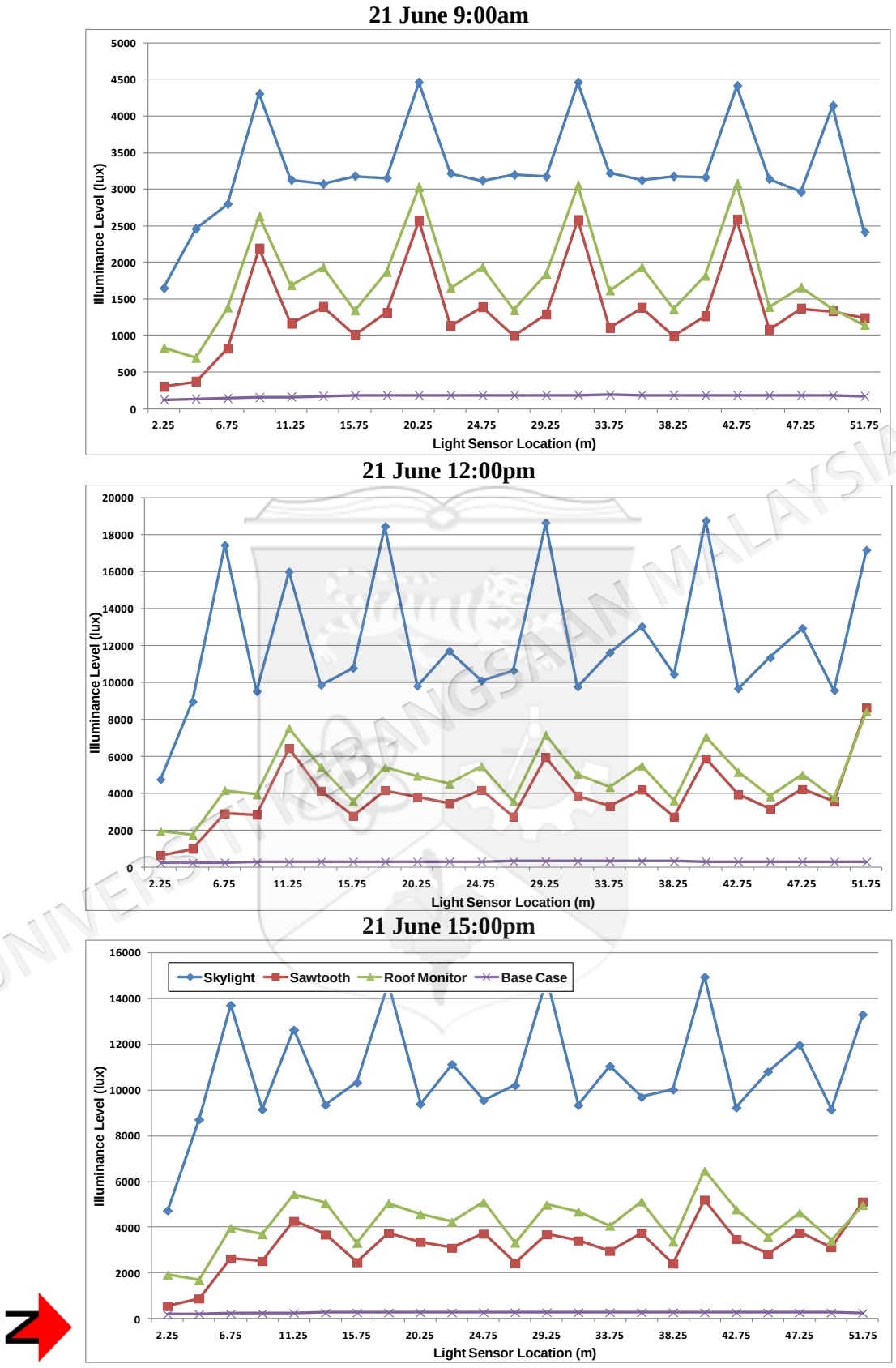

Figure B-5 Illuminance Level comparison: 1 to 1 spacing-to-ceiling height ratio, **25**% TFR, double Low-e clear, 21 of June

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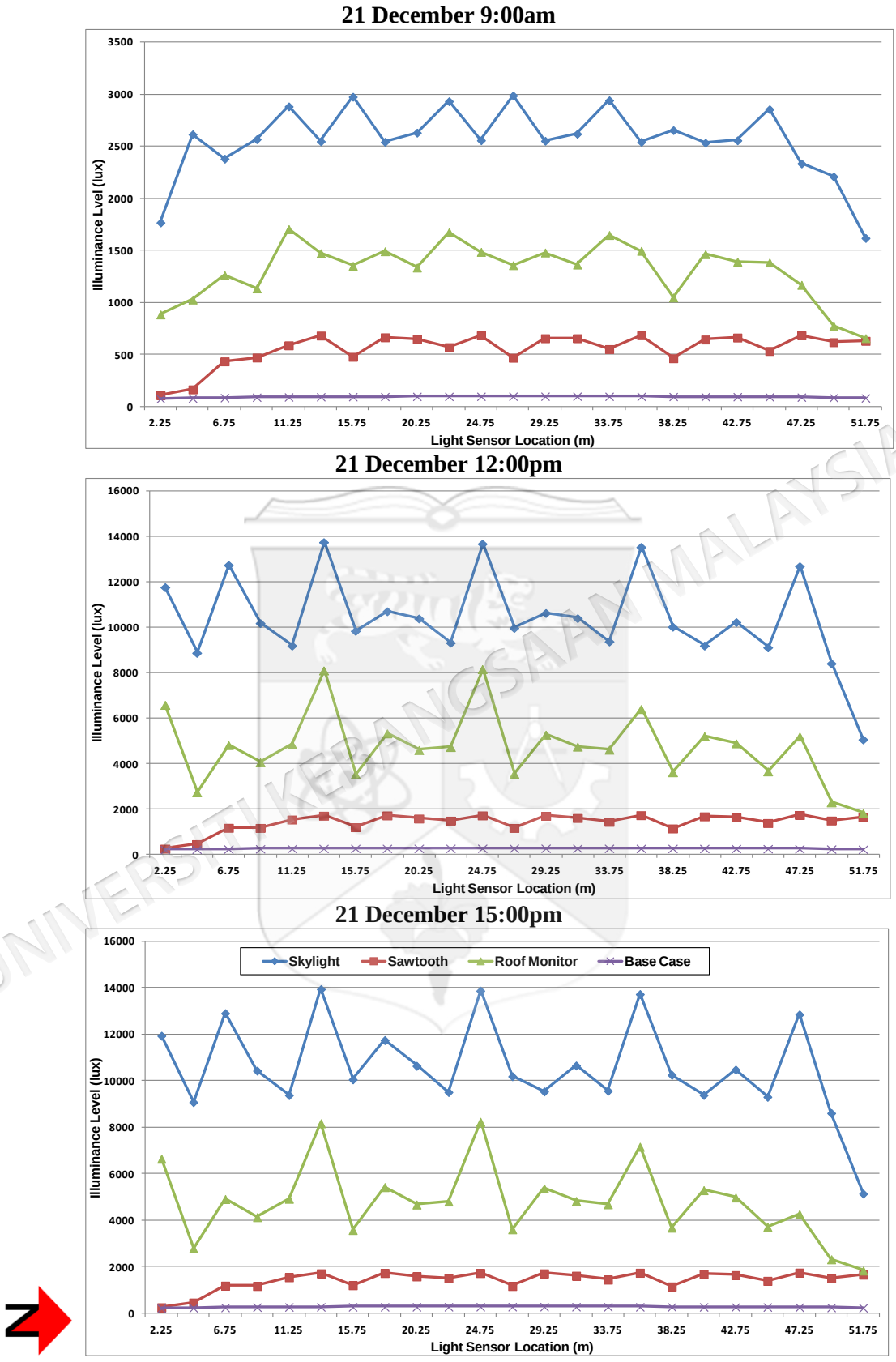

Figure B-6 Illuminance Level comparison: 1 to 1 spacing-to-ceiling height ratio, 25% TFR, double Low-e clear, 21 of December

