DEVELOPING A SIMULATION-BASED WORKFLOW FOR HEALING BUILDING ENVELOPES IN HEALTHCARE DESIGN

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DEVELOPING A SIMULATION-BASED WORKFLOW FOR HEALING BUILDING ENVELOPES IN HEALTHCARE DESIGN

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TABLE OF CONTENTS

ACKNOWLEDGEMENTS **iii**

LIST OF TABLES **vi**

LIST OF FIGURES **vii**

LIST OF SYMBOLS AND ABBREVIATIONS **xii**

SUMMARY **xiii**

CHAPTER 1: INTRODUCTION **1**
1.1 Research Purpose 2
1.1.1 Research Goal 2
1.2 Research methodology and structure 3
1.2.1 Background and significance 3
1.2.2 Research objectives 3
1.2.3 Research questions 3
1.2.4 Target audience 4
1.2.5 Thesis Overview 4
1.3 Acknowledgements 5

CHAPTER 2: LITERATURE REVIEW **6**
2.1 Daylighting in built environment 6
2.2 Factors affecting daylighting performance 7
2.3 Daylighting in healthcare design 8
2.4 Lighting and human health 9
2.5 Daylighting and average length of stay period 11
2.6 Identifying gaps in the literature review 12

CHAPTER 3: EXPERIMENT DESIGN **14**
3.1 Experiment goals and objectives 14
3.2 Experiment Design 15
3.2.1 Stage 1 – setting up base 3D model of patient room 16
3.2.2 Stage 2 – Daylighting Optimization of building envelope parameters 20
3.2.3 Stage 3 – Circadian rhythm analysis 22

CHAPTER 4: RESULTS **28**
4.1 Patient Room Orientation – North 29
4.1.1 Daylighting Optimization 29
4.1.2 Glare Analysis 37
4.1.3 Circadian Rhythm analysis 38
4.2 Patient Room Orientation - South 44
4.2.1 Daylighting Optimization 44

4.2.2 Glare Analysis 45
4.2.3 Circadian Rhythm analysis 46
4.3 Patient Room Orientation – East 49
4.3.1 Daylighting optimization 49
4.3.2 Glare Analysis 50
4.3.3 Circadian Rhythm analysis 51
4.4 Patient Room Orientation – West 54
4.4.1 Daylighting optimization 54
4.4.2 Glare Analysis 55
4.4.3 Circadian Rhythm analysis 56

CHAPTER 5: DISCUSSION, LIMITATIONS, FUTURE RESEARCH, AND CONCLUSION 59
5.1 Discussion on the simulation results 59
5.2 Limitations 62
5.3 Future Research 63
5.4 Conclusion 64

APPENDIX 65

REFERENCES 96

LIST OF TABLES

Table 1	- ALFA results summary for melanopic lux levels	xv
Table 2	- Comparative analysis of sDA values	62
Table 3	- Comparative analysis of melanopic lux values at 9:00 am, clear sky condition	62
Table 4	- Comparative analysis of melanopic lux values at 9:00 am, overcast sky condition	62

LIST OF FIGURES

Figure 1 - Research process flowchart 4

Figure 2 - Experiment Design flowchart 15

Figure 3 - Layout and isometric view of ASU level in HMHI, Salt Lake City, Utah 16

Figure 4 - Patient room North – enlarged 2D&3D diag., daylighting analysis 17

Figure 5 - Patient room South – enlarged 2D&3D diag., daylighting analysis 18

Figure 6 - Patient room East – enlarged 2D&3D diag., daylighting analysis 19

Figure 7 - Patient room West – enlarged 2D&3D diag., daylighting analysis 19

Figure 8 - Daylighting Optimization process flowchart 20

Figure 9 - DOE tables generated for Optimization 21

Figure 10 - Circadian rhythm analysis flowchart 22

Figure 11 - Selection of clear and overcast sky conditions based on climate data 23

Figure 12 - Existing patient room – North: comparative melanopic lux analysis 24

Figure 13 - Existing patient room – South: comparative melanopic lux analysis 25

Figure 14 - Existing patient room – East: comparative melanopic lux analysis 26

Figure 15 - Existing patient room – West: comparative melanopic lux analysis 27

Figure 16 - North Orientation – Daylighting optimization iterations using louvers as shading mechanism 29

Figure 17 - North Orientation – Comparative analysis of louvers iterations using Design Explorer 30

Figure 18 - North Orientation – Selection of optimum louvers iteration 31

Figure 19 - North Orientation – Daylighting optimization iterations using fins as shading mechanism 32

Figure 20 - North Orientation – Comparative analysis of fins iterations using Design Explorer 33

Figure 21 - North Orientation – Selection of optimum fins iteration 34

Figure 22 - North Orientation – Comparative analysis of shortlisted louvers and fins iterations 35

Figure 23 - North Orientation – Shortlisted iteration for circadian rhythm analysis 36

Figure 24 - North Orientation – Patient room Glare analysis 37

Figure 25 - North Orientation – Circadian rhythm analysis Scene 1A and Scene 1B 38

Figure 26 - North Orientation – Circadian rhythm analysis Scene 1C and Scene 1D 39

Figure 27 - North Orientation – Circadian rhythm analysis Scene 1E and Scene 2A 40

Figure 28 - North Orientation – Circadian rhythm analysis Scene 2B and Scene 2C 41

Figure 29 - North Orientation – Circadian rhythm analysis Scene 2D and Scene 2E 42

Figure 30 - North Orientation – Circadian rhythm analysis summary 43

Figure 31 - South Orientation – Shortlisted iteration for circadian rhythm analysis 44

Figure 32 - South Orientation – Patient room Glare analysis 45

Figure 33 - South Orientation – Circadian rhythm analysis Scene 1A and Scene 1B 46

Figure 34 - South Orientation – Circadian rhythm analysis Scene 2B and Scene 2C 47

Figure 35 - South Orientation – Circadian rhythm analysis summary 48

Figure 36 - East Orientation – Shortlisted iteration for circadian rhythm analysis 49

Figure 37 - East Orientation – Patient room Glare analysis 50

Figure 38 - East Orientation – Circadian rhythm analysis Scene 1A and Scene 1B 51

Figure 39 - East Orientation – Circadian rhythm analysis Scene 2B and Scene 2C 52

Figure 40 - East Orientation – Circadian rhythm analysis summary 53

Figure 41 - West Orientation – Shortlisted iteration for circadian rhythm analysis 54

Figure 42 - West Orientation – Patient room Glare analysis 55

Figure 43 - West Orientation – Circadian rhythm analysis Scene 1A and Scene 1B 56

Figure 44 - West Orientation – Circadian rhythm analysis Scene 2B and Scene 2C 57

Figure 45 - West Orientation – Circadian rhythm analysis summary 58

Figure 46 - South Orientation – Daylighting optimization iterations using louvers as shading mechanism 66

Figure 47 - South Orientation – Comparative analysis of louvers iterations using Design Explorer 67

Figure 48 - South Orientation – Selection of optimum louvers iteration 68

Figure 49 - South Orientation – Daylighting optimization iterations using fins as shading mechanism 69

Figure 50 - South Orientation – Comparative analysis of fins iterations using Design Explorer 70

Figure 51 - South Orientation – Selection of optimum fins iteration 71

Figure 52 - South Orientation – Comparative analysis of shortlisted louvers and fins iterations 72

Figure 53 - South Orientation – Circadian rhythm analysis Scene 1C and Scene 1D 73

Figure 54 - South Orientation – Circadian rhythm analysis Scene 1E and Scene 2A 74

Figure 55 - South Orientation – Circadian rhythm analysis Scene 2D and Scene 2E 75

Figure 56 - East Orientation – Daylighting Optimization iterations using louvers as shading mechanism 76

Figure 57 - East Orientation - Comparative analysis of louvers iterations using Design Explorer 77

Figure 58 - East Orientation - Selection of optimum louvers iteration 78

Figure 59 - East Orientation - Daylighting Optimization iterations using fins as shading mechanism 79

Figure 60 - East Orientation - Comparative analysis of fins iterations using Design Explorer 80

Figure 61 - East Orientation – Selection of optimum fins iteration 81

Figure 62 - East Orientation – Comparative analysis of shortlisted louvers and fins iterations 82

Figure 63 - East Orientation – Circadian rhythm analysis Scene 1C and Scene 1D 83

Figure 64 - East Orientation – Circadian rhythm analysis Scene 1E and Scene 2A 84

Figure 65 - East Orientation – Circadian rhythm analysis Scene 2D and Scene 2E 85

Figure 66 - West Orientation – Daylighting Optimization iterations using louvers as shading mechanism 86

Figure 67 - West Orientation – Comparative analysis of louvers iterations using Design Explorer 87

Figure 68 - West Orientation - Selection of optimum louvers iteration 88

Figure 69 - West Orientation - Daylighting Optimization iterations using fins as shading mechanism 89

Figure 70 - West Orientation – Comparative analysis of shortlisted louvers and fins iterations 90

Figure 71 - West Orientation – Selection of optimum fins iteration 91

Figure 72 - West Orientation – Comparative analysis of shortlisted louvers and fins iterations 92

Figure 73 - West Orientation – Circadian rhythm analysis Scene 1C and Scene 1D 93

Figure 74 - West Orientation – Circadian rhythm analysis Scene 1E and Scene 2A 94

Figure 75 - West Orientation – Circadian rhythm analysis Scene 2D and Scene 2E 95

LIST OF SYMBOLS AND ABBREVIATIONS

LEED	Leadership in Energy and Environmental Design
WELL	building performance standard to measure impact on human health
sDA	Spatial Daylight Autonomy
ASE	Annual Sunlight Exposure
DGP	Daylight Glare Probability
EML	Equivalent Melanopic Lux
IES	Illuminating Engineering Society
ALFA	Adaptive Lighting for Alertness – circadian lighting software
HMHI	Huntsman Mental Health Institute
ASU	Acute Stabilization Unit
FFKR	Architects based in Salt Lake City, Utah
VT	Visible Transmittance
DOE	Design of Experiment
JMP	Statistical Analysis Software

SUMMARY

With the rapid progress and advancement in electrical lighting solutions for the interior built environment, daylighting has lost its due priority in the overall planning and design process. Apart from being a source of connection to the exterior built environment, daylighting significantly impacts the occupants' physiological and psychological well-being. In today’s ever-changing era of technology, incorporating ambient daylighting levels within the indoor built environment has become of paramount importance.

The degree of facilitating daylighting differs for different building typologies and depends significantly on the nature of the occupants. This thesis develops a simulation-based workflow to assess the impact of daylighting in patient room settings within a healthcare-built environment. This workflow would primarily assess the impact of building envelope parameters like window-to-wall ratios and shading mechanisms in impacting daylighting in general. LEED and WELL building standards are used as benchmark performance indicators to evaluate the overall performance of the building envelope.

The aim of this thesis is twofold i) to optimize the building envelope parameters such as window-to-wall ratio and shading mechanisms and evaluate the impact of each on daylighting through metrics such as sDA and ASE ii) to evaluate the impact of daylighting on the circadian rhythms of occupants within a patient room setting by analyzing the melanopic lux levels. The simulations evaluate the impact of building envelope parameters on daylighting through the Optimization platform Colibri using Honeybee as a front-end software and Radiance as a backend daylighting performance engine. For the circadian

rhythm analysis ALFA – a circadian lighting software evaluates the melanopic lux levels inside the patient room for different orientations.

The experiment is set in a crisis care centre facility in Salt Lake City, Utah. The project has been designed by FFKR architects and funded by the Huntsman Mental health Foundation. Results from the Optimization stage are analyzed using Design Explorer to evaluate metrics such as spatial daylight autonomy (sDA) and Annual sunlight exposure (ASE) for patient rooms in all orientations of the healthcare setting. It was observed that the North and South orientations recorded sDA values in the range of 85-95% and ASE values in the range of 1-15% with a window-to-wall ratio of 0.7 and 0.6 respectively, whereas the East and West orientations recorded sDA values in the range of 80-90% and ASE values in the range of 45-50% with a 0.5 window-to-wall ratio. In terms of shading mechanisms, the North orientation patient rooms performed better with fins whereas patient rooms in the South, East, and West orientations required louvers to maintain a balance in sDA and ASE values.

Results from the Circadian analysis stage of the experiment are analyzed using ALFA which records the melanopic lux levels during clear and overcast sky conditions at different times of the day viz. 9:00 am, 10:00 am, 11:00 am, 12:00 pm, and 1:00 pm at a work plane level of 1000mm from floor level. The height of the analysis plane is considered as an average height with reference to the eye level of the patient in two positions viz. sleeping on an inclined bed and sitting on a chair. Apart from the average melanopic lux levels, the melanopic lux levels for both bed and chair positions will be analyzed. This occupant-centric approach analyzes the melanopic lux levels generated under varying climatic conditions. The results will be evaluated with reference to the benchmark

minimum melanopic lux level threshold set as per WELL standards for living environments.

The different sky conditions impact the melanopic lux levels due to varying daylighting levels. The table below summarizes the varying melanopic lux levels for different patient room orientations.

Table 1: ALFA results summary for melanopic lux levels

ALFA results summary for melanopic lux levels				
Sr.no	Patient room orientation	avg. melanopic lux level range - overcast to clear sky conditions	**Bed level** - melanopic lux level range - overcast to clear sky conditions	**Chair level** - melanopic lux level range - overcast to clear sky conditions
1	North orientation	925 - 2693 lux	1117 - 3374 lux	764 - 2234 lux
2	South orientation	230 - 1377 lux	283 - 1743 lux	183 - 1012 lux
3	East orientation	287 - 1628 lux	356 - 1939 lux	203 - 1190 lux
4	West orientation	247 - 1206 lux	289 - 1476 lux	171 - 776 lux

To maximize the impact of daylighting, an integrated approach towards designing a building envelope in healthcare design is discussed to benefit the occupants inside a patient room setting. This thesis provides a simulation-based framework to design building envelopes in healthcare design focusing on facilitating ambient daylighting within a patient room setting and regulating the circadian rhythms of its occupants through an analysis of the melanopic lux levels.

CHAPTER 1: INTRODUCTION

Over the years, daylighting has impacted key decisions of architects and urban planners in designing and shaping the built environment. Apart from recording the changing times of the day daylighting also aided in understanding seasonal changes and variations. In terms of framing construction codes and regulations, daylighting played a key role in facilitating micro-level changes such as building floor depths, the overall form of the building, and other fundamental parameters. (Konis, 2019) On an urban scale, one of the most prominent examples was the resolution passed by New York City commissioner Edward M Bassett for 'setbacks' in skyscrapers to facilitate natural light on the streets and sidewalks.(Bliss, 2016)

Daylighting is essentially the combination of direct and indirect sunlight visible to the human eye at any given point during the daytime. Considering the vast expanse of the earth, this daytime varies from the location and time of the year. Daylighting also helps to establish a visual connection to the immediate outdoors and absorb a plethora of information provided by the surrounding context. The varying stimulation levels daylighting provides also aid in reducing stress and increasing productivity. (MBC Aries, 2013) However, glare from daylighting can cause visual discomfort, and when daylighting is coupled with heat it can also result in an increase in cooling loads within the interiors of the built environment. (WKE, 2005)

A significant innovation in electrical lighting towards the end of the 20th century resulted in people spending close to 90% of their time indoors in a controlled lighting environment which in the long run has severely impacted the overall health and well-being of mankind. (Konis, 2019) The primary objective of daylighting is to minimize the

dependence on electrical lighting during daytime hours, which also has an impact on the overall energy savings to some extent. Apart from providing visual comfort, daylighting plays a pivotal role in regulating the circadian clock of occupants thereby affecting their sleep, and wake cycles. There is significant research conducted in the past that established a relationship between daylighting and the average length of stay (LOS) periods. The higher the penetration of daylighting inside the patient rooms shorter is the length of stay (LOS) period. (Man Young Park, 2018)

It is important to assess the parameters of the building envelope in regulating daylighting within the interior built environment. Particularly in healthcare design, where daylighting is often considered a vital factor impacting the health of patients and healthcare staff. Although there has been significant development in tunable electrical lighting, the focus should be on creating ambient daylighting conditions.

1.1 Research Purpose

1.1.1 Research Goal

To understand the impact of daylighting in regulating the circadian rhythms of occupants within a patient room setting using a simulation-based workflow analyzing building envelope parameters like window-to-wall ratio and shading.

1.2 Research methodology and structure

1.2.1 Background and significance

The research assumes the importance of daylighting in interior-built environments. Therefore, it investigates how daylighting as a parameter can impact circadian rhythms and create a visually comforting environment for occupants within a patient room setting inside healthcare buildings.

1.2.2 Research objectives

- To evaluate opportunities to harness the daylighting potential within a patient room setting by incorporating strategies in the building envelope design.
- To assess the potential of envelope parameters such as window-to-wall ratio, and shading mechanisms in regulating daylighting within the interiors of a patient room.
- To understand the impact of varying climatic conditions on daylighting and the subsequent effect on melanopic lux levels.

1.2.3 Research questions

1) How can the existing knowledge on daylighting be integrated with emerging simulation workflows for evaluating building envelope parameters?
2) How can building envelope parameters facilitating daylighting in the interior built environment help in regulating the circadian rhythms of its occupants?

1.2.4 Target audience

This thesis is an attempt to enhance the current understanding of daylighting and its subsequent impact on human health. The primary target audiences are both architects and planners in the healthcare design sector. The results and findings of this thesis can help in making informed decisions focusing on daylighting and building envelope design.

1.2.5 Thesis Overview

The first chapter introduces the thesis and underlines its goals and objectives. The second chapter investigates the impact of daylighting on the built environment and healthcare design in general through a literature review. The third chapter gives an insight into the simulation experiment. The fourth chapter demonstrates the results of the simulation experiments. The fifth and final chapter is an evaluation of the findings, results, limitations, future research, and conclusion of the thesis.

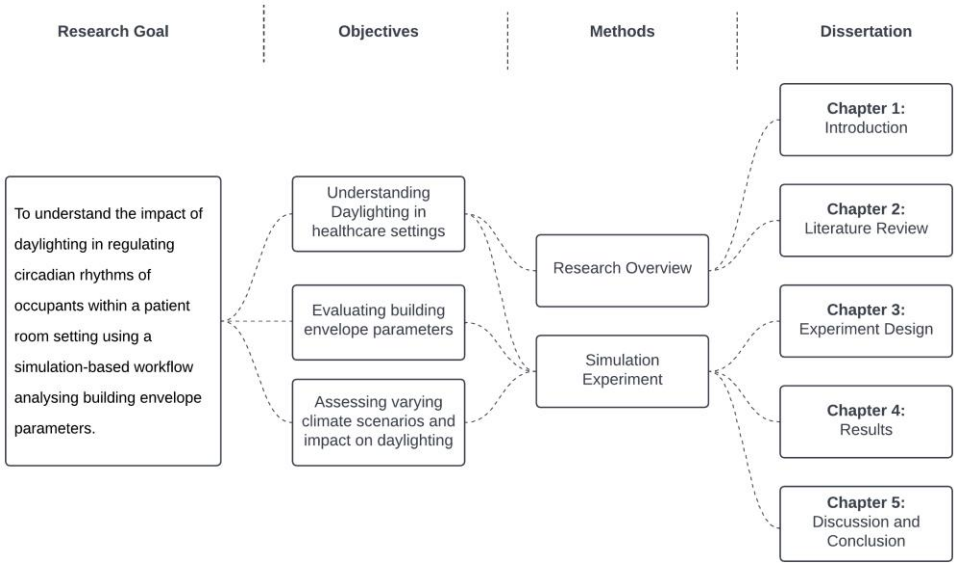


Figure 1: Research Process Flowchart

1.3 Acknowledgements

The information, data, and work presented herein is an academic & research-based perspective of an ongoing project designed by FFKR architects of a Crisis Care Center funded by the Huntsman Mental Health foundation based in Salt Lake City, Utah. SimTigrate design Lab served as a consultant providing suggestions on the lighting aspects of the project and its potential impact on the behavioral health of occupants. The views, analysis, and opinions expressed herein do not necessarily state or reflect those of HMHI and its stakeholders, FFKR, or SimTigrate Design Lab.

CHAPTER 2: LITERATURE REVIEW

This chapter aims to investigate the evolution and role of daylighting in the built environment and how it impacts human health in general. The role of the building envelope in regulating daylighting within the built environment is also discussed. Specific gaps in the literature review are highlighted towards the end of this chapter.

2.1 Daylighting in built environment

Throughout the history of the built environment, daylighting has played a significant role in the design of buildings. The iconic 'oculus' in the dome of Pantheon, Rome facilitated daylighting illuminating the interior and serving as a bridge between heaven and earth. In Gothic architecture, the development of 'the window' was done as a part of the structural system and an important characteristic of Renaissance work is the repetition of elaborate window units. (Bell, 1973) These were some of the techniques used to facilitate daylighting in interior spaces and establish a visual connection with the outdoors.

The nature of daylight and sunlight is characterized by constant change. Light intensity and quantity vary during the day, from dawn to dusk, depending on the season, climate, and other factors. (Bell, 1973) Since natural light offers consistent alterations in intensity, direction, and spectral composition, it provides better viewing conditions than artificial light and benefits all life on earth ecologically and physiologically. (Wong, 2017)

Utilizing daylighting has been recognized as a beneficial strategy for increasing energy efficiency in buildings and improving the visual quality of the interior built environment. (Wong, 2017) Previous research indicated that daylighting could aid in the reduction of

223 million tons of CO2 emissions or achieve 24,000 MW of energy demand. (Burton SH, 1991) (MbHugh J, 2004) However, daylighting can only contribute to energy and cost savings if sensor technology is integrated with artificial lighting to dim or switch off mode based on the exposure to daylighting levels within a room. (Wong, 2017)

2.2 Factors affecting daylighting performance

Over the years there have been numerous factors affecting daylighting performance in the interior built environment. One of the most significant factors contributing to this is the location and context. The tilt in the Earth's orbit at 23.4 degrees results in a variation of solar energy according to latitude. As a result, the amount of daylight and sunlight that reaches the surface varies seasonally. This also results in a variation in intensity.

Existing buildings and trees within the context also result in variations in daylighting performance. Especially tall buildings and trees which often cause overshadowing during the day. (Wong, 2017) Building orientation also plays a significant role as designers, planners need to keep in mind to orient the longer facades in a north-south orientation as against the east-west orientation to better regulate daylighting in the interior spaces. There should be an equal focus on the geometry of the building especially while designing balconies and overhangs.

The building envelope plays a key role in regulating daylighting. Parameters such as window-to-wall ratio, and shading mechanisms such as louvers & fins define the intensity of incident daylighting and illuminance within the interior spaces. (Wong, 2017) These parameters differ for different building typologies and the nature of occupants. For example, the daylighting requirements in habitable spaces such as residential homes,

offices, schools, and healthcare institutions are different compared to warehouses, data centers, film studio floors, and industrial buildings.

2.3 Daylighting in healthcare design

The advent of HVAC systems and fluorescent lighting in the early 20th century resulted in the construction of deeper building floorplates with less emphasis on daylighting. Most of these structures built over the last 70 years have had a negative influence on human health, productivity, and well-being, resulting in sick building syndrome (SBS). The issues of SBS and daylight deprivation, together with low-energy building design, have rekindled interest in the use of daylighting in interior built environments. (Strong, 2020)

The primary aim of healthcare facilities is to treat patients and improve human well-being. The therapeutic space's interior design is an important aspect of the environment's overall design quality. Previous research indicates therapeutic environments require a high level of adaptability, security, privacy, and relaxation. Users are dissatisfied due to a lack of attention to physical design and interior design in therapeutic areas. (Husein Ali Husein, 2020) Lighting acts as one of the primary environmental factors in providing users with the right healing conditions. (Kellert, 2015)

The hospital's patient rooms are crucial for patient observation and treatment. Daylighting and quality views can help patients recover more rapidly, reduce discomfort, and cut down on their length of stay (LOS). Keeping this in mind the external facade should be constructed to enhance daylighting and provide the best daylighting performance to aid in patient health care and comfort. (Ahmed S, 2015) Building envelope parameters like the window-to-wall ratio and shading mechanisms impact daylighting levels to a significant

extent. Recent research suggests that daylighting has an impact on the human circadian clock and the cognitive performance of patients recovering in a hospital. (Maria Englezou, 2020) Studies have also indicated the positive impact of daylighting on the overall work performance of the healthcare staff. (Aripin, 2007)

Typically, patients are among those who spend more than one hour in a closed environment with limited access to natural light based on location and context. Especially healthcare institutions in dense urban settings pose a significant challenge while trying to achieve good daylighting conditions. Furthermore, most healthcare settings rely on artificial lighting, which causes substantial retinal damage. (Husein Ali Husein, 2020) Eye fatigue, headaches, and vision impairment are just a few of the negative impacts of too much exposure to artificial lights. (Knez, 1995) As a result, hospitals must aim to achieve effective daylighting to meet patient health, safety, and ergonomic objectives. (Husein Ali Husein, 2020)

2.4 Lighting and human health

Keeping in mind the delicate nature of 'treating a human body' within a healthcare context, it should be designed with the highest level of physical, social, and symbolic comfort and care. Therefore, maintaining a bright environment within the healthcare setting becomes an integral part of the healing environment. (Aripin, 2007) Several previous studies have implied that daylight has a substantial impact on human health, both physically and psychologically. Research also indicates that our circadian rhythm is greatly influenced by lighting conditions. (Aripin, 2007) After food light is the most vital input from the environment in maintaining control of our physical functions. (Campbell, 1988)

It is necessary to understand the mechanism of light to understand its impact on human physiology. Light is specifically electromagnetic radiation that falls within a specified range. The amount of energy (or the number of photons) as a function of wavelength is quantified by its spectral distribution. (Visible light with wavelengths ranging from 380 to 780 nm) (Christine Blume, 2019) During the day, light intensities can reach 100,000 lux in direct sunlight and 25,000 lux in full daylight. Closed rooms within the built environment have much lower intensities and conventional electrical lighting is only 500 lux or less. (Manuel Spitschan, 2016) The presence of visible light in an interior setting affects physiological responses, mood, and visual demands. (Aripin, 2007) (Schweitzer, 2004) According to most psychiatrists, Reduced hours of sunlight exposure due to seasonal shifts may trigger seasonal affective disorder (SAD), which manifests as depression, exhaustion, and irritability. (Aripin, 2007) (R, 2001) (Evans, 2003)

Extensive research on human circadian and sleep have derived two effects of light as follows: (1) melatonin suppression is a short-term reaction to light exposure and (2) the ability of light to change one's circadian phase. (Christine Blume, 2019) This melatonin suppression is mediated through a mechanism with a spectral sensitivity similar to that of melanopsin (Brainard GC, 2001) The timing of light exposure determines the impact of light on the circadian clock phase. The phase response curve (PRC) summarizes this by expressing the amount of phase shift (in minutes and hours) obtained by light exposure at a specific circadian phase. (Christine Blume, 2019)

Over the years, light therapy has become more widely used as an additional treatment for a variety of medical disorders. For example, light not only improves mood in individuals

with anorexia or bulimia nervosa but also aids in the treatment of disease-related symptoms. (BeauchampMT, 2016) Light not only has antidepressant characteristics in age-related depression, but it can also aid dementia patients to slow down their cognitive degeneration, according to other studies. (Ritsaert Lieverse, 2011) Bright light therapy is relatively safe, and there is some evidence to support its use in the treatment of nonseasonal MDD (major depressive disorder); nonetheless, there is a paucity of data in this field. (Mark A. Oldham, 2014)

2.5 Daylighting and average length of stay period

In the healthcare industry, the average length of stay is calculated by dividing the total number of days spent by all inpatients over a year by the number of admissions or discharges. It is frequently used as a measure of healthcare efficiency. Longer stays may indicate a lack of care coordination, causing some patients to remain in the hospital unnecessarily until rehabilitation or long-term care can be arranged. (OECD, 2019) The ALOS analysis is also used in determining the quality of patient treatment and estimating resource allocation in hospitals. Apart from this, it has also aided in comparing treatments in hospitals between different nations and determining the required number of beds during the design & planning process. (Man Young Park, 2018)

There is a wide range of studies in the healthcare-built environment, including controlled laboratory tests and real-world field investigations, to determine the correlations between daylight and a patient's clinical recovery process. (AR Joarder, 2013) The degree of a patient’s physiological and clinical improvement is directly proportional to the daylight availability in patient rooms. (Ulrich, 1984) According to recent studies, patients with beds

adjacent to the window had a shorter LOS than those with beds next to the door because of daylight penetration in those specific patient rooms. (Man Young Park, 2018) In addition, increasing the intensity of daylight near a patient's head in hospital rooms has resulted in reducing patient LOS. (AR Joarder, 2013)

2.6 Identifying gaps in the literature review

The existing literature review indicates that daylighting has a significant impact on the circadian rhythms of occupants recovering inside a patient room setting. Previous research work included the use of optimization simulation tools and on-site field measurements for assessing daylighting performance and correlating the findings with the average length of stay periods. However, specific gaps identified in the literature review are as follows:

- Assessing daylighting during occupied hours through metrics such as spatial daylight autonomy (sDA) and annual sunlight exposure (ASE)
- Assessment of parameters like window-to-wall ratios, and exterior shading devices like louvers and fins on daylighting performance in different orientations.
- Analyzing the impact of varying climatic conditions specifically clear and overcast sky conditions on daylighting and the subsequent impact on circadian rhythms within the patient room.

It is important to study the sDA or the spatial Daylight Autonomy, which uses hourly illuminance grids on the horizontal work plane to determine whether a space receives enough daylight during normal operating hours (8 a.m. to 6 p.m.) on an annual basis. It is a reliable metric adopted by IES or Illuminating Engineering Society with reference to analyzing daylighting levels. ASE or Annual Sunlight Exposure is meant to complement

spatial Daylight Autonomy. It is intended to help designers limit excessive sunlight in the interiors. Both sDA and ASE give a holistic understanding of daylighting penetration in the interior built environment. Hence as a part of bridging the existing literature on daylighting, both sDA and ASE will be analyzed as a part of daylighting optimization. A comprehensive simulation-based framework must be adopted to evaluate the impact of daylighting on circadian rhythms within the patient room setting.

CHAPTER 3: EXPERIMENT DESIGN

This chapter aims to enhance the understanding of building envelope parameters like window-to-wall ratios, and shading mechanisms like louvers and fins as agents in regulating daylighting within a patient room setting. Emphasis is given to the performance of the envelope in different orientations of patient rooms in terms of facilitating daylighting under varying climatic conditions.

3.1 Experiment goals and objectives

Daylighting of interior built environments poses significant challenges to designers and planners due to factors such as building typology, outdoor context, varying climate conditions, and occupant nature. In the context of healthcare institutes, daylighting plays a vital role in creating a therapeutic environment for patients and impacts the overall work performance of healthcare staff. Since the building envelope plays a crucial role in facilitating daylighting some of the questions which need to be addressed are as follows:

1. What is the impact of building envelope design on daylighting in interior built environments?
2. Apart from regulating daylighting levels, can the building envelope also impact melanopic lux levels in the interior built environment?
3. Can building envelope parameters like window-to-wall ratio, and shading mechanisms like louvers and fins balance daylighting and glare?

The examination of these questions would help assess the performance of building envelope parameters in the context of a healthcare setting. The experiment workflow would

help designers and healthcare planners in evaluating the role of building envelope in generating ambient daylighting conditions and subsequently impacting the overall health and comfort of the occupants.

3.2 Experiment Design

The experiment design will take place in three stages which will be repeated for each patient room orientation. Figure 2 showcases the experimental design flowchart:

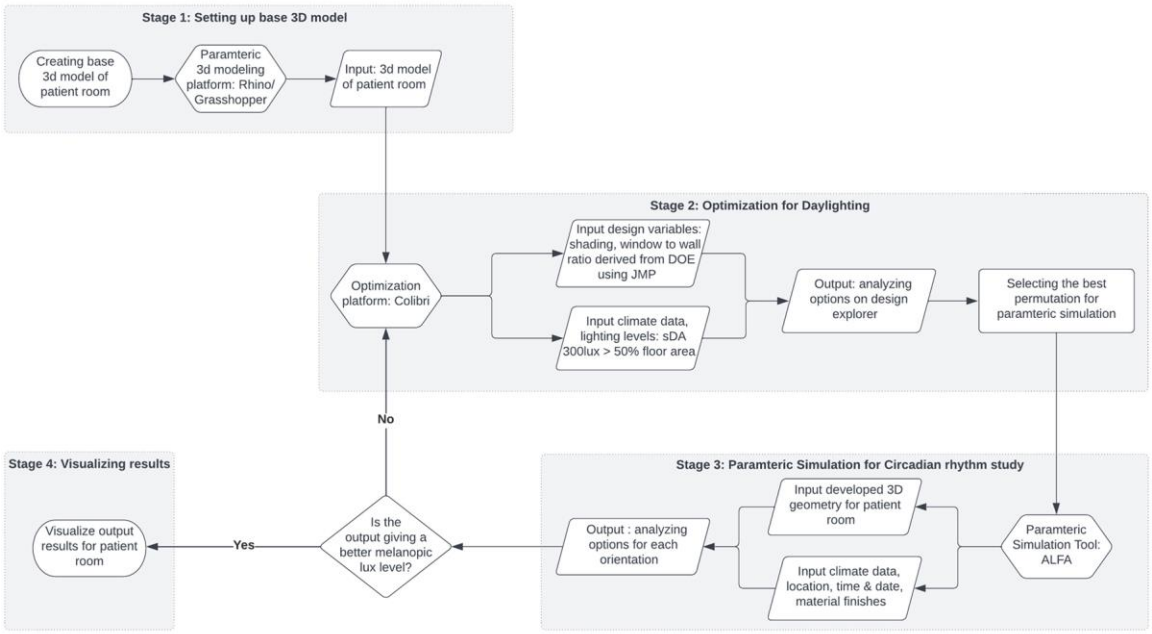


Figure 2: Experimental Design flowchart

The workflow devised for the experiment goes through three stages viz. setting up base 3D model, Optimization for Daylighting, and Circadian rhythm analysis. The fourth stage of the experiment focuses on visualizing results from the simulation runs

3.2.1 Stage 1 – setting up base 3D model of patient room

The experiment is conducted in the HMHI Crisis Care centre facility in Salt Lake City, Utah. The Acute Stabilization Unit within the facility consists of 24 nos. of in-patient rooms catering to the long-term recuperation of patients.

Figure 3: Layout and isometric view of ASU level in HMHI, Salt Lake City, Utah

The single occupancy rooms are equipped with the necessary furniture and in-suite toilet facility. To understand the existing daylighting conditions, a performance analysis test was carried out for each of the shortlisted patient room orientations to evaluate the sDA and ASE values. A base box model was generated using Grasshopper from the Rhino 3D model to carry out the daylighting analysis. The VT level of glass was considered as 0.4 based on the inputs received from FFKR architects and their vendors for this simulation. The results will serve as benchmark threshold values for sDA and ASE to evaluate and improve upon in the Optimization stage.

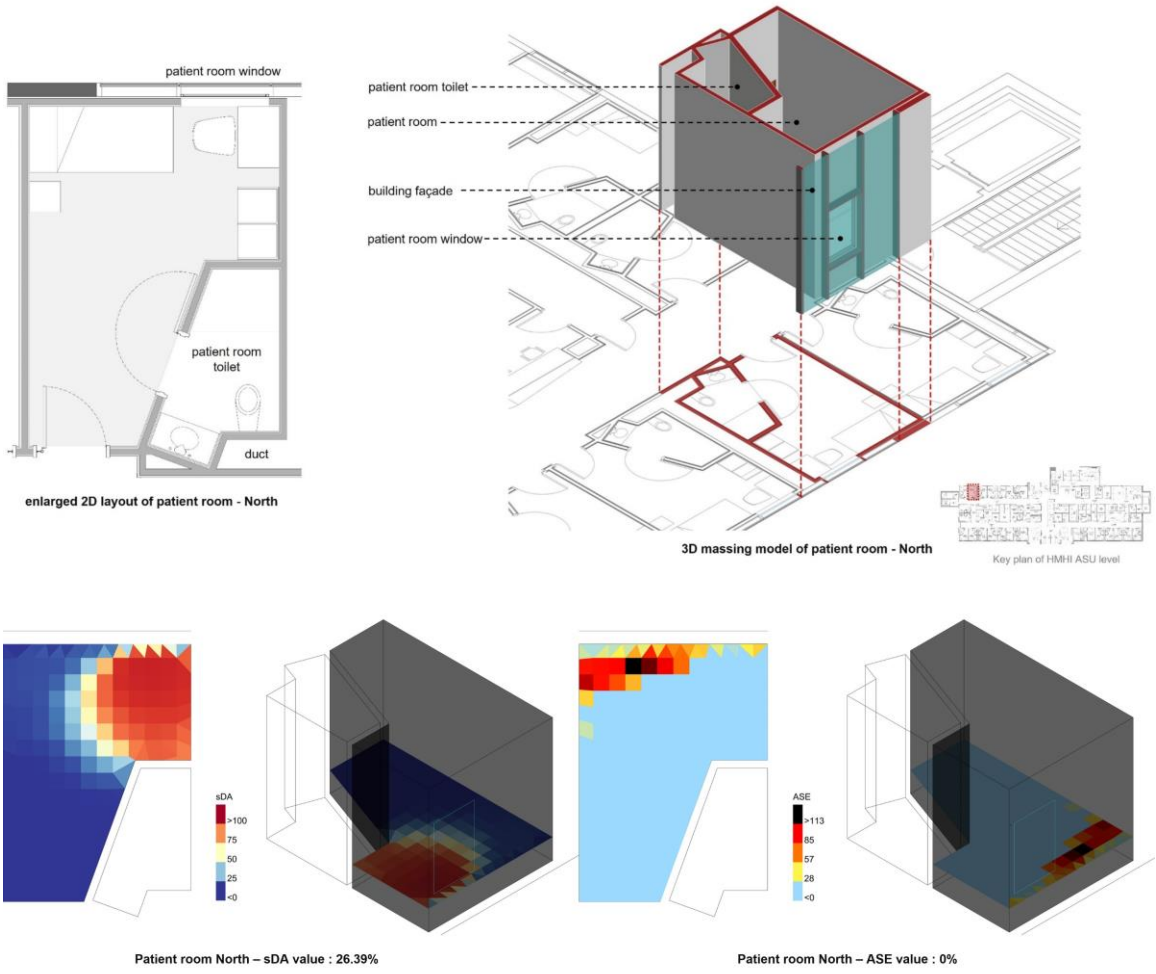
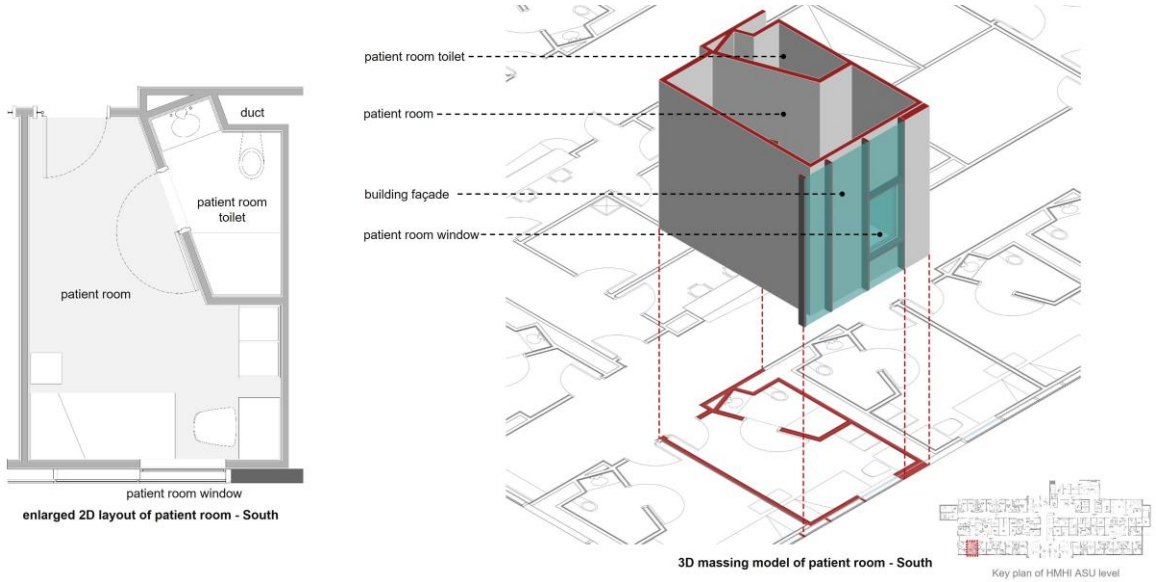