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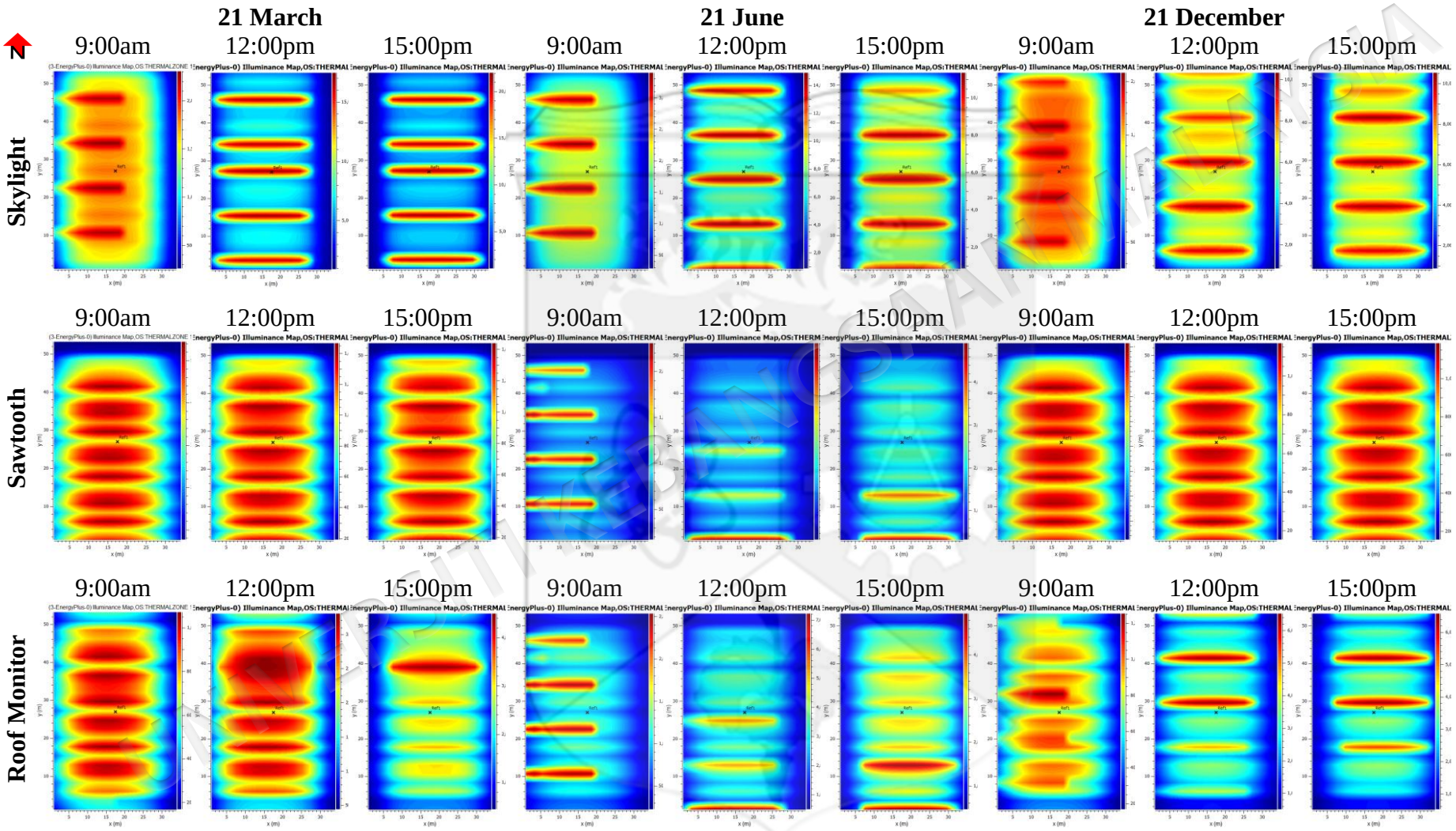

Figure B-7 Illuminance map comparison: 1to1 spacing-to-height ratio toplighting alternatives, 15% TFR, dabule Low-e clear

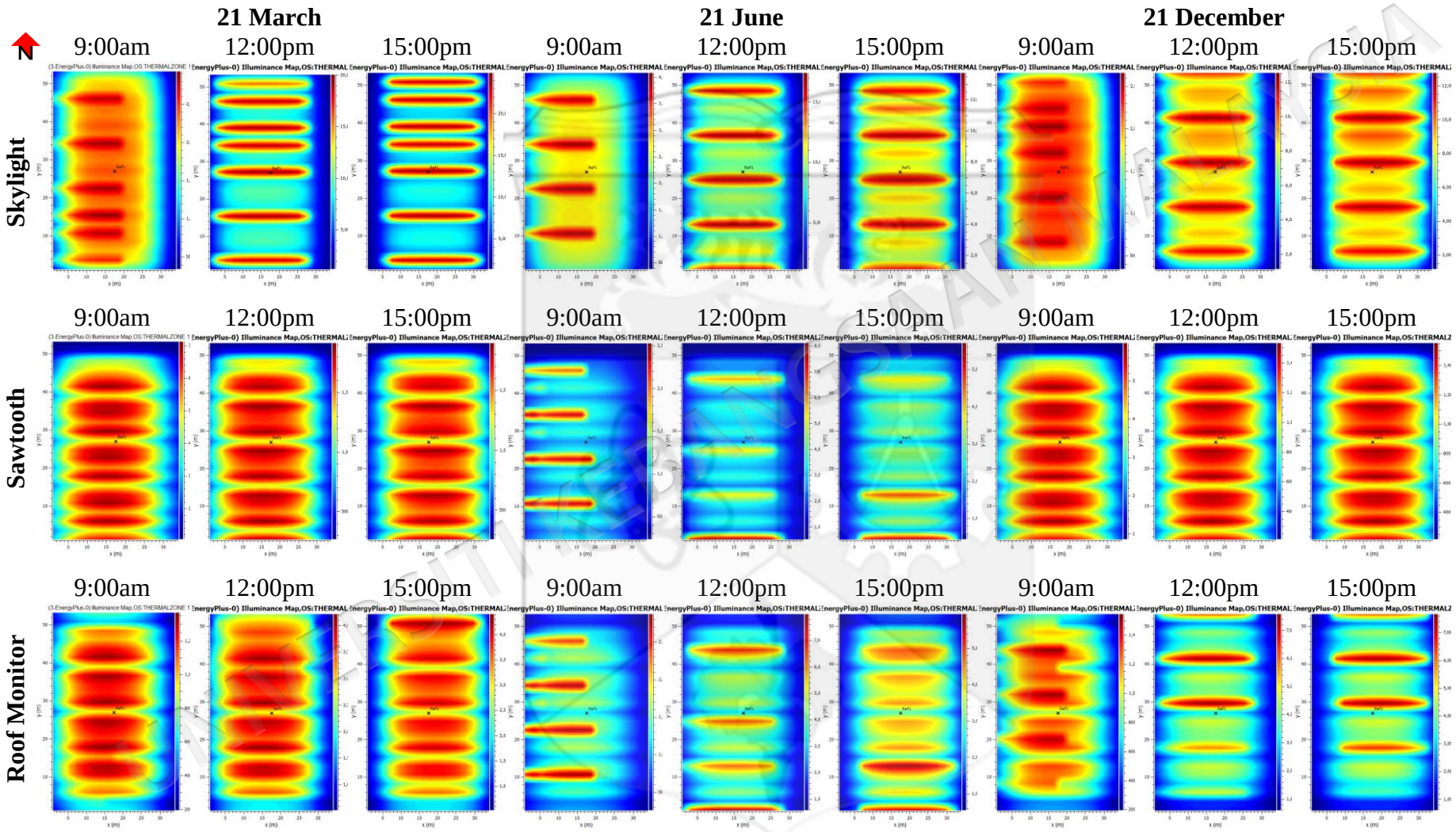

Figure B-8 Illuminance map comparison: 1to1 spacing-to-height ratio toplighting alternatives, 20% TFR, dabule Low-e clear