Figure 4: Patient room North – enlarged 2D&3D diag., daylighting analysis



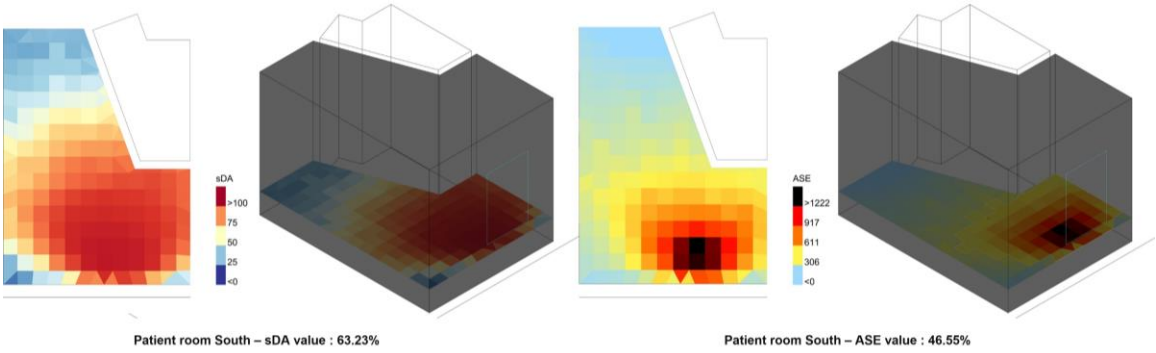
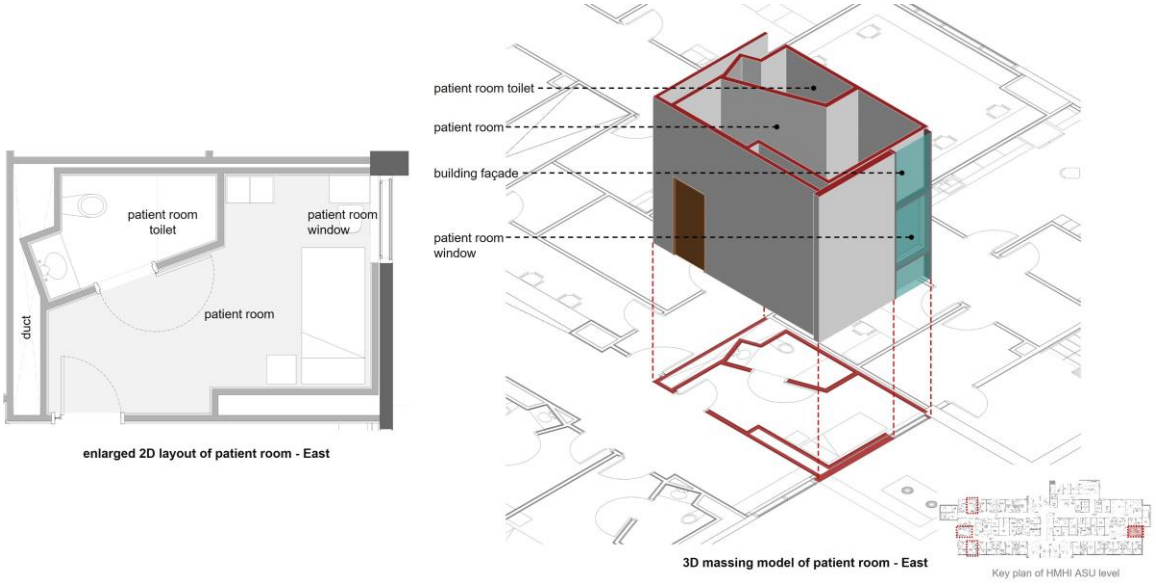


Figure 5: Patient room South – enlarged 2D&3D diag., daylighting analysis



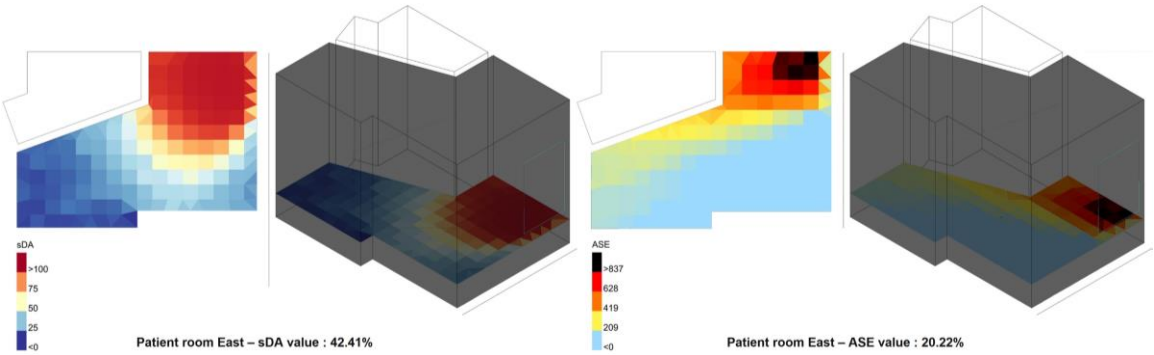
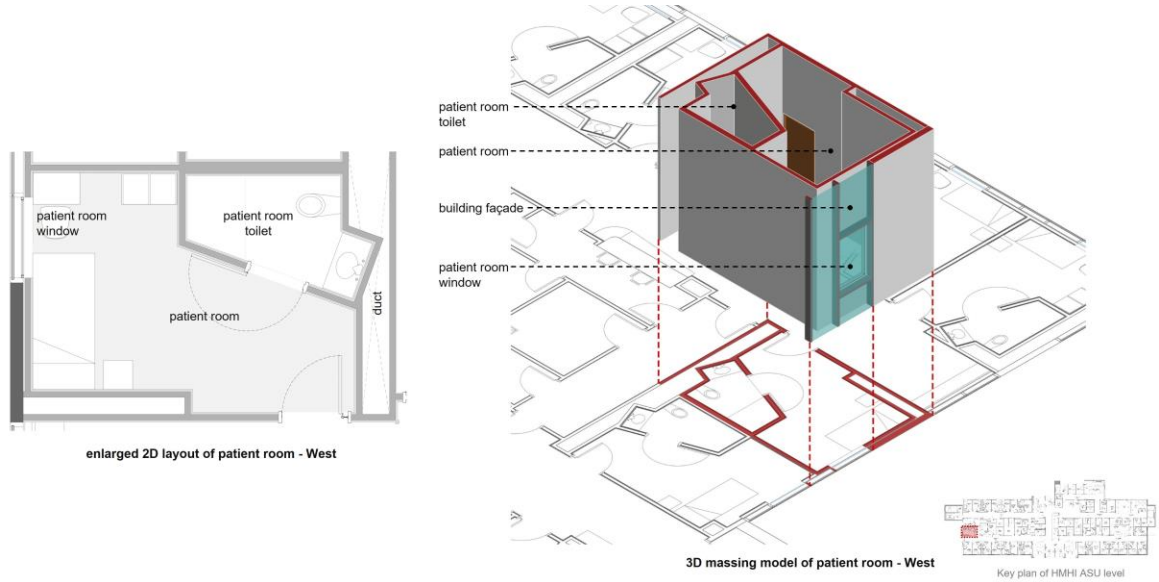


Figure 6: Patient room East – enlarged 2D&3D diag., daylighting analysis (contd. pg 18)



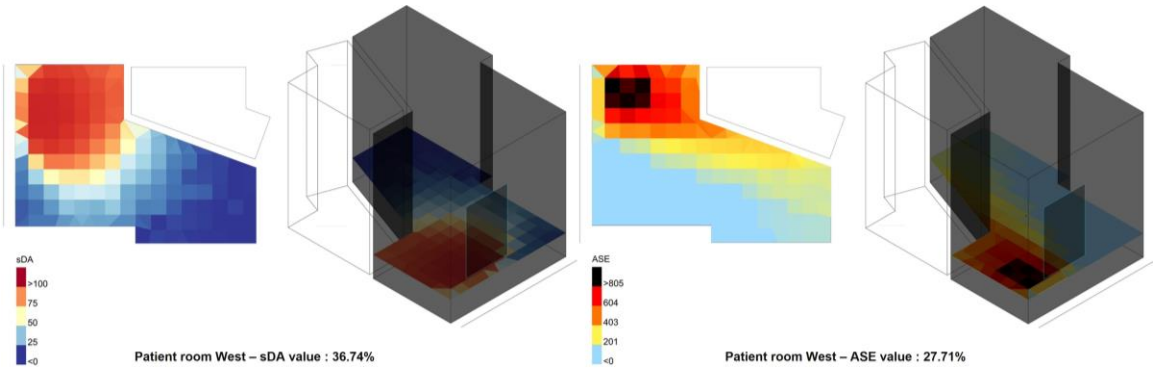


Figure 7: Patient room West – enlarged 2D&3D diag., daylighting analysis

From the initial daylighting performance of existing envelope parameters, it is observed that the sDA values range between 26% - 64% whereas the ASE values range between 0% - 47% where the South orientation recorded the highest sDA value of 63.23% and ASE value of 46.55%. To improve the daylighting conditions inside the patient rooms and achieve higher sDA values, optimization of the building envelope parameters is carried out in Stage 2 of the experiment.

3.2.2 Stage 2 – Daylighting Optimization of building envelope parameters

This stage involves the optimization of building envelope parameters like window-to-wall ratio and shading mechanisms. Figure 8 describes the flowchart for the Optimization process.

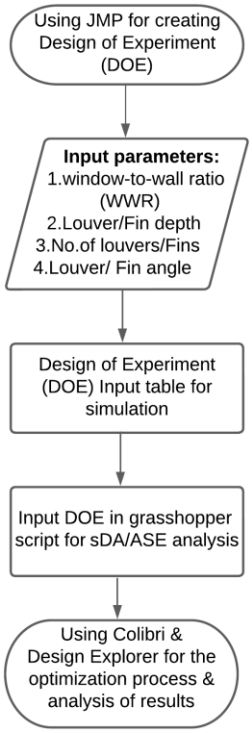


Figure 8: Daylighting Optimization process flowchart

In this stage, a Design of Experiment or DOE is developed using the statistical analysis tool JMP. The DOE mainly consists of iterations derived from a combination of input parameters like window-to-wall ratio, no. of louvers/fins, depth of lovers/fins, and angle of louvers/fins. For the North and South orientations, a window-to-wall ratio range of 0.4 to 0.7 is considered whereas for East and West orientations a range of 0.2 to 0.5 is considered to reduce glare from daylighting. The VT value of glazing is considered as 0.65 for the simulation runs to facilitate higher daylighting levels in the patient rooms.

Iteration no.	WWR	Louver / Fin depth	No. of Louvers / Fins	Louver / Fin angle
1	0.5	0.6	2	15
2	0.4	0.6	3	0
3	0.6	0.4	3	15
4	0.5	0.4	4	0
5	0.6	0.6	2	45
6	0.7	0.5	2	0
7	0.4	0.3	2	15
8	0.6	0.6	5	15
9	0.5	0.3	5	0
10	0.6	0.5	5	30
11	0.5	0.6	2	30
12	0.7	0.4	2	30
13	0.7	0.6	3	0
14	0.6	0.3	4	45
15	0.4	0.5	2	45
16	0.7	0.3	3	45
17	0.7	0.5	4	15
18	0.4	0.6	4	30
19	0.4	0.4	5	45
20	0.4	0.5	5	0
21	0.7	0.3	5	30
22	0.5	0.5	3	45
23	0.6	0.3	2	0
24	0.4	0.3	3	30
25	0.7	0.6	5	45

Design of Experiment (DOE) table for North & South orientations

Iteration no.	WWR	Louver / Fin depth	No. of Louvers / Fins	Louver / Fin angle
1	0.4	0.6	2	15
2	0.5	0.3	2	45
3	0.2	0.6	2	15
4	0.2	0.3	3	30
5	0.3	0.4	2	0
6	0.5	0.4	5	15
7	0.2	0.4	4	0
8	0.5	0.3	3	30
9	0.3	0.6	5	30
10	0.2	0.4	5	45
11	0.5	0.6	3	0
12	0.2	0.5	2	45
13	0.3	0.3	4	45
14	0.5	0.6	4	45
15	0.3	0.5	3	15
16	0.2	0.6	3	0
17	0.5	0.4	2	30
18	0.4	0.5	4	30
19	0.2	0.3	5	15
20	0.4	0.6	5	45
21	0.5	0.3	4	15
22	0.4	0.4	3	45
23	0.4	0.3	2	0
24	0.5	0.5	5	0
25	0.4	0.3	5	0

Design of Experiment (DOE) table for East & West orientations

Figure 9: DOE tables generated for Optimization

The DOE tables (Figure 9) generated from JMP are then added as inputs in the grasshopper script, using Colibri as an Optimization platform to generate the simulation output. A total of 50 iterations are carried out for each patient room orientation. The results are then analyzed in Design Explorer to select the optimum building envelope iteration for each orientation. A sensitivity analysis is carried out to understand the impact of different input parameters on the sDA and ASE values.

3.2.3 Stage 3 – Circadian rhythm analysis

In this stage, the shortlisted iterations for each patient room orientation are further analyzed to understand the impact of daylighting on the melanopic lux levels. The shortlisted patient room iterations are modelled using Rhino and the simulation is carried out using ALFA a circadian lighting software. The necessary input parameters like climate data, date/time, and material finishes are added before running the simulations. The location is based on the latitude, longitude, and elevation levels of the site. Figure 10 describes the flowchart for the Circadian rhythm analysis process.

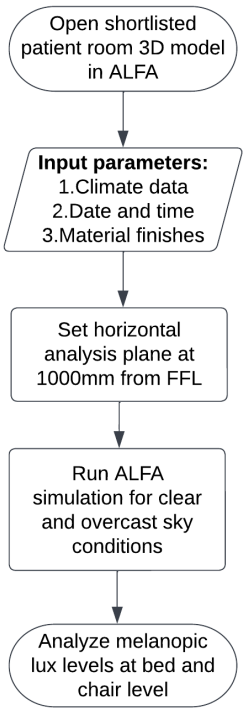
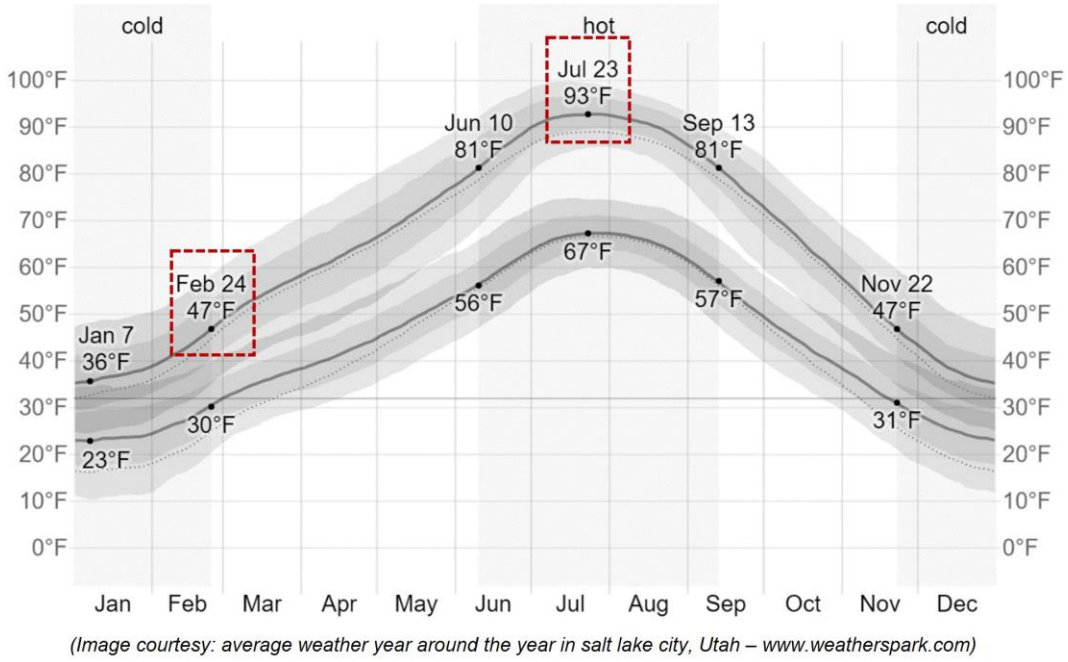


Figure 10: Circadian rhythm analysis flowchart

To understand the performance of the building envelope, seasonal variations like the clear sky and overcast sky conditions are considered. Based on the climate data of Salt Lake City, Utah two days each from the summer season and winter seasons are selected

for the clear and overcast sky conditions respectively. In terms of evaluating the melanopic lux levels at different times of the day, five separate time slots viz. 9:00 am, 10:00 am, 11:00 am 12:00 pm, and 1:00 pm are considered to understand the variations in the values. To make the study more occupant-centric, the analysis planes are set over the bed and chair to simulate the position of the occupant within the patient room. Figure 11 indicates the selection of clear and overcast sky conditions based on the climate data.



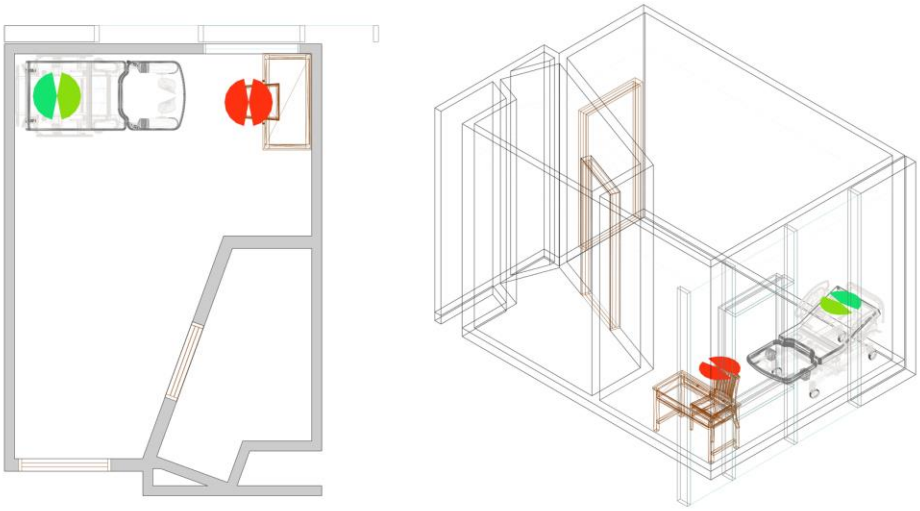
(Image courtesy: average weather year around the year in salt lake city, Utah – www.weatherspark.com)

Figure 11: Selection of clear and overcast sky conditions based on climate data

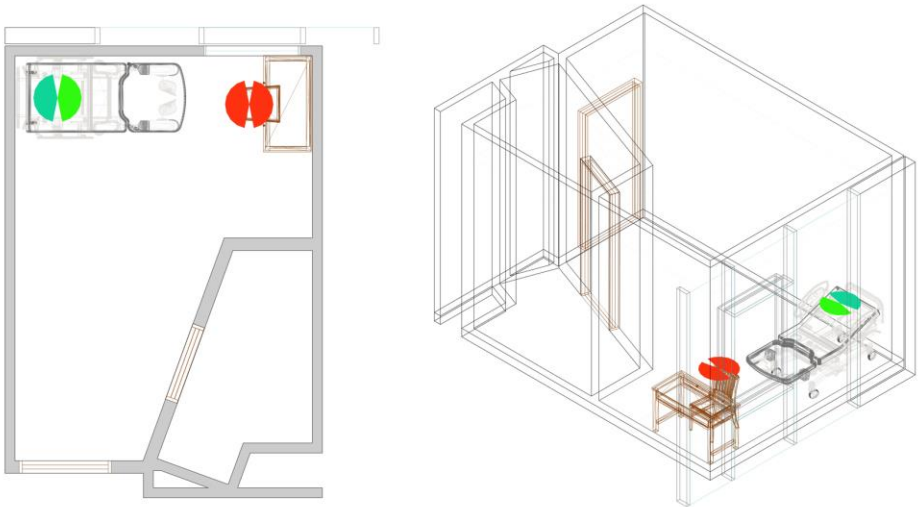
3.2.3.1 Circadian rhythm analysis of existing patient rooms

The above methodology of evaluating the melanopic lux levels is first tested on the existing patient rooms. One iteration each in clear and overcast sky conditions at 9:00 am is tested and melanopic lux levels are recorded. The readings will serve as benchmark values to be improved upon based on shortlisted iterations derived from the Optimization stage of the building envelope for all patient room orientations.