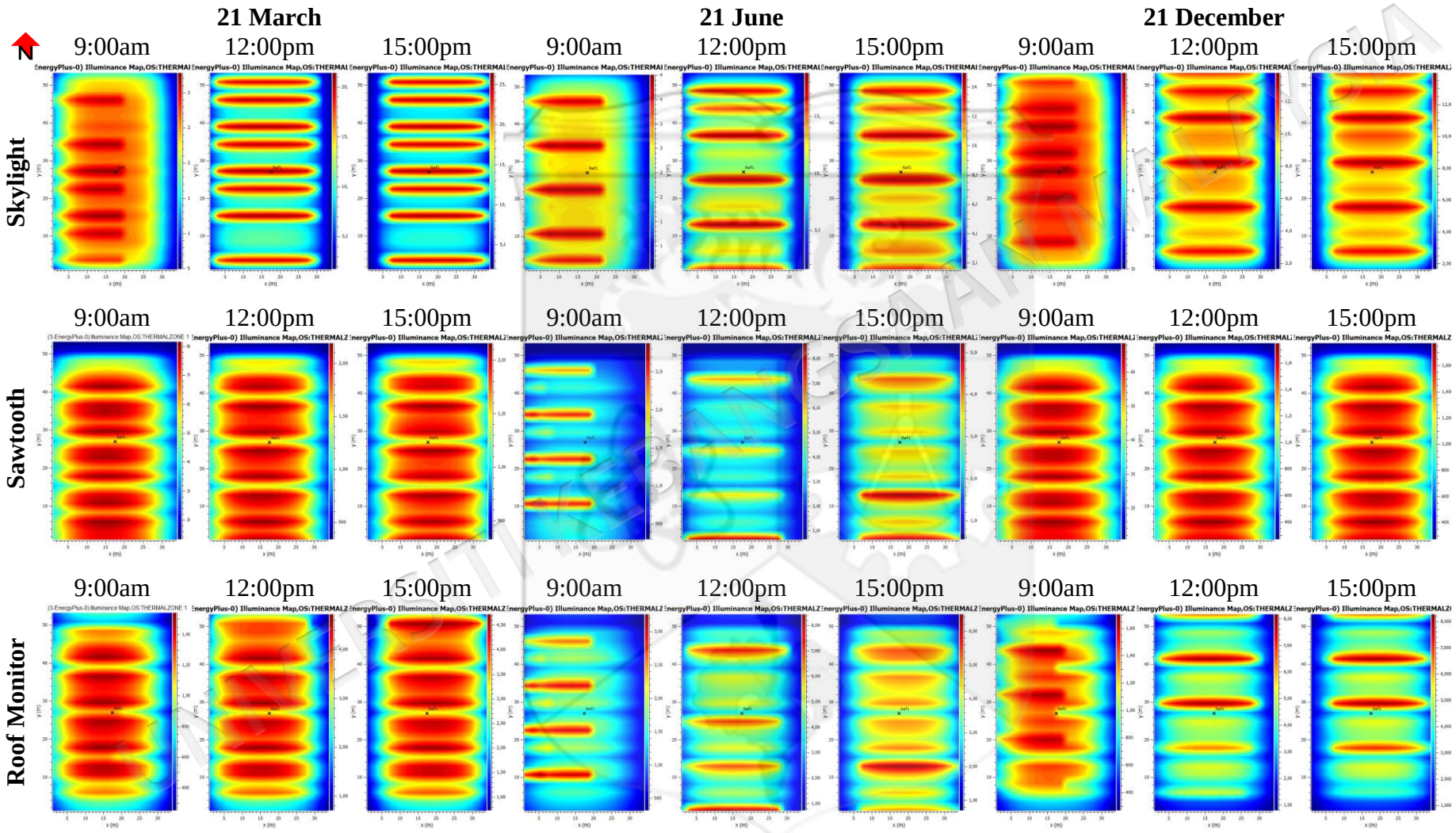

Figure B-9 Illuminance map comparison: 1to1 spacing-to-height ratio toplighting alternatives, 25% TFR, dabule Low-e clear

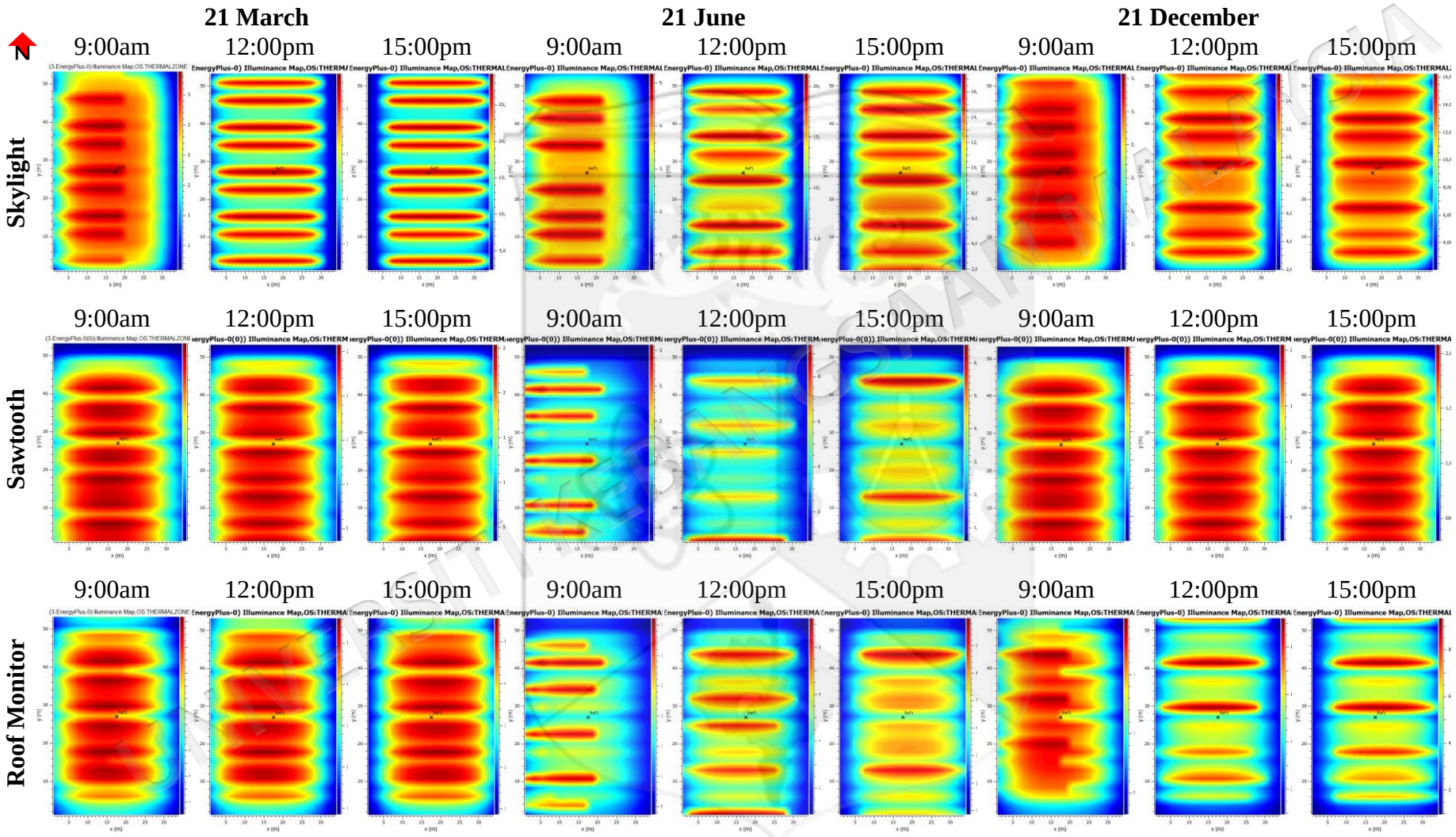

Figure B-10 Illuminance map comparison: 1to1 spacing-to-height ratio toplighting alternatives, 30% TFR, dabule Low-e clear

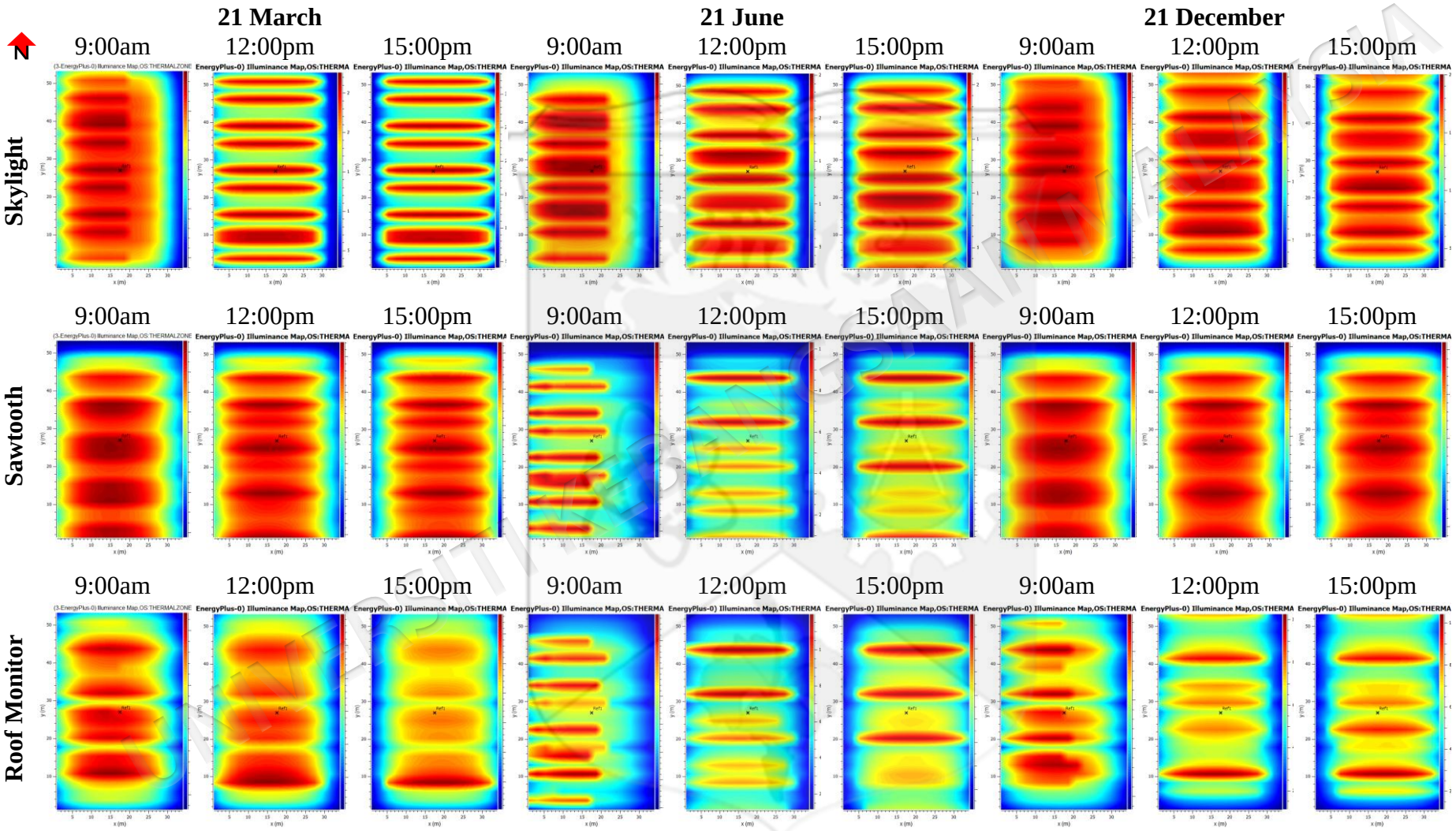

Figure B-11 Illuminance map comparison: 1to1 spacing-to-height ratio toplighting alternatives, 40% TFR, double Low-e clear

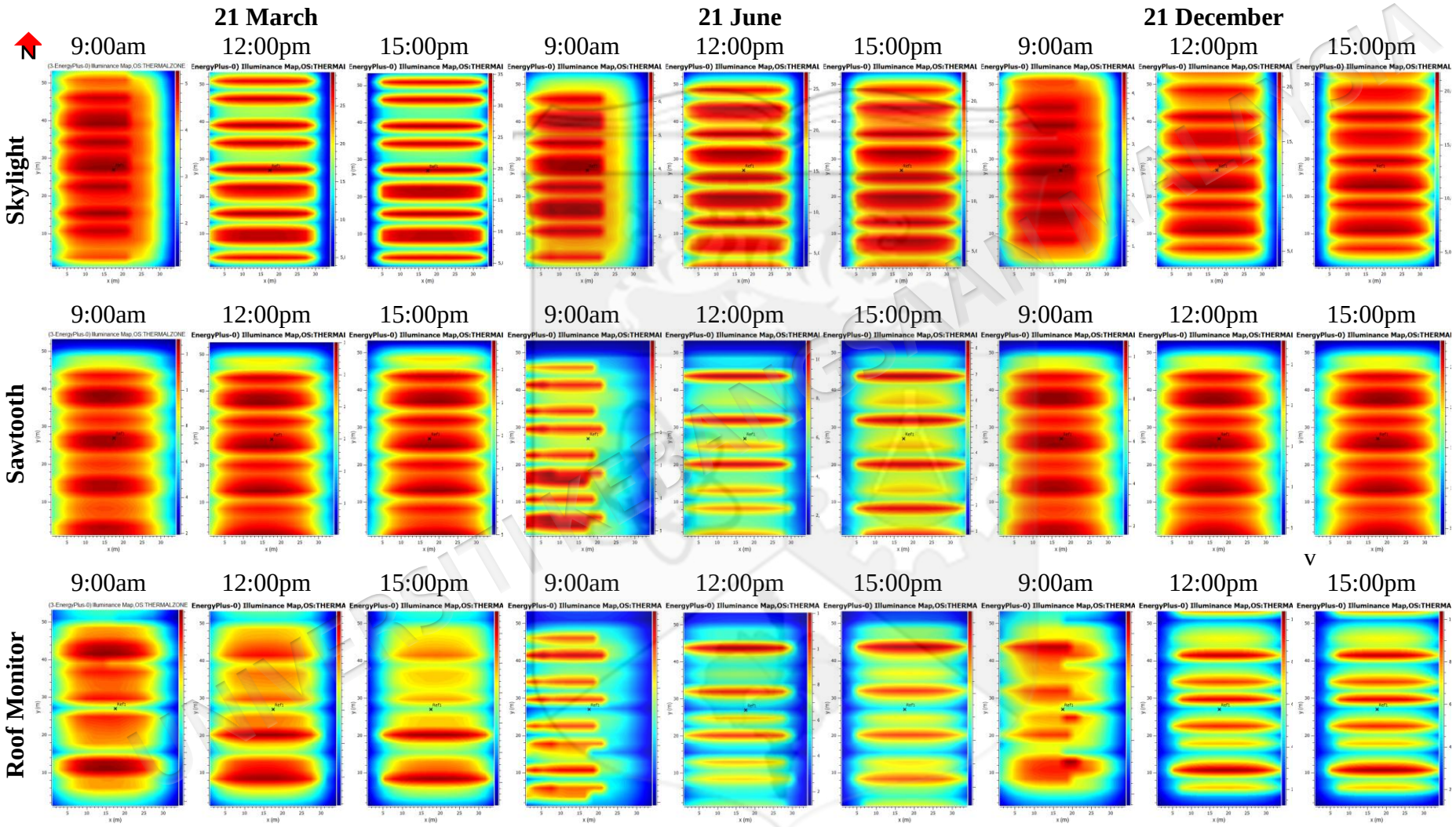

Figure B-12 Illuminance map comparison: 1to1 spacing-to-height ratio toplighting alternatives, 50% TFR, double Low-e clear

Table B-1 Daylight illuminance uniformity comparison: 1 to 1 spacing-to- ceiling height ratio toplighting alternatives, 20% TFR

	Skylight	**Sawtooth**	**Roof Monitor**
21 Mar 9:00am	0.19	0.24	0.23
21 Mar 12:00pm	0.14	0.22	0.20
21 Mar 15:00pm	0.13	0.22	0.20
21 Jun 9:00am	0.18	0.27	0.22
21 Jun 12:00pm	0.14	0.20	0.17
21 Jun 15:00pm	0.15	0.20	0.19
21 Dec 9:00am	0.20	0.23	0.23
21 Dec 12:00pm	0.17	0.22	0.19
21 Dec 15:00pm	0.16	0.22	0.19