Existing Patient room - North Orientation



Scene 1: 9:00am, clear sky | avg. melanopic lux: 151 lux



Scene 2: 9:00am, overcast sky | avg. melanopic lux: 68 lux

Figure 12: Existing patient room – North: comparative melanopic lux analysis

The melanopic lux level for the overcast sky drops to 68 lux compared to 151 lux for the clear sky. The levels recorded in bed were 96 lux for a clear sky and 32 lux for an overcast sky whereas in chair they are 295 lux for clear sky and 141 lux for an overcast sky.

Existing Patient room – South Orientation

Figure 13: Existing patient room – South: comparative melanopic lux analysis

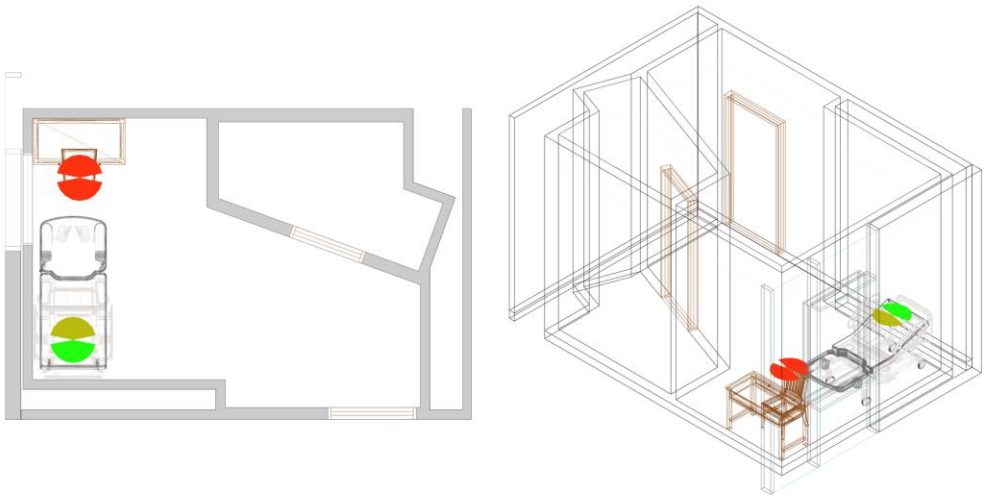
The melanopic lux level for the overcast sky drops to 70 lux compared to 183 lux for the clear sky. The levels recorded in bed were 157 lux for a clear sky and 42 lux for overcast sky whereas in the chair they are 108 lux for a clear sky and 37 lux for an overcast sky condition.

Existing Patient room – East Orientation

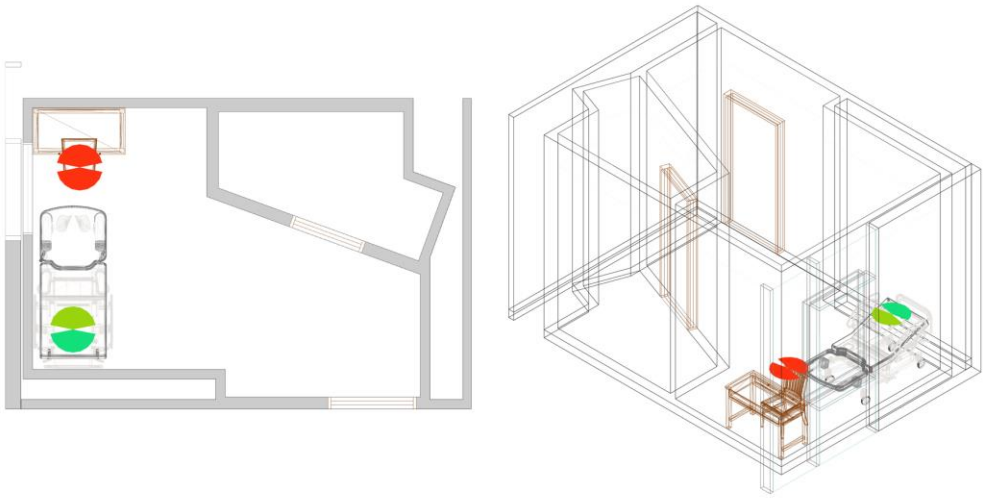
Figure 14: Existing patient room – East: comparative melanopic lux analysis

The melanopic lux level for the overcast sky drops to 81 lux compared to 962 lux for the clear sky. The levels recorded in bed were 488 lux for a clear sky and 49 lux for an overcast sky whereas in chair they are 1514 lux for clear sky and 169 lux for an overcast sky condition.

Existing Patient room – West Orientation



Scene 1: 9:00am, clear sky | avg. melanopic lux: 159 lux



Scene 2: 9:00am, overcast sky | avg. melanopic lux: 72 lux

Figure 15: Existing patient room – West: comparative melanopic lux analysis

The melanopic lux level for the overcast sky drops to 72 lux compared to 159 lux for the clear sky. The levels recorded in bed were 125 lux for clear sky and 50 lux for overcast sky whereas in chair they are 183 lux for clear sky and 79 lux for an overcast sky condition.

CHAPTER 4: RESULTS

This chapter aims to present the simulation and experiment findings for both the Optimization and Circadian analysis stages. Each subsection will reflect on the results of both stages for patient rooms in different orientations.

Stage 2: Optimization for Daylighting

The results for the North orientation will be discussed stepwise and in-depth to understand the methodology involved in selecting the shortlisted iterations. For the South, East, and West orientations only the shortlisted iteration will be discussed. (The stepwise details for deriving the results have been added in the Appendix section)

Stage 3: Circadian Rhythm Analysis

The results for the North orientation will be discussed in depth and step wise to understand the different melanopic lux levels derived during the different times of the day for both clear and overcast sky conditions. For the South, East, and West orientations one iteration each from clear and overcast sky conditions will be discussed. (The remainder results have been added in the Appendix section)

4.1 Patient Room Orientation – North

4.1.1 Daylighting Optimization

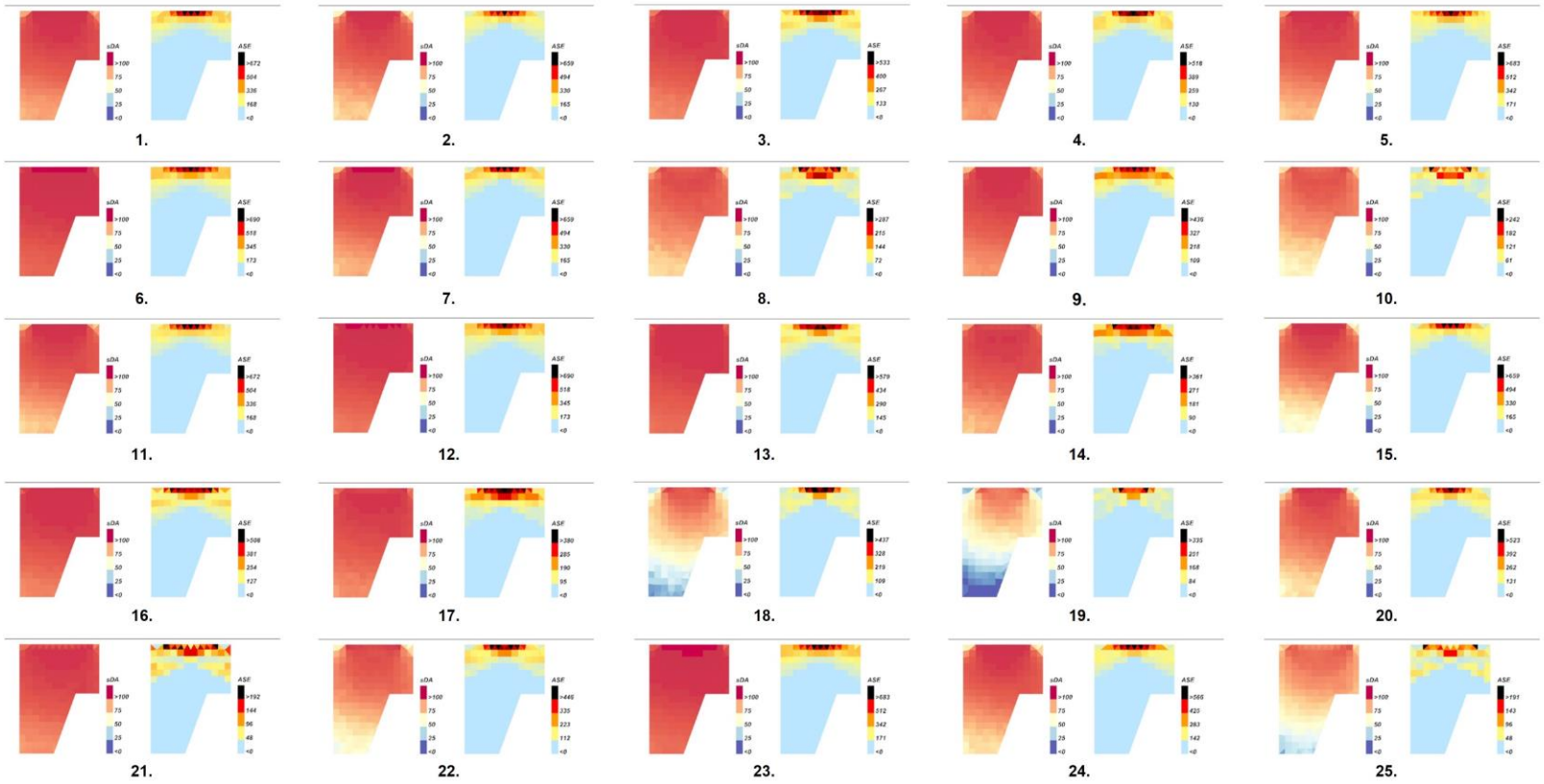


Figure 16: North Orientation - Daylighting Optimization iterations using louvers as shading mechanism

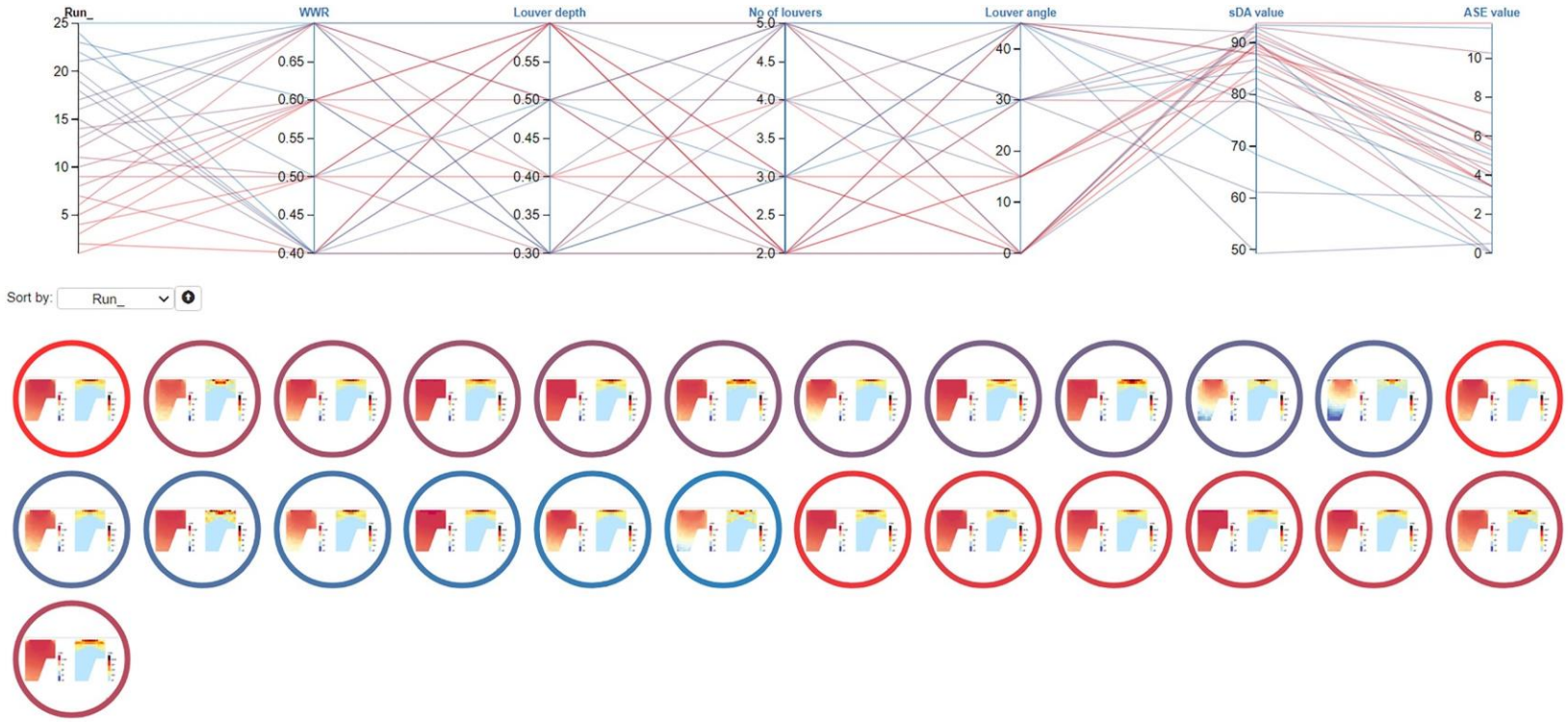
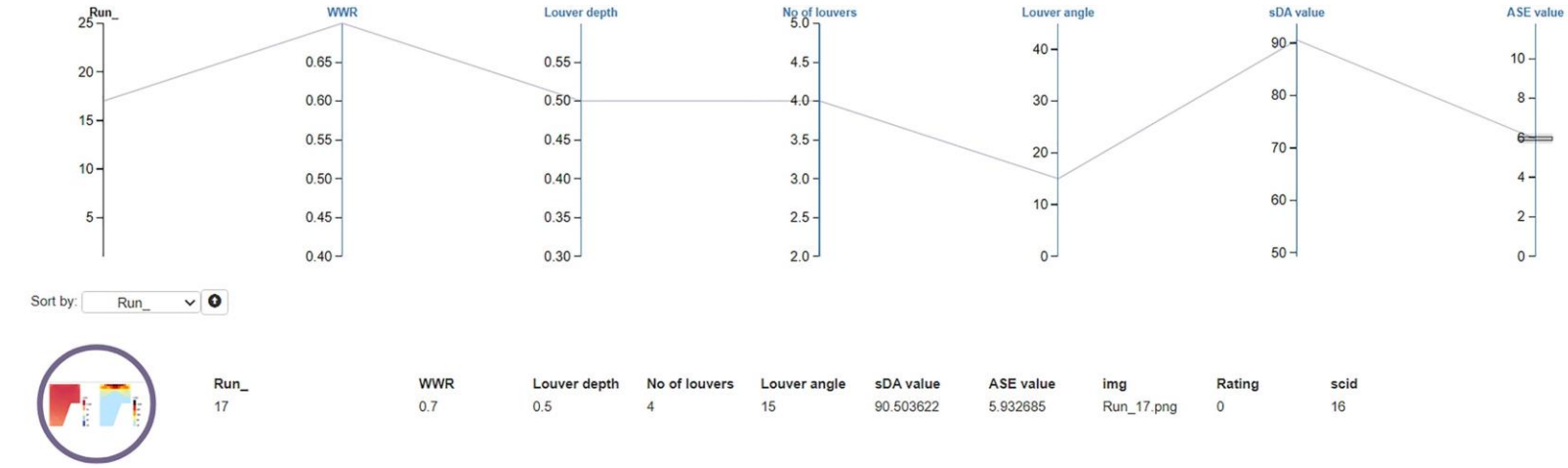


Figure 17: North Orientation – Comparative analysis of louvers iterations using Design Explorer

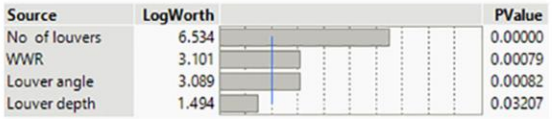
The results from the Optimization stage are analyzed using Design Explorer, which helps in evaluating the better-performing iterations based on the sDA and ASE values.



- Based on the comparative analysis **iteration no. 17** provides a better balance of sDA and ASE values as compared to other iterations.

Sensitivity Analysis:

- From the sensitivity analysis, it can be observed that No. of louvers as a parameter considerably impacts the sDA and ASE values followed by window-to-wall ratio (WWR)



Source	LogWorth	PValue
No of louvers	6.534	0.00000
WWR	3.101	0.00079
Louver angle	3.089	0.00082
Louver depth	1.494	0.03207

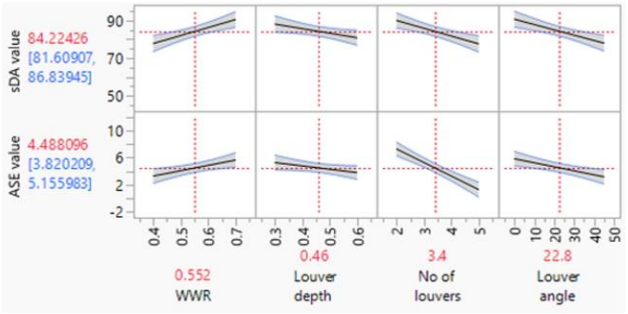


Figure 18: North Orientation – Selection of optimum louvers iteration

The optimum iteration is selected based on higher sDA and lower ASE values to achieve the intended balance between daylighting metrics. Sensitivity analysis using JMP evaluates the parameters that have a higher weightage in regulating the sDA and ASE values.

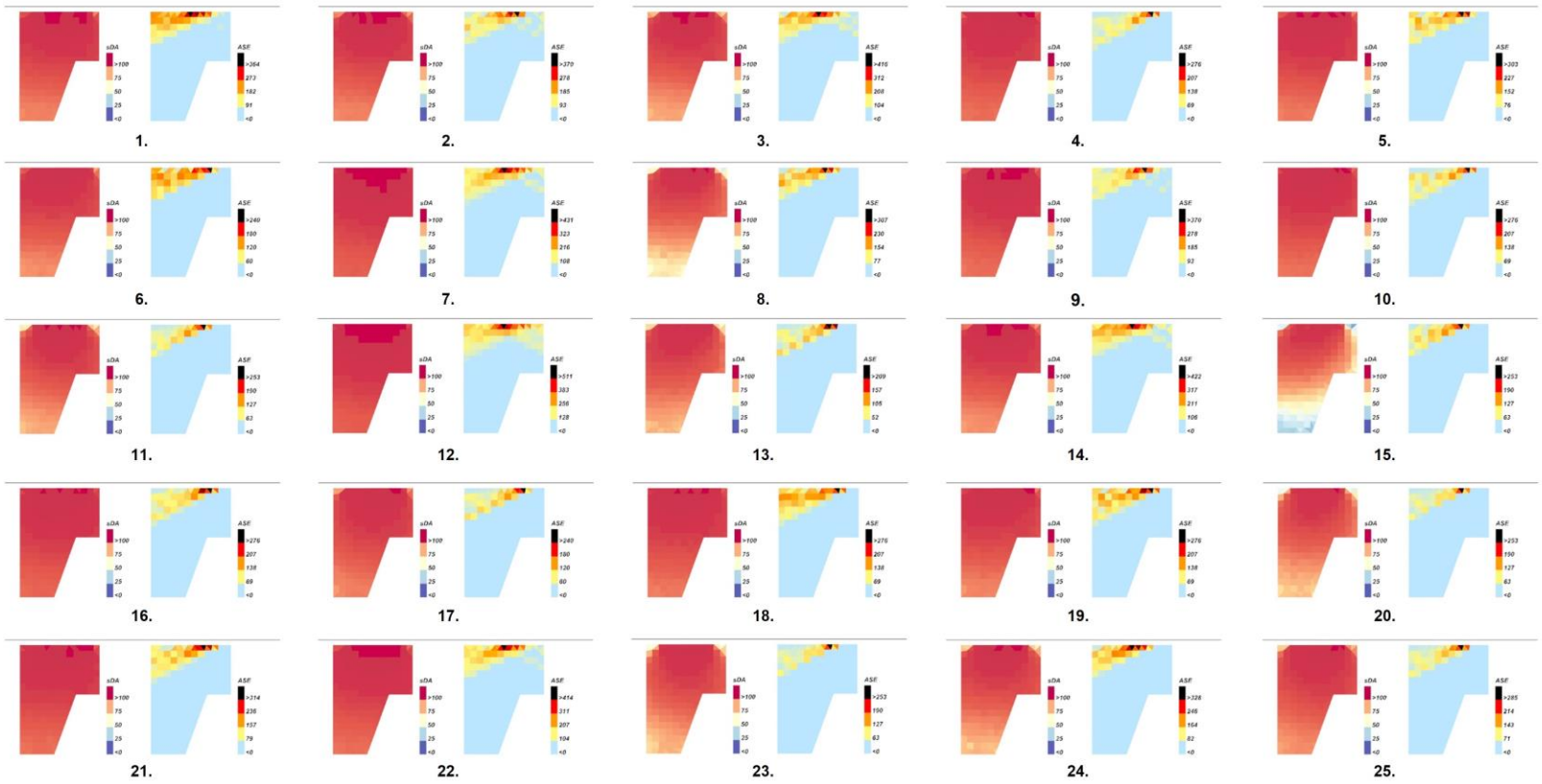


Figure 19: North Orientation - Daylighting Optimization iterations using fins as shading mechanism

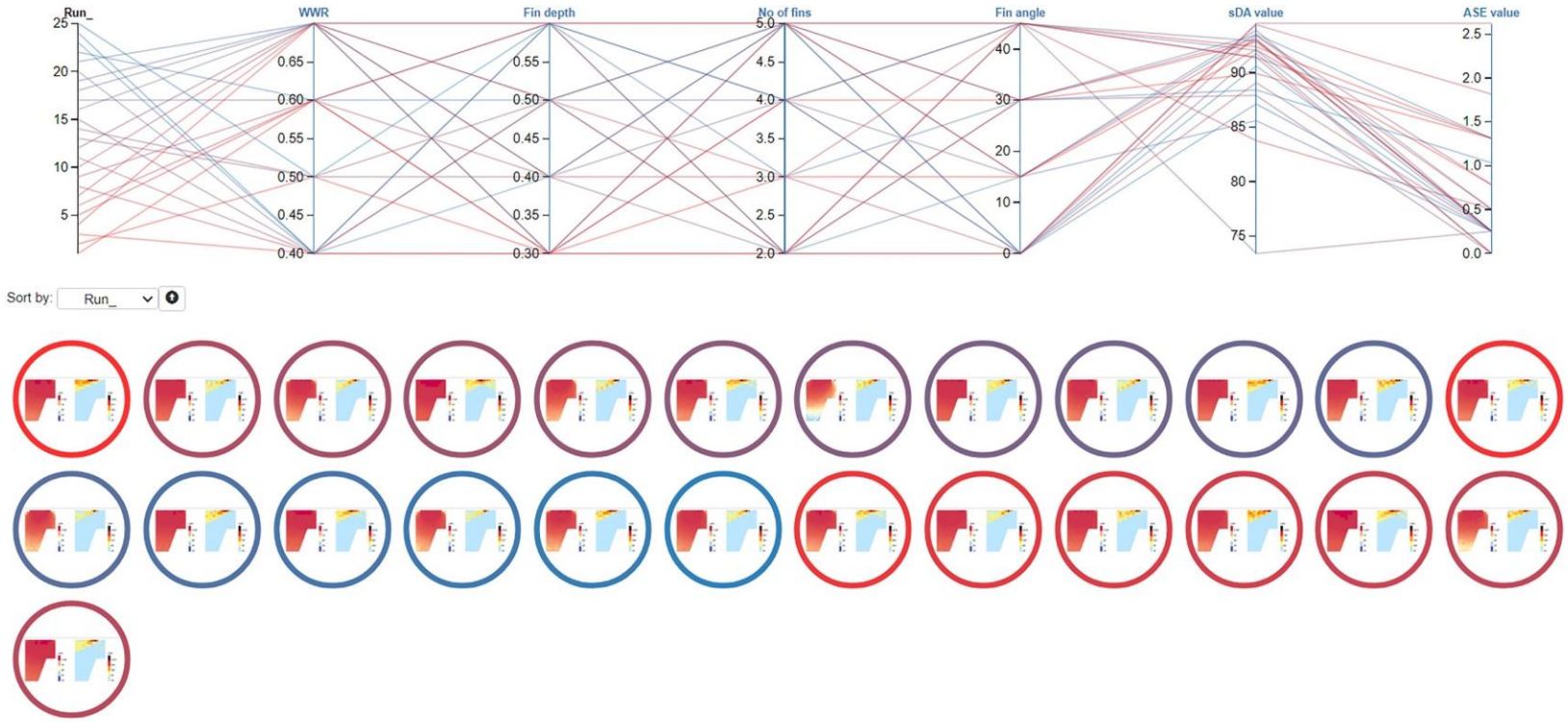
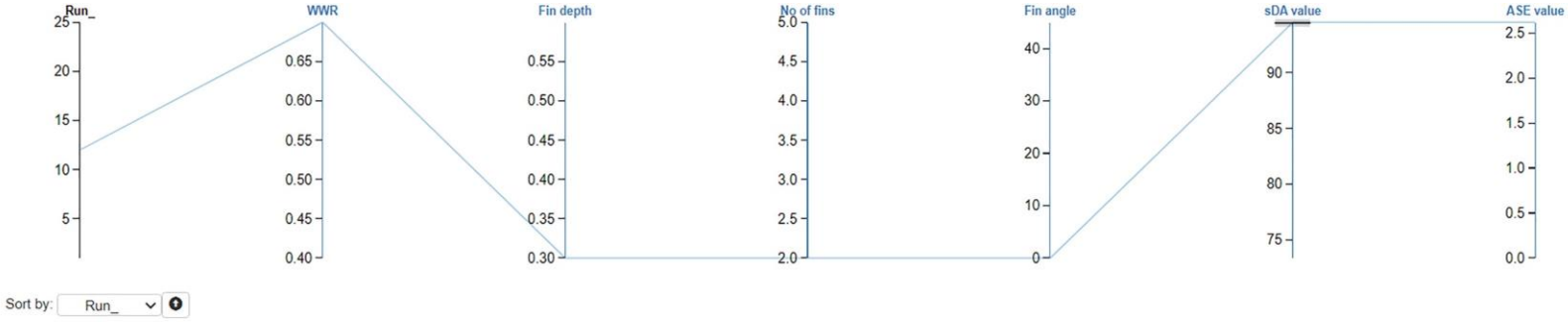


Figure 20: North Orientation – Comparative analysis of fins iterations using Design Explorer



Run_	WWR	Fin depth	No of fins	Fin angle	sDA value	ASE value	img	Rating	scid
12	0.7	0.3	2	0	94.489297	2.619425	Run_12.png	0	11

- Based on the comparative analysis **iteration no. 12** provides a better balance of sDA and ASE values as compared to other iterations.

Sensitivity Analysis:

- From the sensitivity analysis, it can be observed that No. of fins as a parameter considerably impacts the sDA and ASE values followed by window-to-wall ratio (WWR)

Source	LogWorth	PValue
No of fins	7.821	0.00000
WWR	5.037	0.00001
Fin angle	1.372	0.04241
Fin depth	1.302	0.04994

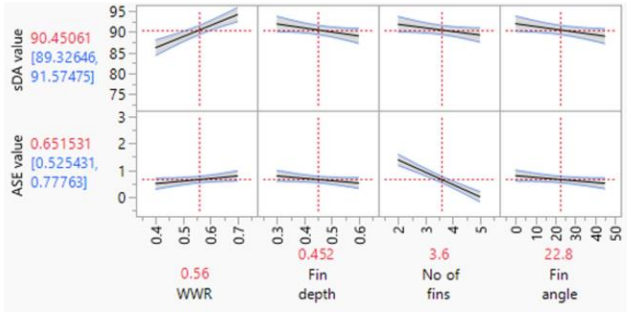


Figure 21: North Orientation – Selection of optimum fins iteration

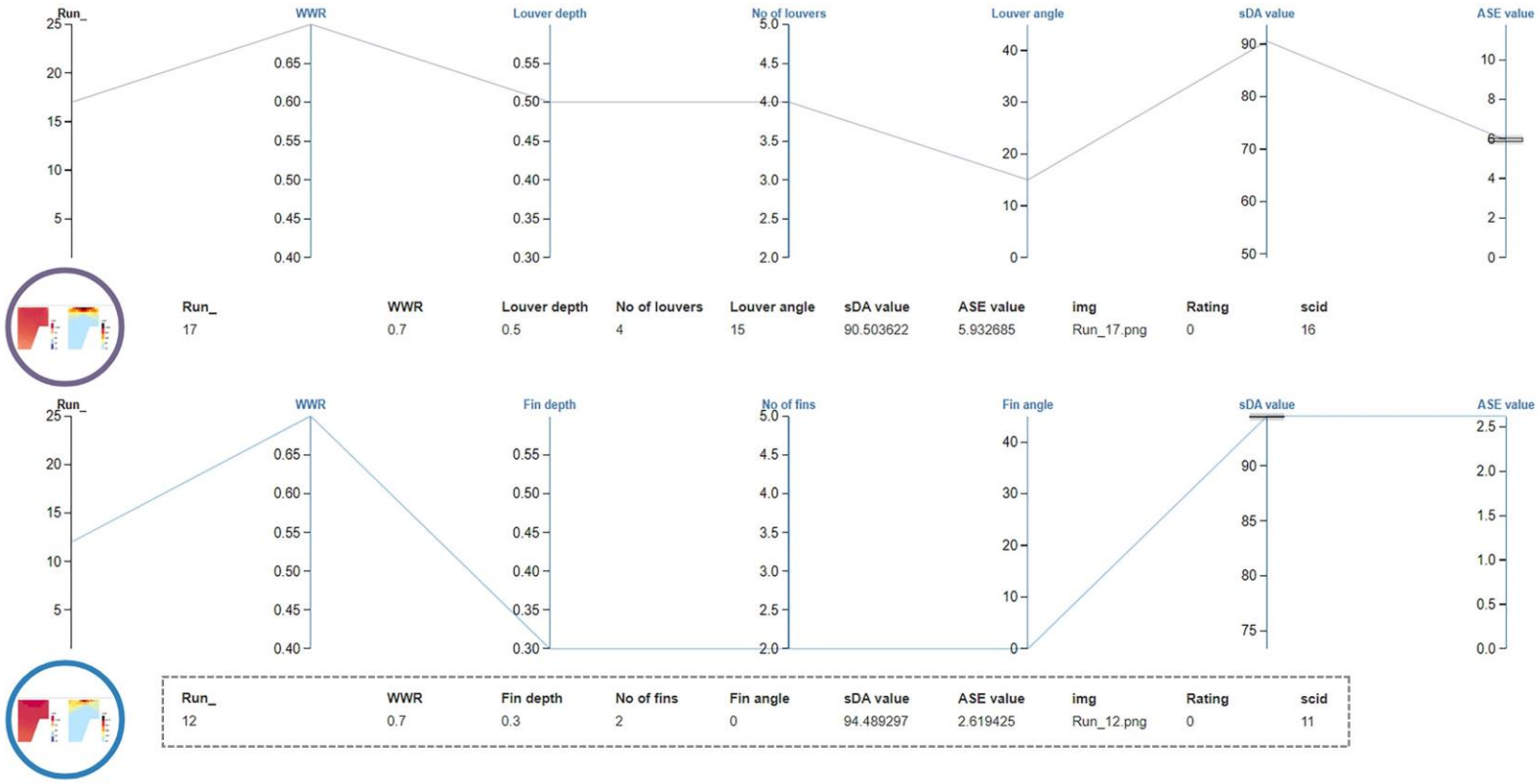


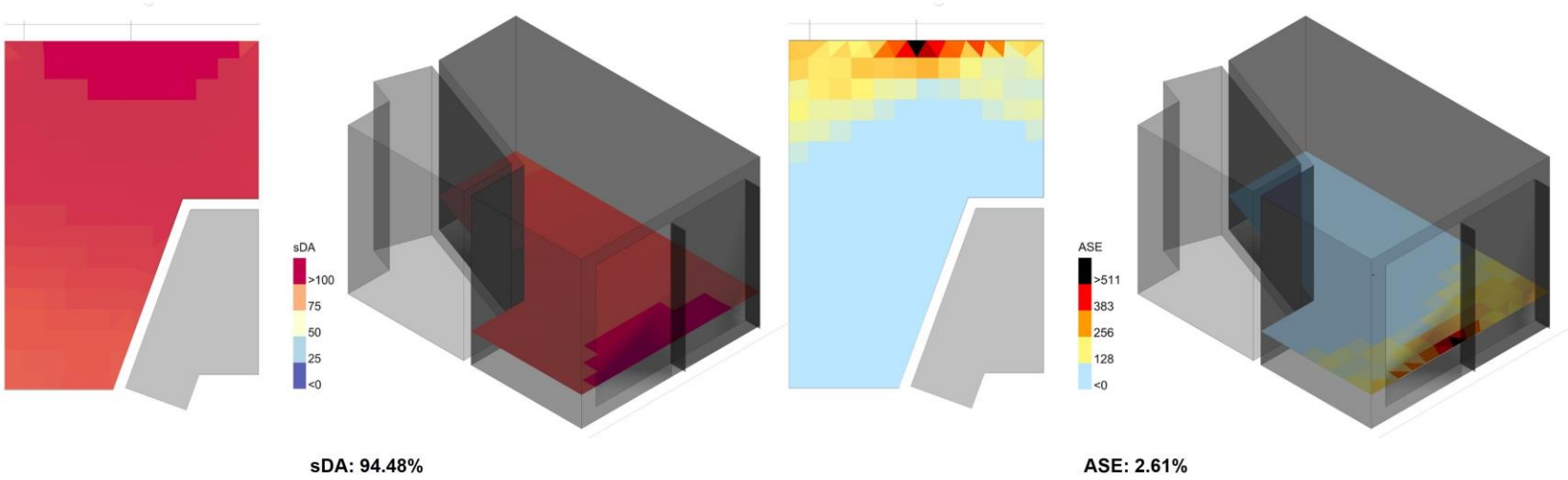
Figure 22: North Orientation – Comparative analysis of shortlisted louvers and fins iterations

A comparative analysis of the shortlisted louvers and fins iterations results in the final selection of the optimum iteration based on achieving a better balance in sDA and ASE values. In this scenario, the fins iteration has been shortlisted for circadian rhythm analysis.

Input parameters:
- Window-to-wall ratio (WWR) – 70%
- Fin depth – 0.30m
- No. of fins – 2
- Fin angle – 0°

Spatial daylight autonomy (sDA):
- sDA value – 94.48%

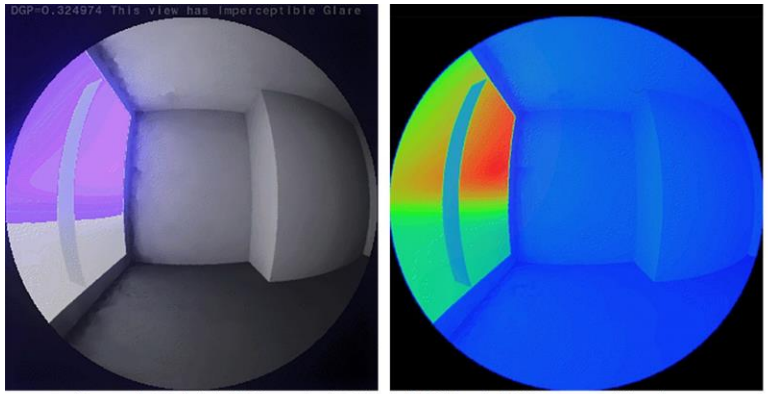
Annual sunlight exposure (ASE):
- ASE value – 2.61%



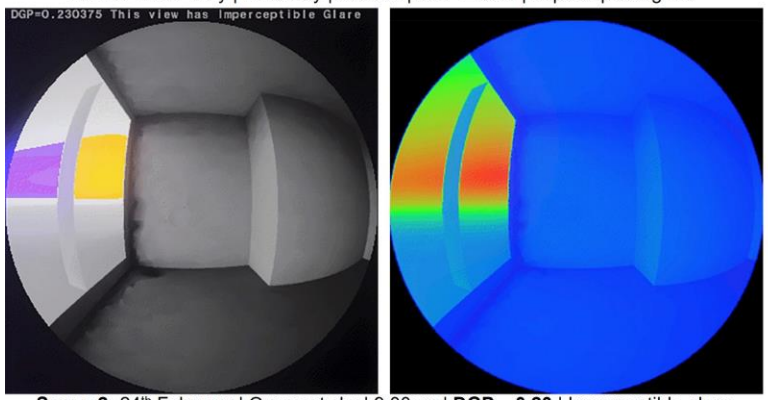
sDA: 94.48% **ASE: 2.61%**

Figure 23: North Orientation – Shortlisted iteration for circadian rhythm analysis

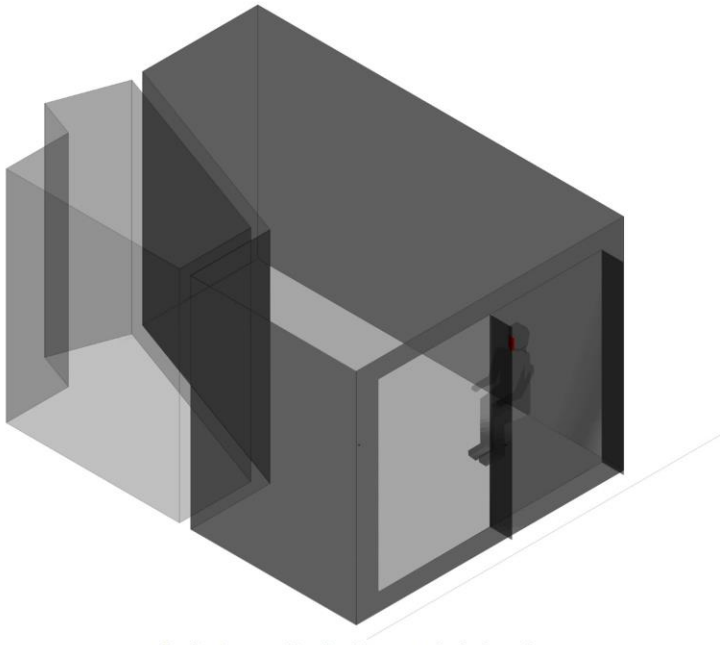
4.1.2 Glare Analysis



Scene 1: 23rd July | Clear sky | 9:00am | **DGP – 0.32** | Imperceptible glare



Scene 2: 24th February | Overcast sky | 9:00am | **DGP – 0.23** | Imperceptible glare