Table B-2 Daylight illuminance uniformity comparison: 1 to 1 spacing-to-ceiling height ratio toplighting alternatives, 25% TFR

	Skylight	**Sawtooth**	**Roof Monitor**
21 Mar 9:00am	0.23	0.25	0.25
21 Mar 12:00pm	0.16	0.23	0.23
21 Mar 15:00pm	0.15	0.23	0.23
21 Jun 9:00am	0.20	0.27	0.23
21 Jun 12:00pm	0.16	0.21	0.19
21 Jun 15:00pm	0.18	0.21	0.21
21 Dec 9:00am	0.24	0.24	0.26
21 Dec 12:00pm	0.19	0.23	0.21
21 Dec 15:00pm	0.19	0.23	0.21

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Table B-3 Daylight illuminance uniformity comparison: 1 to 1 spacing-to- ceiling height ratio toplighting alternatives, 30% TFR

	Skylight	**Sawtooth**	**Roof Monitor**
21 Mar 9:00am	0.23	0.21	0.25
21 Mar 12:00pm	0.16	0.21	0.23
21 Mar 15:00pm	0.16	0.20	0.24
21 Jun 9:00am	0.20	0.24	0.22
21 Jun 12:00pm	0.16	0.19	0.19
21 Jun 15:00pm	0.18	0.18	0.20
21 Dec 9:00am	0.24	0.21	0.26
21 Dec 12:00pm	0.19	0.21	0.21
21 Dec 15:00pm	0.19	0.21	0.20

Table B-4 Daylight illuminance uniformity comparison: 1 to 1 spacing-to- ceiling height ratio toplighting alternatives, 35% TFR

	Skylight	**Sawtooth**	**Roof Monitor**
21 Mar 9:00am	0.23	0.21	0.27
21 Mar 12:00pm	0.17	0.20	0.25
21 Mar 15:00pm	0.20	0.20	0.26
21 Jun 9:00am	0.20	0.24	0.23
21 Jun 12:00pm	0.16	0.18	0.20
21 Jun 15:00pm	0.22	0.18	0.22
21 Dec 9:00am	0.25	0.20	0.28
21 Dec 12:00pm	0.19	0.20	0.22
21 Dec 15:00pm	0.24	0.20	0.21

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Table B-5 Daylight illuminance uniformity comparison: 1 to 1 spacing-to- ceiling height ratio toplighting alternatives, 40% TFR

	Skylight	**Sawtooth**	**Roof Monitor**
21 Mar 9:00am	0.23	0.22	0.26
21 Mar 12:00pm	0.17	0.21	0.23
21 Mar 15:00pm	0.21	0.21	0.23
21 Jun 9:00am	0.20	0.24	0.23
21 Jun 12:00pm	0.16	0.18	0.20
21 Jun 15:00pm	0.22	0.19	0.22
21 Dec 9:00am	0.25	0.21	0.26
21 Dec 12:00pm	0.19	0.21	0.20
21 Dec 15:00pm	0.24	0.21	0.20

Table B-6 Daylight illuminance uniformity comparison: 1 to 1 spacing-to- ceiling height ratio toplighting alternatives, 50% TFR

	Skylight	**Sawtooth**	**Roof Monitor**
21 Mar 9:00am	0.27	0.22	0.31
21 Mar 12:00pm	0.20	0.21	0.27
21 Mar 15:00pm	0.20	0.21	0.27
21 Jun 9:00am	0.23	0.24	0.25
21 Jun 12:00pm	0.19	0.19	0.22
21 Jun 15:00pm	0.21	0.19	0.26
21 Dec 9:00am	0.30	0.22	0.31
21 Dec 12:00pm	0.23	0.22	0.23
21 Dec 15:00pm	0.23	0.22	0.23

* The daylight illuminance uniformity ratio is the ratio of lowest illuminance value to average illuminance of the space area for each case: higher value indicates better uniformity

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Table B-7 Daylight illuminance gradient comparison: 1 to 1 spacing-to-ceiling height ratio toplighting alternatives, 20% TFR

	Skylight	**Sawtooth**	**Roof Monitor**
21 Mar 9:00am	8.6	6.7	7.0
21 Mar 12:00pm	16.4	7.2	8.1
21 Mar 15:00pm	18.2	7.3	8.4
21 Jun 9:00am	10.8	10.7	11.1
21 Jun 12:00pm	15.1	15.6	13.9
21 Jun 15:00pm	12.2	12.9	10.8
21 Dec 9:00am	7.8	7.0	7.9
21 Dec 12:00pm	11.0	7.2	12.7
21 Dec 15:00pm	10.8	7.1	12.5

Table B-8 Daylight illuminance gradient comparison: 1 to 1 spacing-to-ceiling height ratio toplighting alternatives, 25% TFR

	Skylight	**Sawtooth**	**Roof Monitor**
21 Mar 9:00am	6.7	6.1	6.1
21 Mar 12:00pm	12.4	6.5	6.7
21 Mar 15:00pm	13.4	6.7	6.5
21 Jun 9:00am	8.6	9.7	10.3
21 Jun 12:00pm	11.7	13.2	11.6
21 Jun 15:00pm	9.4	9.4	9.2
21 Dec 9:00am	6.0	6.3	6.3
21 Dec 12:00pm	8.4	6.5	10.3
21 Dec 15:00pm	8.3	6.4	10.1

* The daylight illuminance gradient ratio can be found by calculating the ratio of maximum to minimum illuminance value of the space area of each case: lower value indicates better uniformity

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Table B-9 Daylight illuminance gradient comparison: 1 to 1 spacing-to-ceiling height ratio toplighting alternatives, 30% TFR

	Skylight	**Sawtooth**	**Roof Monitor**
21 Mar 9:00am	6.5	6.9	6.1
21 Mar 12:00pm	11.4	7.2	6.6
21 Mar 15:00pm	12.3	7.3	6.4
21 Jun 9:00am	8.2	9.8	9.7
21 Jun 12:00pm	11.0	13.4	10.5
21 Jun 15:00pm	9.0	11.0	9.3
21 Dec 9:00am	5.9	7.1	6.2
21 Dec 12:00pm	8.0	7.1	9.7
21 Dec 15:00pm	7.9	7.0	9.6

Table B-10 Daylight illuminance gradient comparison: 1 to 1 spacing-to-ceiling height ratio toplighting alternatives, 35% TFR

	Skylight	**Sawtooth**	**Roof Monitor**
21 Mar 9:00am	6.1	6.9	5.5
21 Mar 12:00pm	10.4	7.1	5.8
21 Mar 15:00pm	8.8	7.2	5.7
21 Jun 9:00am	7.7	9.3	8.8
21 Jun 12:00pm	10.1	12.5	10.2
21 Jun 15:00pm	7.0	10.4	8.0
21 Dec 9:00am	5.6	7.0	5.5
21 Dec 12:00pm	7.5	7.0	8.6
21 Dec 15:00pm	6.0	6.9	8.5

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Table B-11 Daylight illuminance gradient comparison: 1 to 1 spacing-to-ceiling height ratio toplighting alternatives, 40% TFR

	Skylight	**Sawtooth**	**Roof Monitor**
21 Mar 9:00am	6.1	6.6	5.9
21 Mar 12:00pm	9.8	6.9	6.8
21 Mar 15:00pm	8.2	7.0	7.2
21 Jun 9:00am	7.5	8.1	8.5
21 Jun 12:00pm	9.7	11.3	10.4
21 Jun 15:00pm	6.7	9.9	8.3
21 Dec 9:00am	5.5	6.8	6.5
21 Dec 12:00pm	7.3	6.8	9.1
21 Dec 15:00pm	5.8	6.7	9.0

* The daylight illuminance gradient ratio can be found by calculating the ratio of maximum to minimum illuminance value of the space area of each case: lower value indicates better uniformity

Table B-12 Daylight illuminance gradient comparison: 1 to 1 spacing-to-ceiling height ratio toplighting alternatives, 50% TFR

	Skylight	**Sawtooth**	**Roof Monitor**
21 Mar 9:00am	4.9	6.7	5.0
21 Mar 12:00pm	7.4	6.8	5.3
21 Mar 15:00pm	7.6	6.8	5.9
21 Jun 9:00am	6.2	7.3	8.0
21 Jun 12:00pm	7.7	10.3	9.8
21 Jun 15:00pm	6.5	9.3	7.6
21 Dec 9:00am	4.4	6.7	5.1
21 Dec 12:00pm	5.9	6.6	8.3
21 Dec 15:00pm	5.7	6.5	8.1

* The daylight illuminance gradient ratio can be found by calculating the ratio of maximum to minimum illuminance value of the space area of each case: lower value indicates better uniformity

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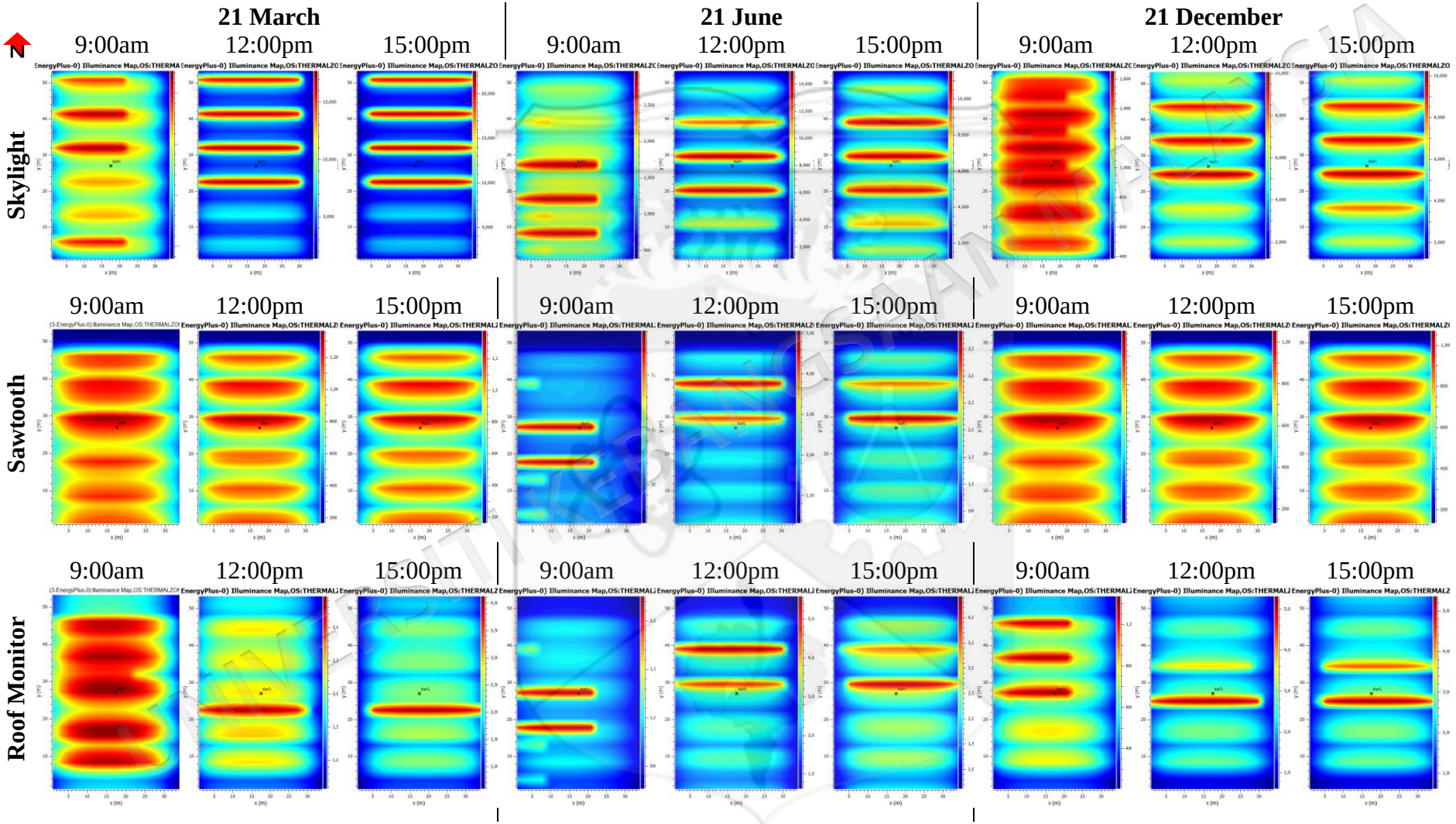

Figure B-13 Illuminance map comparison: 1to1.5 spacing-to-height ratio toplighting alternatives, **15% TFR**, double low-e clear

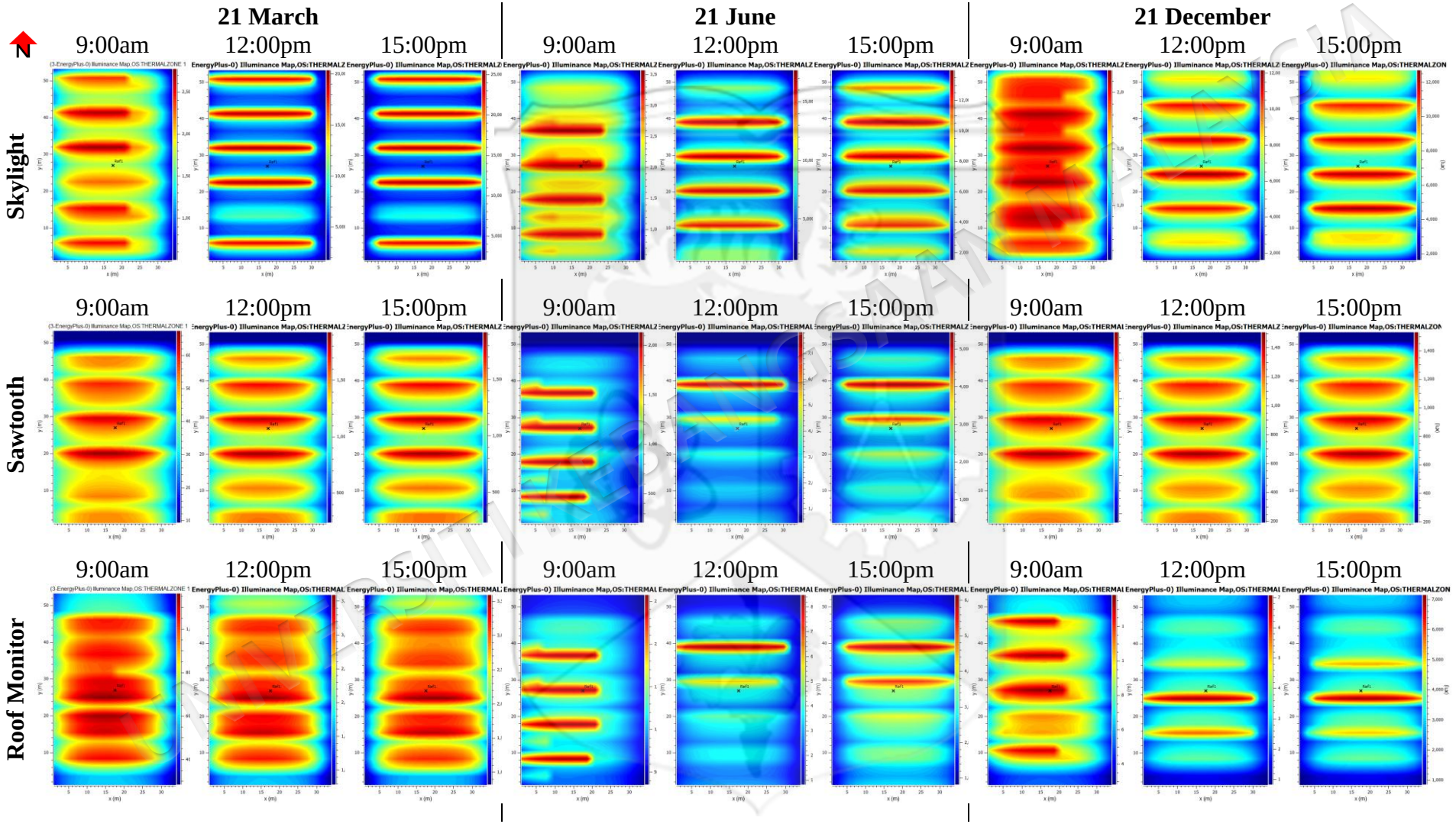

Figure B-14 Illuminance map comparison: 1 to 1.5 spacing-to-height ratio toplighting alternatives, **20% TFR**, dabule Low-e clear