Patient room North: Glare analysis iso view

Figure 24: North Orientation – Patient room Glare analysis

4.1.3 Circadian Rhythm analysis

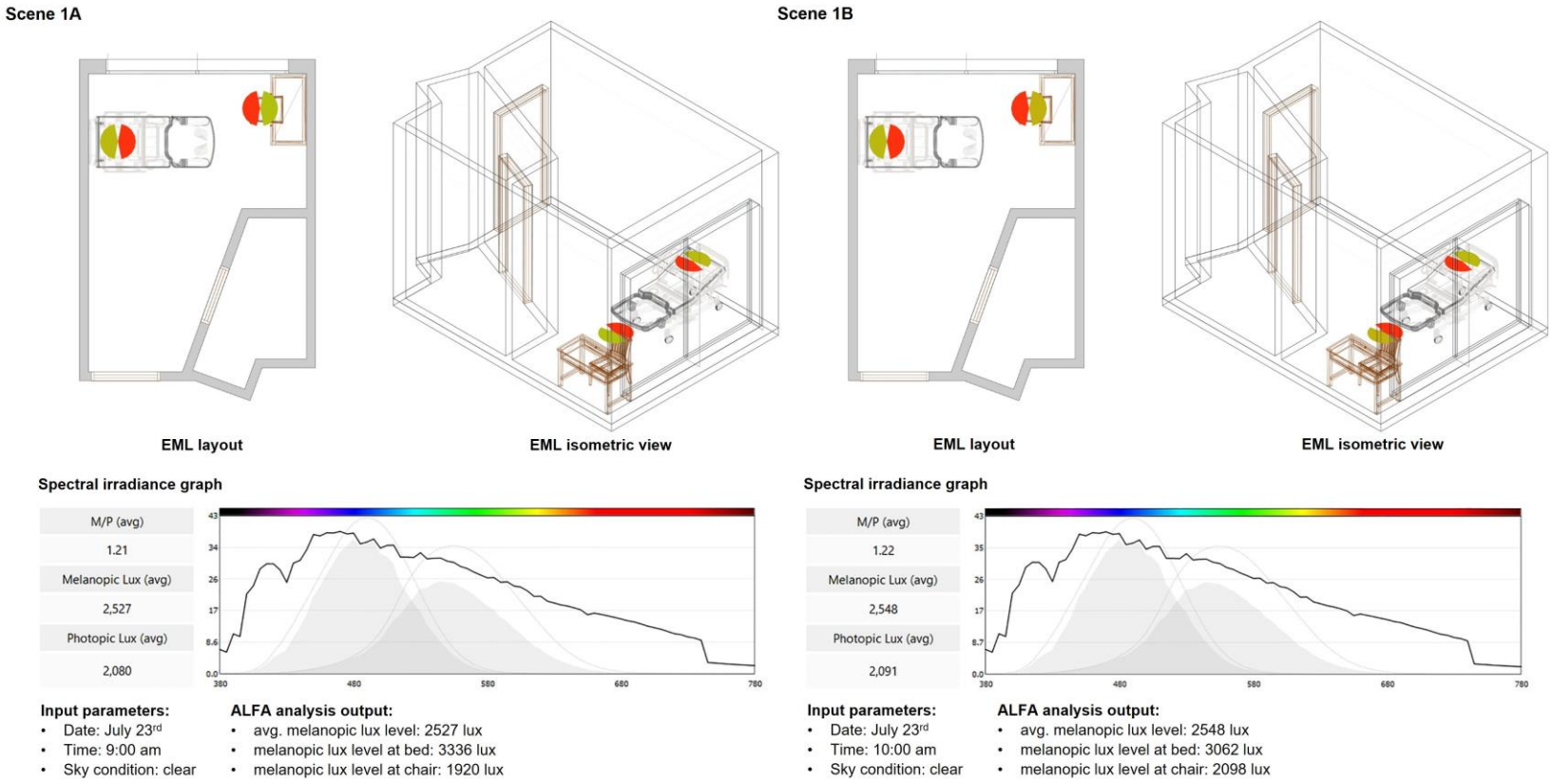


Figure 25: North Orientation – Circadian rhythm analysis Scene 1A and Scene 1B

Scene 1A: 9:00 am, clear sky | melanopic lux values: avg. – 2527 lux, bed – 3336 lux, chair – 1920 lux

Scene 1B: 10:00 am, clear sky | melanopic lux values: avg. – 2548 lux, bed – 3062 lux, chair – 2098 lux

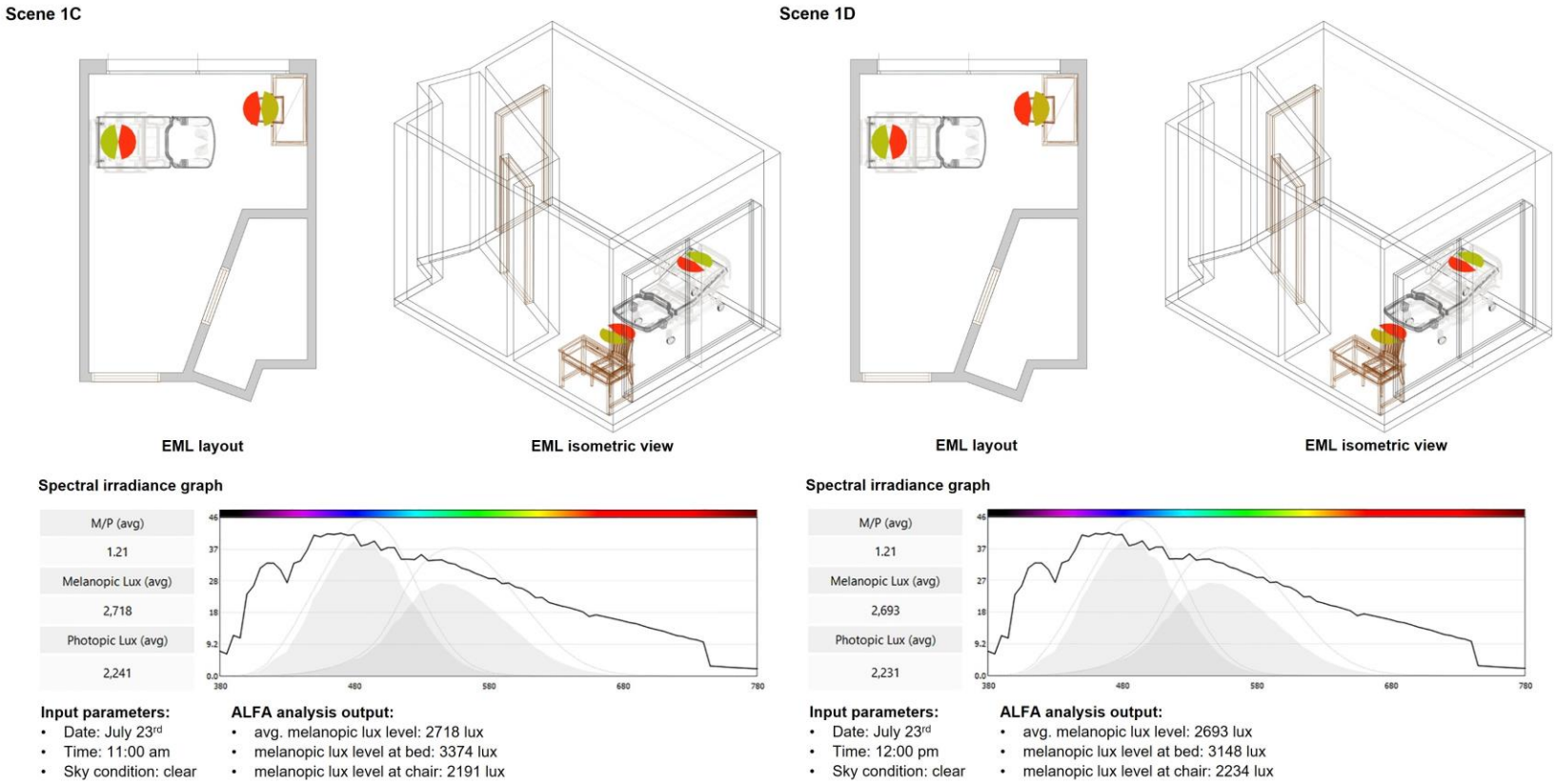


Figure 26: North Orientation – Circadian rhythm analysis Scene 1C and Scene 1D

Scene 1C: 11:00 am, clear sky | melanopic lux values: avg. – 2718 lux, bed – 3374 lux, chair – 2191 lux

Scene 1D: 12:00 pm, clear sky | melanopic lux values: avg. – 2693 lux, bed – 3148 lux, chair – 2234 lux

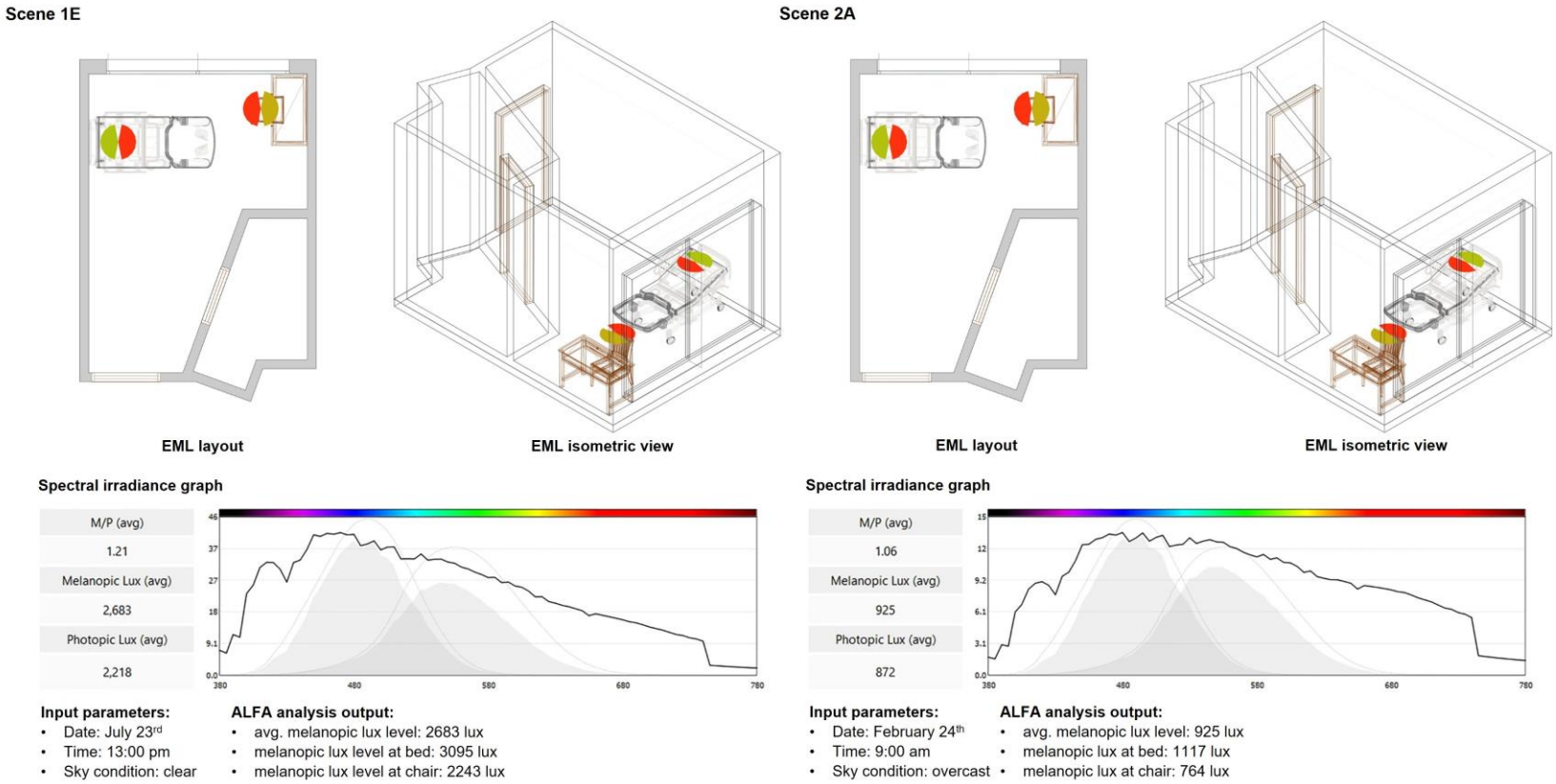


Figure 27: North Orientation – Circadian rhythm analysis Scene 1E and Scene 2A

Scene 1E: 1:00 pm, clear sky | melanopic lux values: avg. – 2683 lux, bed – 3095 lux, chair – 2243 lux

Scene 2A: 9:00 am, overcast sky | melanopic lux values: avg. – 925 lux, bed – 1117 lux, chair – 764 lux

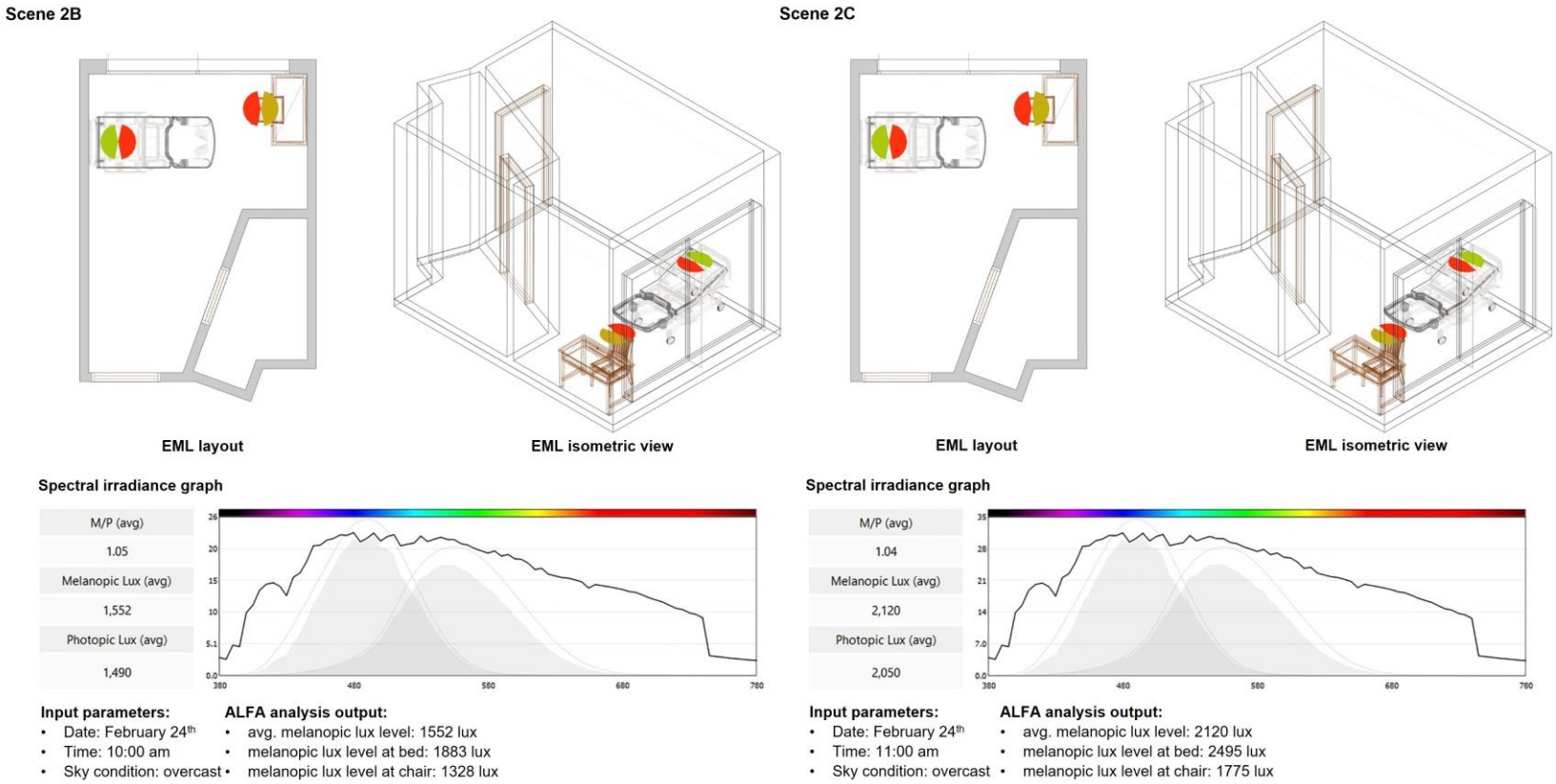


Figure 28: North Orientation – Circadian rhythm analysis Scene 2B and 2C

Scene 2B: 10:00 am, overcast sky | melanopic lux values: avg. – 1552 lux, bed – 1883 lux, chair – 1328 lux

Scene 2C: 11:00 am, overcast sky | melanopic lux values: avg. – 2120 lux, bed – 2495 lux, chair – 1775 lux

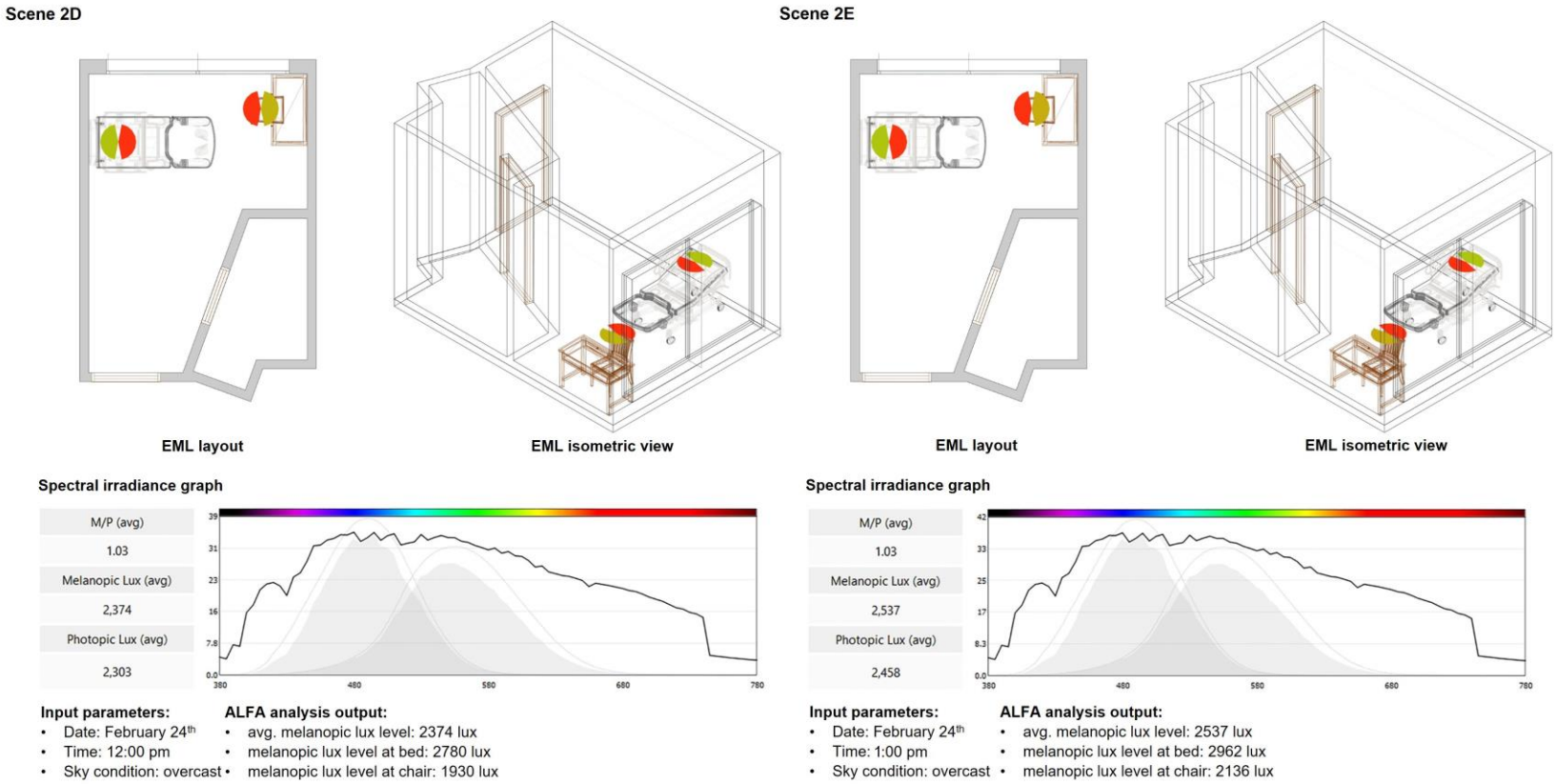
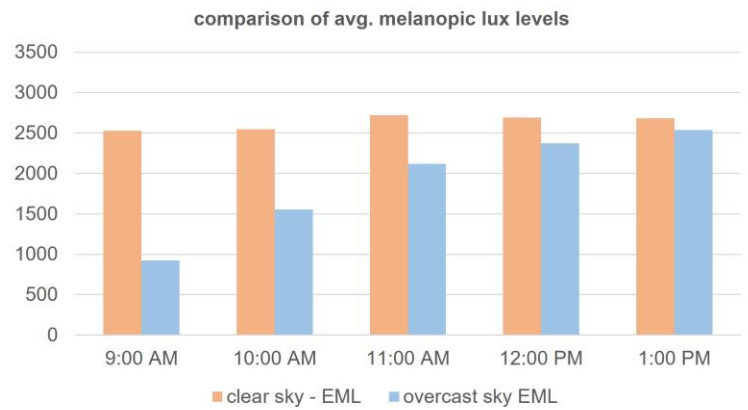
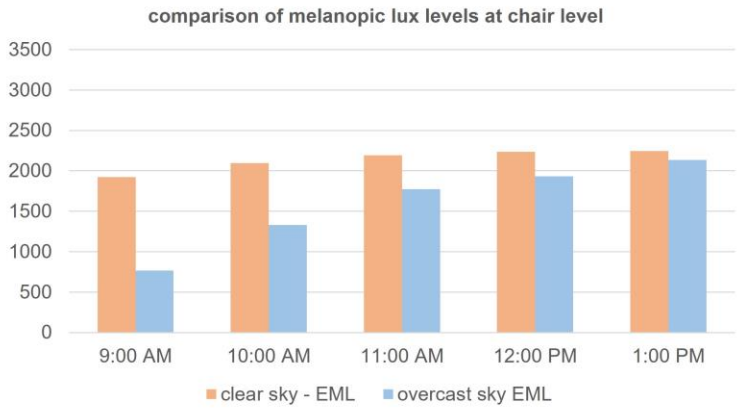


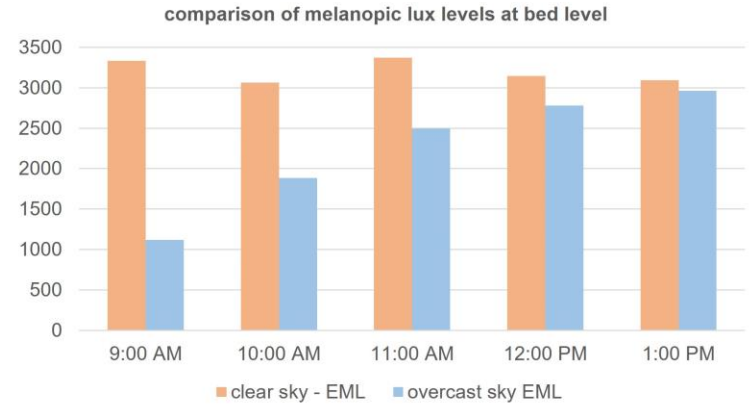
Figure 29: North Orientation – Circadian rhythm analysis Scene 2D and Scene 2E

Scene 2D: 12:00 pm, overcast sky | melanopic lux values: avg. – 2374 lux, bed – 2780 lux, chair – 1930 lux

Scene 2E: 1:00 pm, overcast sky | melanopic lux values: avg. – 2537 lux, bed – 2962 lux, chair – 2136 lux







Results Summary:

- **average melanopic lux level:**
  - Clear sky condition – moderate variation in levels.
  - Overcast sky condition – levels increase with each passing hour.
- **melanopic lux levels at bed:**
  - Clear sky condition – levels staying above 3000 lux with slight variations.
  - Overcast sky condition – levels increase with each passing hour.
- **melanopic lux levels at chair:**
  - Clear sky condition – marginal increase in levels till 1:00 pm.
  - Overcast sky condition – levels increase with each passing hour.

Figure 30: North Orientation – Circadian rhythm analysis summary

A comparative analysis and summary of the average melanopic lux levels and melanopic lux levels recorded at bed and chair during clear and overcast sky conditions.

4.2 Patient Room Orientation - South

4.2.1 Daylighting Optimization

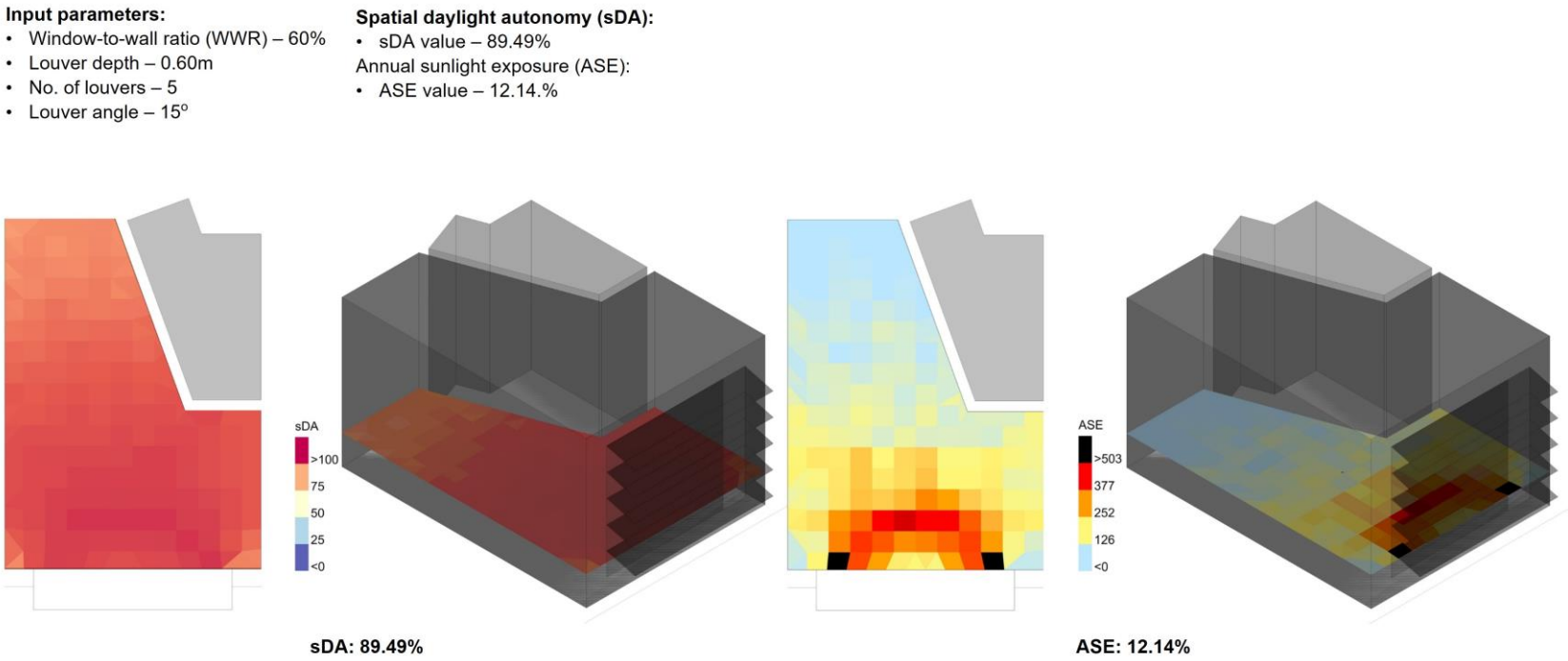
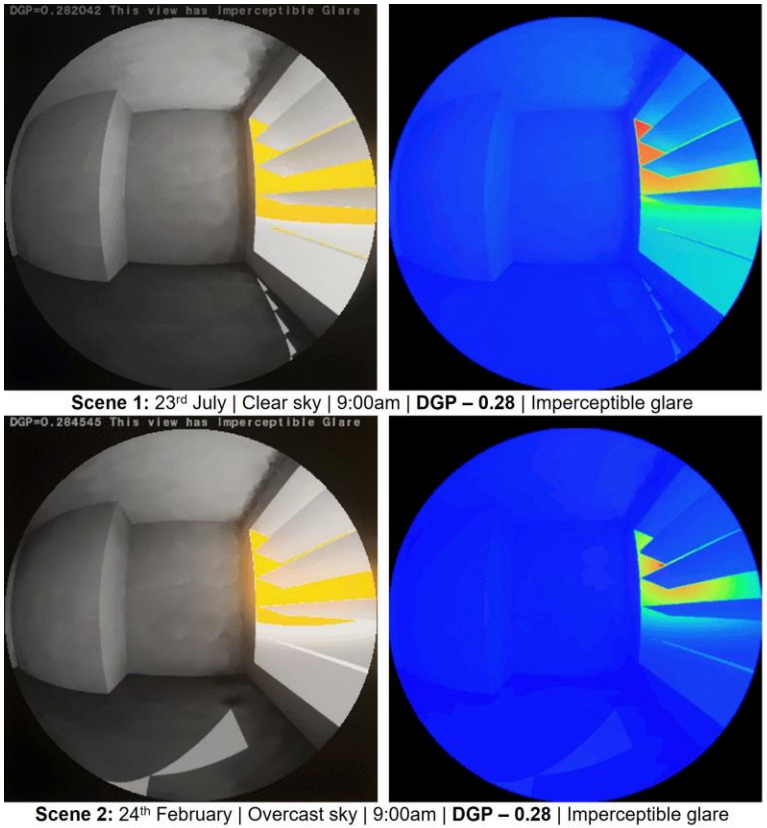


Figure 31: South Orientation – Shortlisted iteration for Circadian rhythm analysis

4.2.2 Glare Analysis



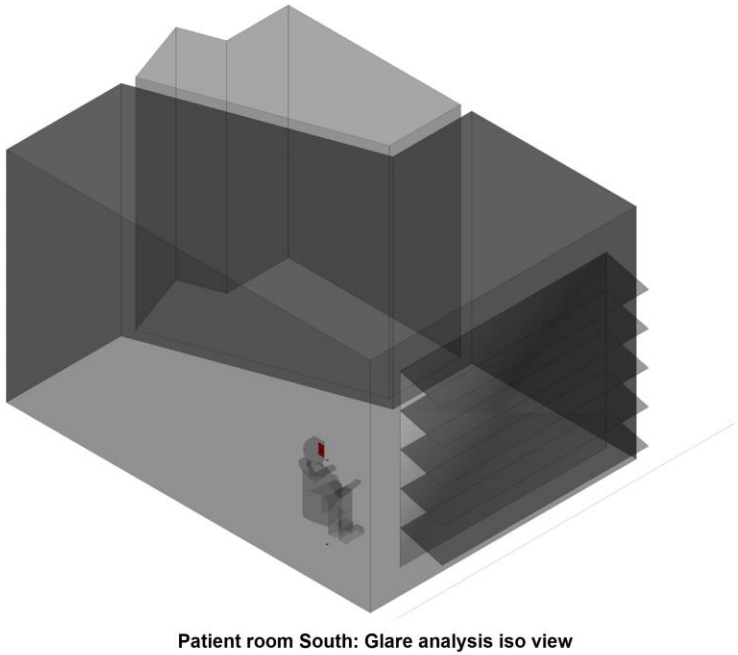


Figure 32: South Orientation – Patient room Glare analysis

4.2.3 Circadian Rhythm analysis

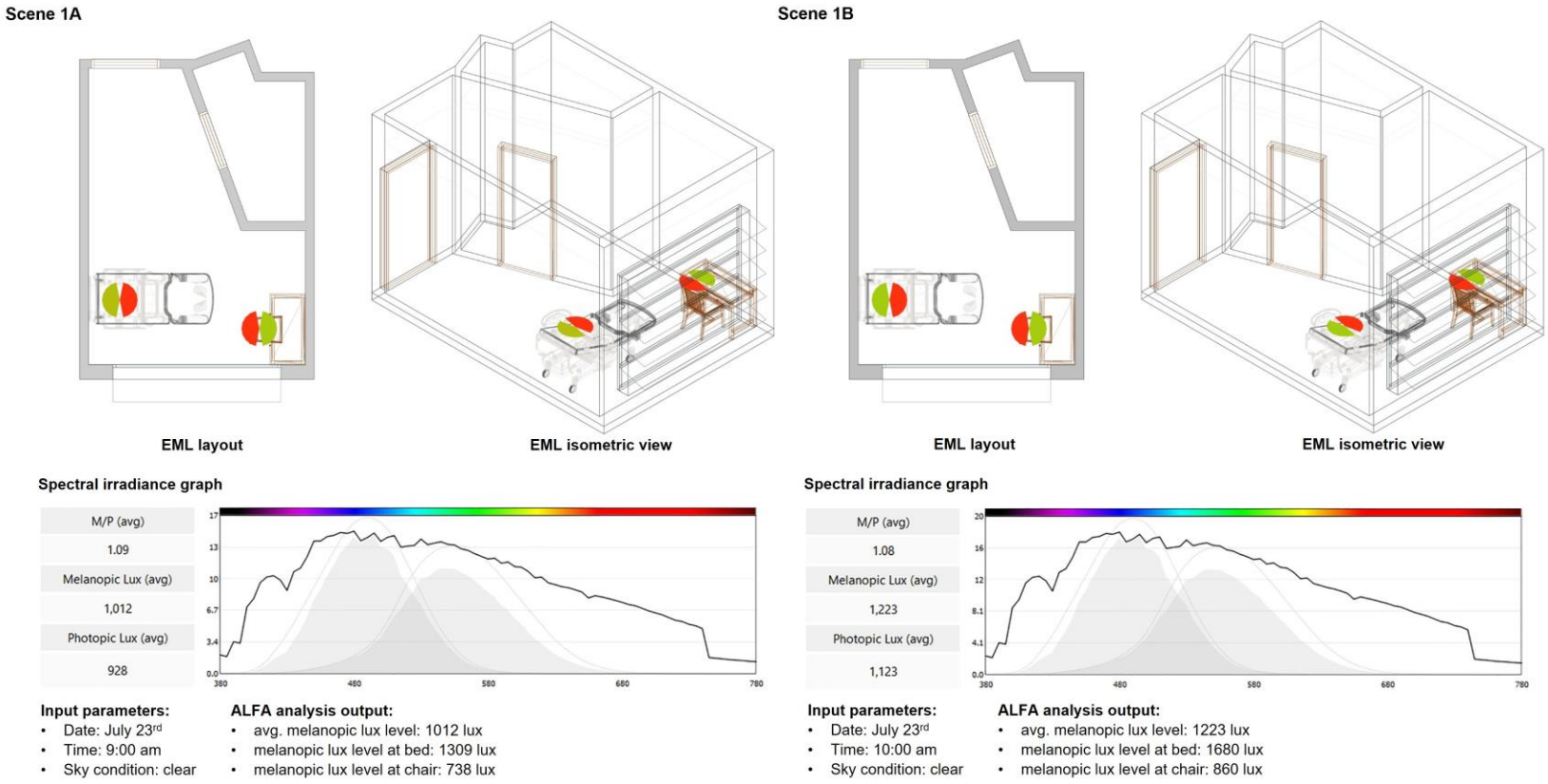


Figure 33: South Orientation – Circadian rhythm analysis Scene 1A and Scene 1B

Scene 1A: 9:00 am, clear sky | melanopic lux values: avg. – 1012 lux, bed – 1309 lux, chair – 738 lux

Scene 1B: 10:00 am, clear sky | melanopic lux values: avg. – 1223 lux, bed – 1680 lux, chair – 860 lux

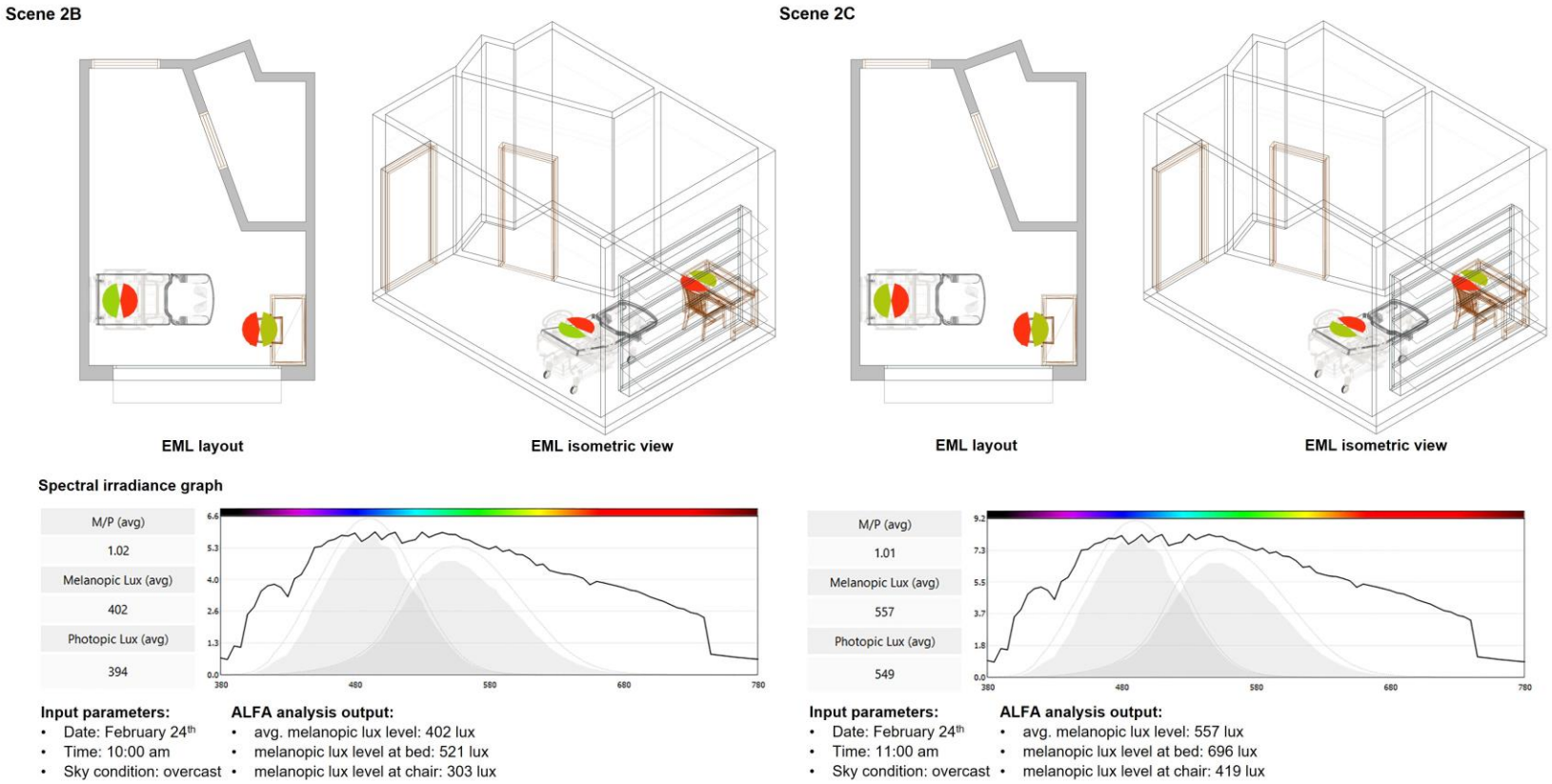
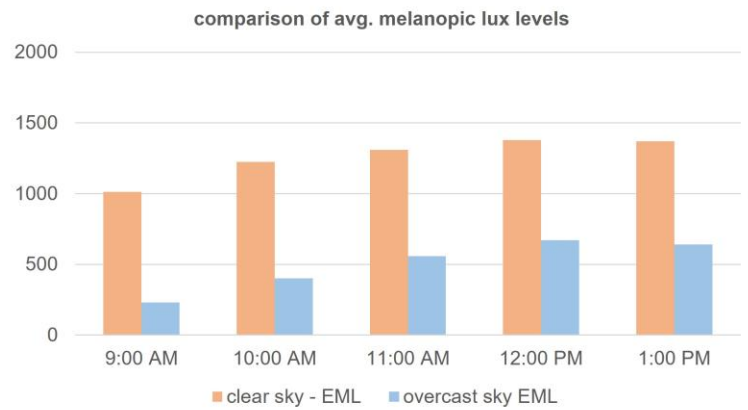
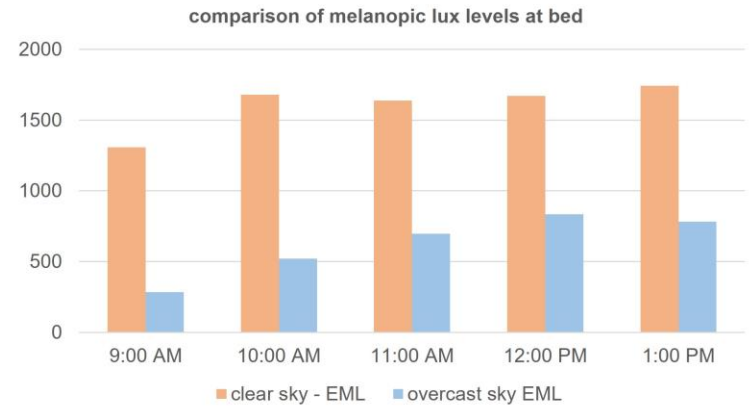