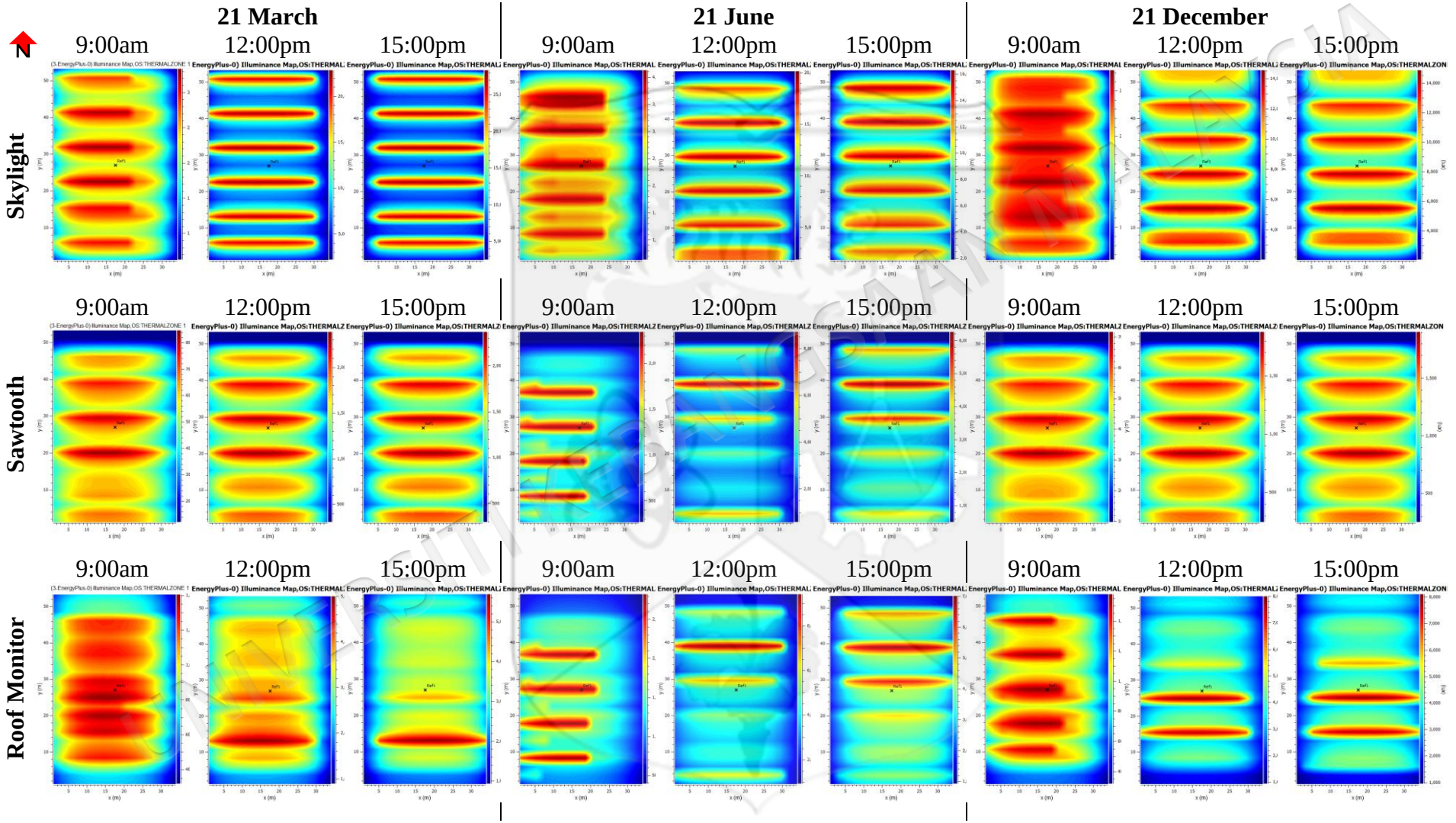

Figure B-15 Illuminance map comparison: 1 to 1.5 spacing-to-height ratio toplighting alternatives, **25% TFR**, dabule Low-e clear

Table B-13 Daylight illuminance gradient comparison: 1 to 1.5 spacing-to-ceiling height ratio toplighting alternatives, 20% TFR

	Skylight	**Sawtooth**	**Roof Monitor**
21 Mar 9:00am	5.5	7.2	4.1
21 Mar 12:00pm	11.4	8.1	4.6
21 Mar 15:00pm	12.7	8.3	4.4
21 Jun 9:00am	7.0	10.3	7.2
21 Jun 12:00pm	11.8	17.0	10.3
21 Jun 15:00pm	9.2	14.0	7.5
21 Dec 9:00am	4.3	7.5	4.9
21 Dec 12:00pm	7.5	7.9	8.5
21 Dec 15:00pm	7.4	7.8	8.3

Table B-14 Daylight illuminance gradient comparison: 1 to 1.5 spacing-to-ceiling height ratio toplighting alternatives, 25% TFR

	Skylight	**Sawtooth**	**Roof Monitor**
21 Mar 9:00am	5.3	7.0	4.4
21 Mar 12:00pm	10.3	7.8	5.6
21 Mar 15:00pm	11.3	7.9	6.1
21 Jun 9:00am	6.5	8.8	7.2
21 Jun 12:00pm	10.8	14.7	10.2
21 Jun 15:00pm	8.6	12.4	7.6
21 Dec 9:00am	4.2	7.3	5.0
21 Dec 12:00pm	7.2	7.6	8.5
21 Dec 15:00pm	7.1	7.5	8.4

* The daylight gradient ratio can be found by calculating the ratio of maximum to minimum illuminance value of the space area of each case: lower value indicates better uniformity

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Table B-15 Daylight illuminance uniformity comparison: 1 to 1.5 spacing-to- ceiling height ratio toplighting alternatives, 20% TFR

	Skylight	**Sawtooth**	**Roof Monitor**
21 Mar 9:00am	0.29	0.23	0.36
21 Mar 12:00pm	0.21	0.22	0.32
21 Mar 15:00pm	0.20	0.21	0.34
21 Jun 9:00am	0.24	0.25	0.31
21 Jun 12:00pm	0.19	0.20	0.27
21 Jun 15:00pm	0.21	0.19	0.29
21 Dec 9:00am	0.32	0.22	0.35
21 Dec 12:00pm	0.24	0.22	0.28
21 Dec 15:00pm	0.23	0.22	0.28

Table B-16 Daylight illuminance uniformity comparison: 1 to 1.5 spacing-to- ceiling height ratio toplighting alternatives, 25% TFR

	Skylight	**Sawtooth**	**Roof Monitor**
21 Mar 9:00am	0.29	0.24	0.33
21 Mar 12:00pm	0.21	0.22	0.30
21 Mar 15:00pm	0.20	0.22	0.31
21 Jun 9:00am	0.24	0.26	0.29
21 Jun 12:00pm	0.18	0.19	0.24
21 Jun 15:00pm	0.21	0.19	0.27
21 Dec 9:00am	0.32	0.23	0.33
21 Dec 12:00pm	0.23	0.22	0.26
21 Dec 15:00pm	0.23	0.22	0.26

* The daylight illuminance uniformity ratio is the ratio of lowest illuminance value to average illuminance of the space area for each case: higher value indicates better uniformity

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APPENDIX C: GLOSSARY

The terms and descriptions in this glossary were taken from ASHRAE Terminology of Heating, Ventilation, Air Conditioning and Refrigeration and IECC (International Energy Conservation Code) 2006.

Term	Description
Daylighting	The use of the sky or the sun as the source of light
Toplighting	The use of the ceiling or roof part of the building to bring daylight into the interior space
Illuminance	The amount of light incident on a surface, measured in Lux
Luminance	The amount of light reflected off a surface, measured in candela/m2
Lumen	A common unit of light output from a source
Luminaire	A complete electric lighting unit including housing, lamp, electrical components, diffusers and focusers. Also called a fixture.
Cooling load	The total energy needed to remove heat from the space
Heating Load	The total energy needed to heat the space to the temperature set point
Heat gains	The amount of heat entering the space through building surfaces, equipments, or people
Heat losses	The amount of heat leaving the space through building surfaces, equipments, or people
Glare	The sensation produced by brightness within the visual field that is greater than the brightness to which the eye is adapted and thus causes annoyance, discomfort, or loss in visual performance and visibility
Contrast Glare	Glare resulting from a large brightness difference in the field of view
Reflected Glare	Glare resulting from mirror-like reflections in shiny surfaces

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Footcandle	A common unit of illuminance used in the U.S. The metric unit is the lux. Footcandle 1 fc = 10.764 lx
Kilowatt	Unit of electric power (the rate at which energy is used). Equals 1000 Watts
Kilowatt-Hour	Unit of energy. Equals 1000 Watthours
Transmittance	The ratio of energy (light) passing through a surface to the amount striking it, expressed as a percentage
Workplane	The plane at which work is performed, usually taken as horizontal and at desk height (30") from the floor
Thermal conduction	The mode of heat transfer through a material by molecular contact. Heat flows from a high-temperature area to one of lower temperature
Thermal conductance (C)	The same as thermal conductivity except that thickness is "as stated' rather than one inch
Thermal conductivity (k)	The heat transfer property of materials, expressed in units of power per area and degree of temperature (e.g., Btu-per-hour per inch of thickness per square foot of surface per one degree F temperature difference).
Thermal mass	The mass in a building (furnishings or structure) that is used to absorb solar gain during the day and release the heat as the space cools in the evening
Daylight Factor	The ratio of interior illuminance at a given point on a given plane (usually the workplane) to the exterior illuminance (reference) under the same overcast sky conditions, eg. The CIE overcast sky distribution. Unit of daylight factor is percent (%)
Clear sky	Has less than 30 % cloud cover, or none. This sky is most likely to be combined with sun
Partly cloudy sky	Has between 30 % and 70 % cloud cover. This sky can be combined with sun in some cases
Cloudy sky	Has more than 70 % cloud cover. This sky normally excludes the sun
Overcast sky	Has a completely closed cloud cover (100 %). Obviously, this sky can't be combined with sun in a meaningful way. This is the sky condition applied in daylight factor calculations

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Energy Simulation Tool	An approved software program or calculation-based methodology that projects the annual energy use of a building
Fenestration	ASHRAE 1. In an external wall of a building, any area which allows light to pass. 2. Commonly used to refer to any opening, usually glazed, in a building envelope
Fenestration	IECC Skylights, roof windows, vertical windows (fixed or movable), opaque doors, glazed doors, glazed blocks, and combination opaque/glazed doors. Fenestration products with glass and non-glass glazing materials

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APPENDIX D: LIGHT METER FEATURES AND SPECIFICATIONS

LIGHT METER *4 light type*

Model : LX-1108 *ISO-9001, CE, IEC1010*

home

FEATURES

* 5 ranges :
  40.00/400.0/4,000/40,000/400,000 Lux.
* Resolution :
  0.01 Lux to 100 Lux.
  0.01 Ft-cd to 10 Ft-cd.
* Selection of lighting type (Tungsten, Fluorescent, Sodium or Mercury).
* Sensor used the exclusive photo diode & color correction filter, spectrum meet C.I.E. photopic.
* Sensor cosine correction factor meet standard.
* Separate Light Sensor allows user to measure the light at an optimum position.
* Lux & Foot-candle unit selection.
* Large LCD display with bar graph.
* Water resistance front panel
* Zero adjusting button.
* Data hold and Peak hold.
* Memory function with Recall. Auto
* Auto power off or manual power off.
* RS-232 computer data output.

ISO 9001

Lutron

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The Art of Measurement

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4 light type selection

LIGHT METER

Model : LX-1108

FEATURES	
* 5 ranges : 40.00/400.0/4,000/40,000/400,000 Lux, wide measuring range.	* Large LCD display with bargraph and indicator.
* High resolution : 0.01 Lux to 100 Lux, 0.01 Fc to 10 Fc	* Water resistance front panel
* Selection of lighting type (Tungsten, Fluorescent, Sodium or Mercury).	* Use the rubber key for the function select.
* Sensor used the exclusive photo diode & color correction filter, spectrum meet C.I.E. photopic.	* LSI circuit provides high reliability and durability.
* Sensor cosine correction factor meet standard.	* Zero adjusting button.
* Separate Light Sensor allows user to measure the light at an optimum position.	* Data hold to freeze the desired reading.
* Lux & Foot-candle unit selection.	* Peak hold measurement.
	* Memory function to display the max. & min. display value with Recall.
	* Auto power auto off or manual power off.
	* Compact size and excellent operation.
	* Built-in low battery indicator.
	* RS-232 computer serial data output.

GENERAL SPECIFICATIONS			
Display	Large LCD dispaly. LCD size 52 x 38 mm, 4 digits. with bargraph indicator.	Data Output	RS-232 serial data output.
		Operating Temperature	0 to 50 ℃ (32 to 122 ℉).
Measurement & ranges	5 ranges : 40.00/400.0 Lux, 4,000/40,000/400,000 Lux.	Operating Humidity	Max. 80% RH.
Unit	Lux, Foot-candle (Ft-cd).	Power Supply	DC 9V battery. 006P, MN1604 (PP3) or equivalent.
Lighting Type Selection	Tungsten, Fluorescent, Sodium, Mercury lamp.	Power Consumption	Approx. DC 8 mA.
Sensor	The exclusive photo diode & color correction filter, spectrum meet C.I.E. Cosine correction factor meet standard.	Weight	220 g/0.48 LB.
		Dimension	*Main instrument :* 200 x 68 x 30 mm (7.9 x 2.7 x 1.2 inch). *Sensor probe :* 82 x 55 x 7 mm (3.2 x 2.2 x 0.3 inch).
Zero Adj.	External adjustment by pushing button.		
	(40.00 Lux range only)		
Peak Hold	To hold the peak display.	Accessories Included	Instruction Manual... 1 PC.
Data Hold	To freeze the display value.		Light Sensor with protection cover..... 1 PC.
Memory	Save the max. & min. value with Recall.	Optional Accessories	RS232 cable, UPCB-02
Power Off	Auto or manaual power off.		USB cable, USB-01
Over and Under range Indication	Over range Indicator : "- - - -"		Application Software, SW-U801-WIN
	Under range Indicator : " "		Hard carryingt case, CA-06
			Soft carryingt case, CA-05A

ELECTRICAL SPECIFICATIONS (23± 5℃)				
Measurement	*Range*	*In-range Display*	*Resolution*	*Accuracy*
Lux	40.00 Lux	0 - 40.00 Lux	0.01 Lux	± (3% rdg + 0.5 % F.S..)
	400.0 Lux	36.0 - 400.0 Lux	0.1 Lux	
	4,000 Lux	360 - 4,000 Lux	1 Lux	
	40,000 Lux	3,600 - 40,000 Lux	10 Lux	
	400,000 Lux	10,000 - 400,000 Lux	100 Lux	< 100,000 Lux : ± (3% rdg + 0.5 % F.S..) ≥ 100,000 Lux : *@ for reference only*
Foot-candle (Fc)	4.000 Fc	0 - 3.720 Fc	0.001 Fc	± (3% rdg + 0.5 % F.S..)
	40.00 Fc	3.35 - 37.20 Fc	0.01 Fc	
	400.0 Fc	33.5 - 372.0 Fc	0.1 Fc	
	4,000 Fc	335 - 3,720 Fc	1 Fc	
	40,000 Fc	930 - 37,200 Fc	10 Fc	< 9,300 Fc : ± (3% rdg + 0.5 % F.S..) ≥ 9,300 Fc *@ for reference only*

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