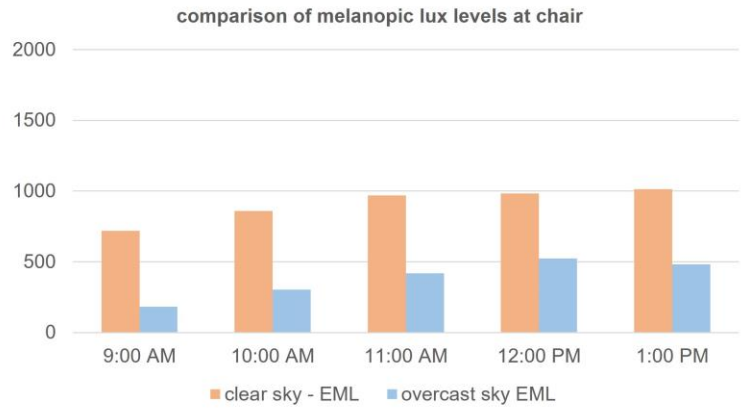
Figure 34: South Orientation – Circadian rhythm analysis Scene 2B and Scene 2C

Scene 2B: 10:00 am, overcast sky | melanopic lux values: avg. – 402 lux, bed – 521 lux, chair – 303 lux

Scene 2C: 11:00 am, overcast sky | melanopic lux values: avg. – 557 lux, bed – 696 lux, chair – 419 lux







Results Summary:

- **average melanopic lux level:**
  - Clear and Overcast sky condition –increase in levels till 12:00 pm and then a slight dip is observed at 1:00 pm.
- **melanopic lux levels at bed:**
  - Clear sky condition – levels stay above 1500 lux between 10:00 am and 1:00 pm.
  - Overcast sky condition – marginal increase in levels till 12:00 pm and then a slight dip is observed at 1:00 pm..
- **melanopic lux levels at chair:**
  - Clear sky condition – marginal increase in levels till 11:00 am.
  - Overcast sky condition – marginal increase in levels till 12:00 pm and then a slight dip is observed at 1:00 pm.

Figure 35: South Orientation – Circadian rhythm analysis summary

A comparative analysis and summary of the average melanopic lux levels and melanopic lux levels recorded at bed and chair during clear and overcast sky conditions.

4.3 Patient Room Orientation – East

4.3.1 Daylighting optimization

Input parameters:
- Window-to-wall ratio (WWR) – 50%
- Louver depth – 0.40m
- No. of louvers – 5
- Louver angle – 15°

Spatial daylight autonomy (sDA):
- sDA value – 87.94%

Annual sunlight exposure (ASE):
- ASE value – 48.62.%

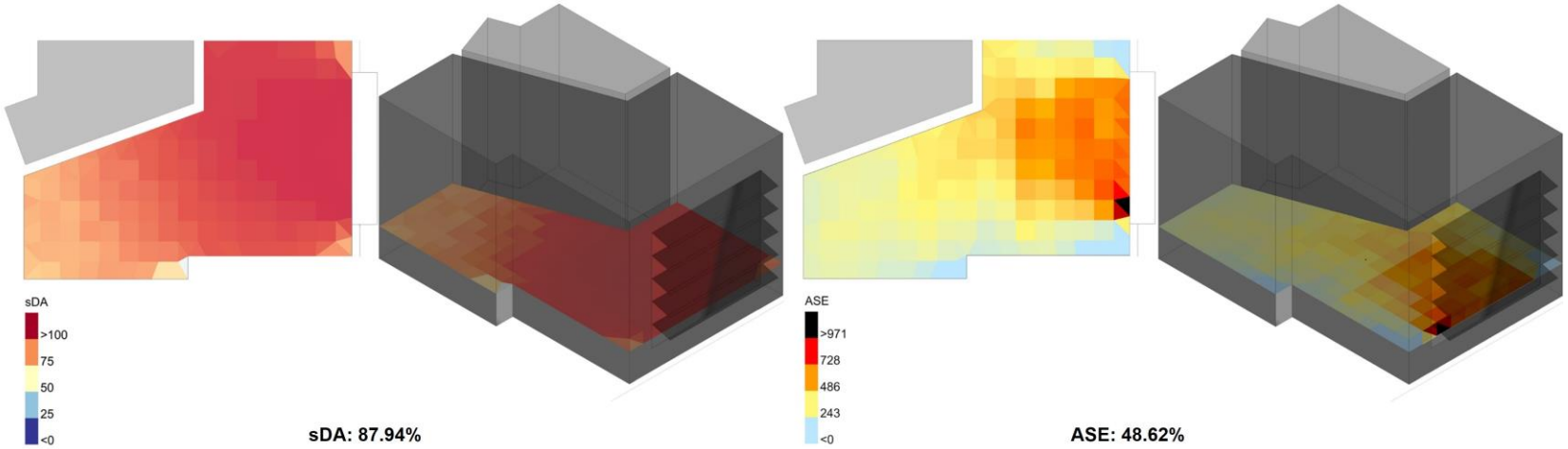
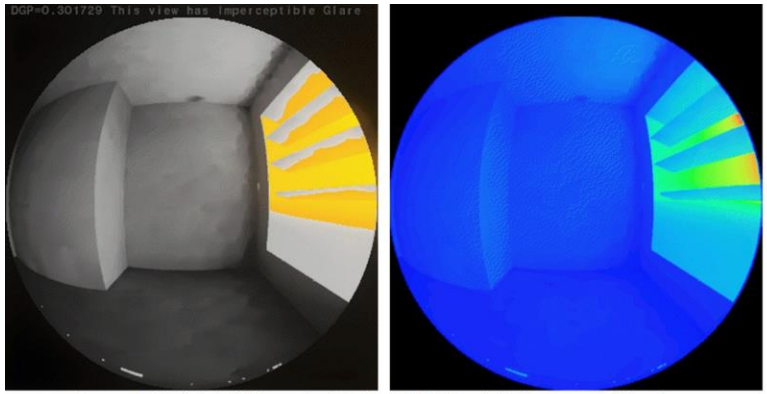
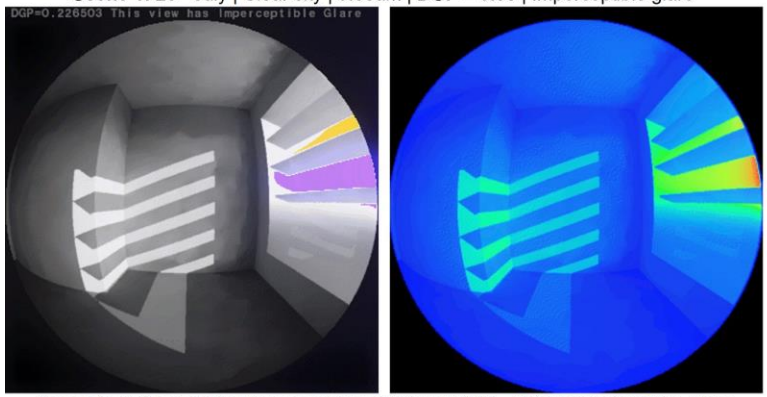


Figure 36: East Orientation – Shortlisted iteration for Circadian rhythm analysis

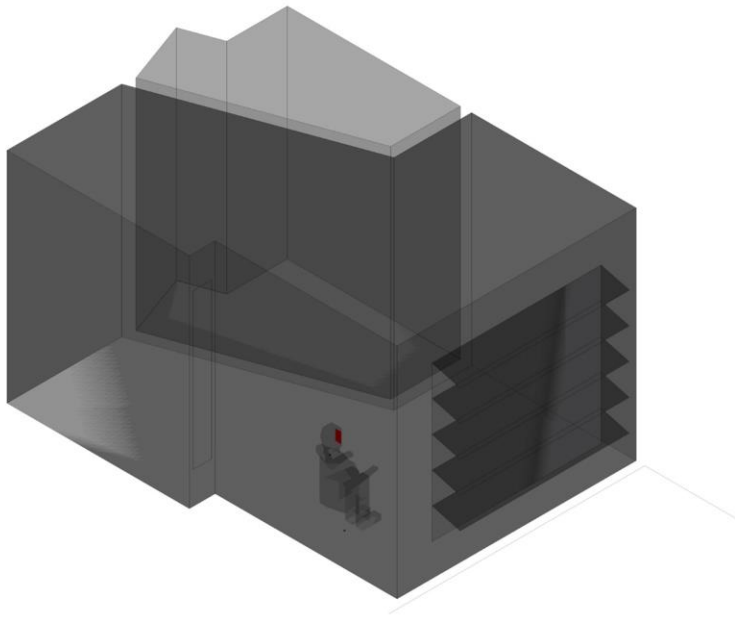
4.3.2 Glare Analysis



Scene 1: 23rd July | Clear sky | 9:00am | **DGP – 0.30** | Imperceptible glare



Scene 2: 24th February | Overcast sky | 9:00am | **DGP – 0.22** | Imperceptible glare



Patient room East: Glare analysis iso view

Figure 37: East Orientation – Patient room Glare analysis

4.3.3 Circadian Rhythm analysis

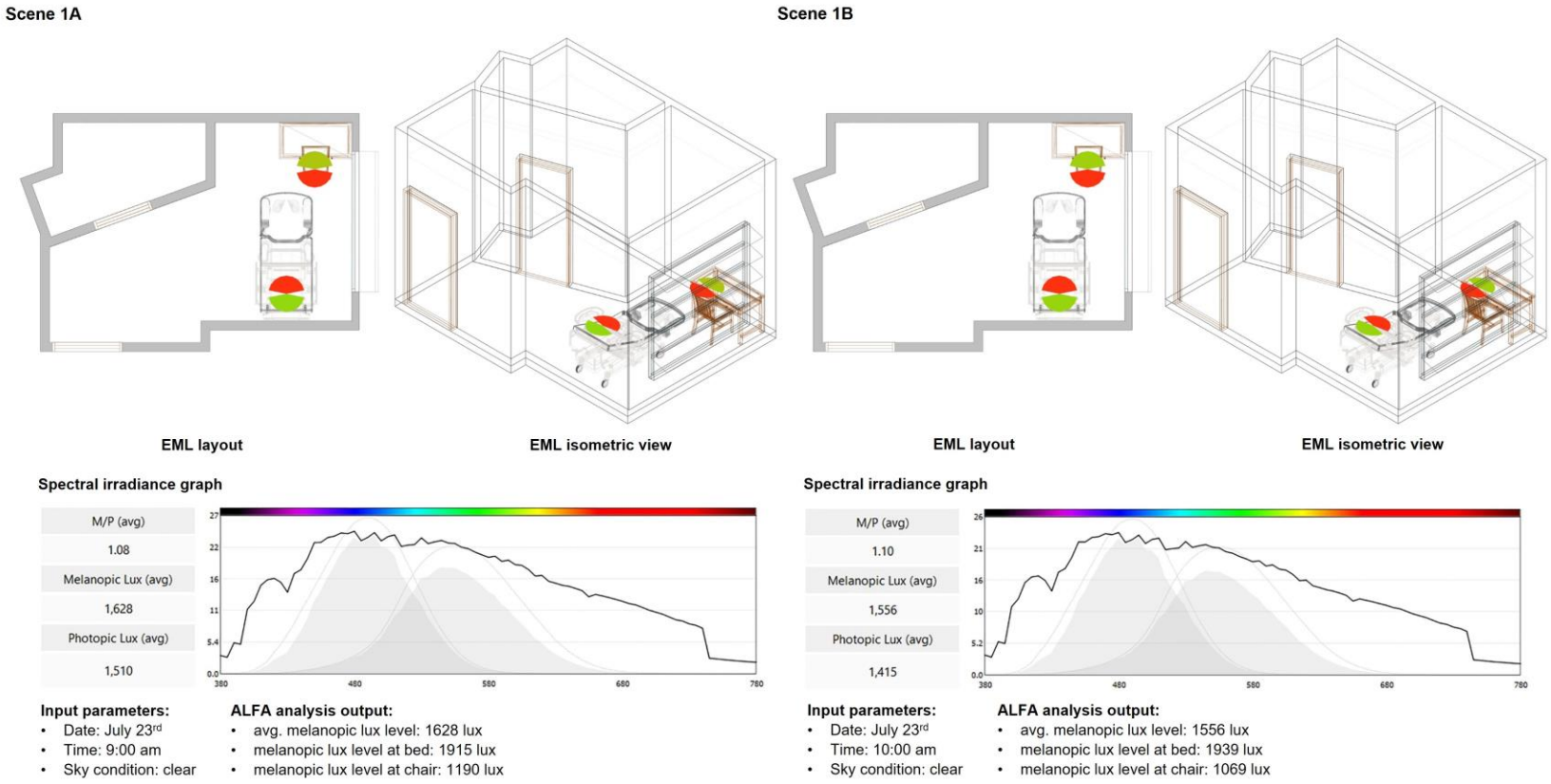


Figure 38: East Orientation – Circadian rhythm analysis Scene 1A and Scene 1B

Scene 1A: 9:00 am, clear sky | melanopic lux values: avg. – 1628 lux, bed – 1915 lux, chair – 1190 lux

Scene 1B: 10:00 am, clear sky | melanopic lux values: avg. – 1556 lux, bed – 1939 lux, chair – 1069 lux

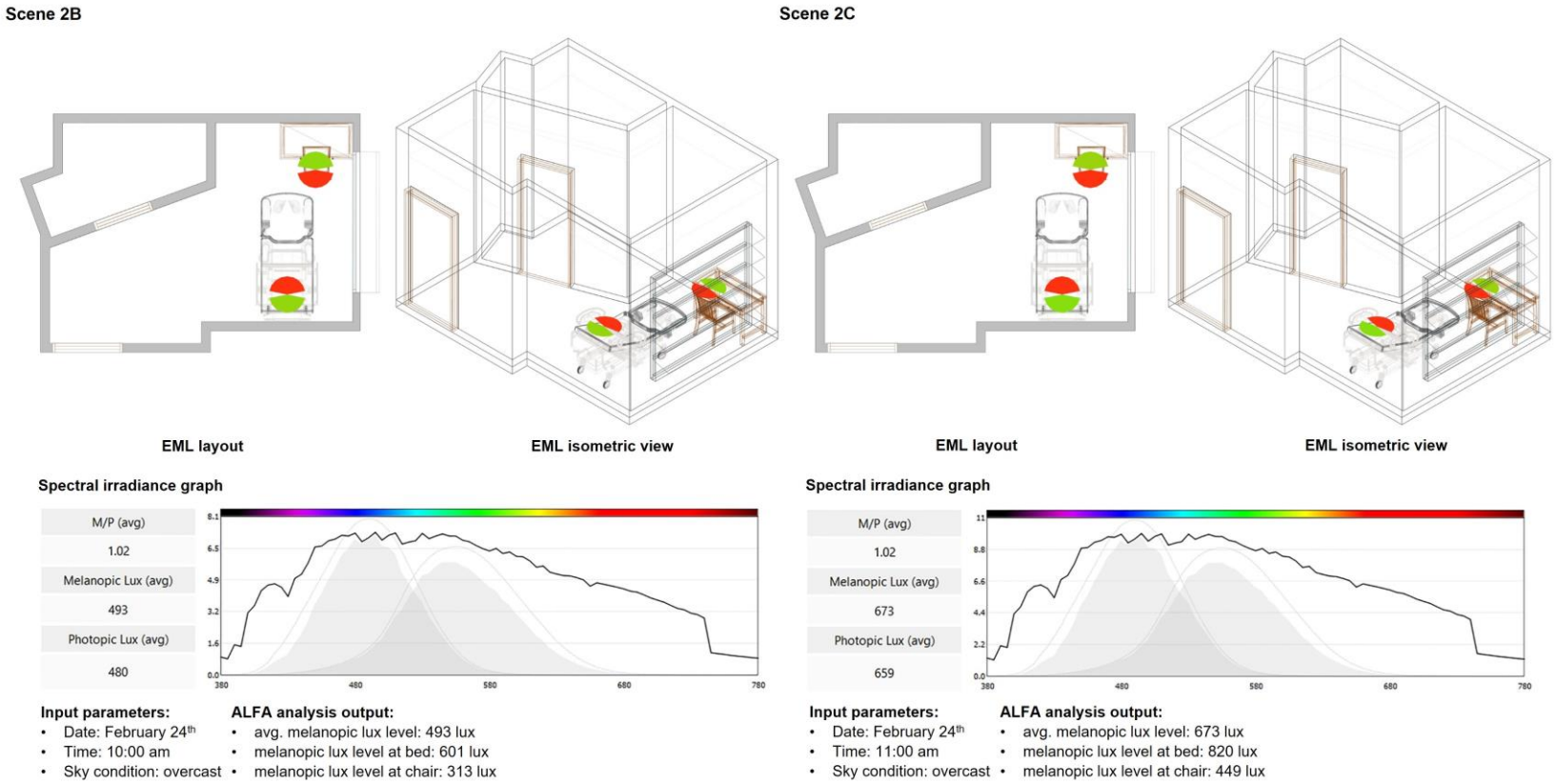
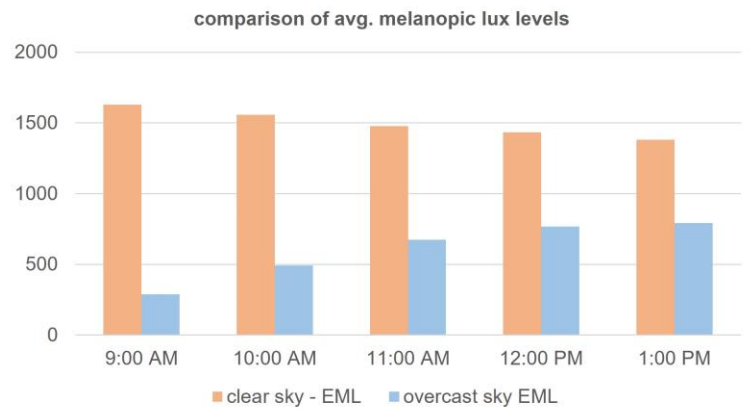
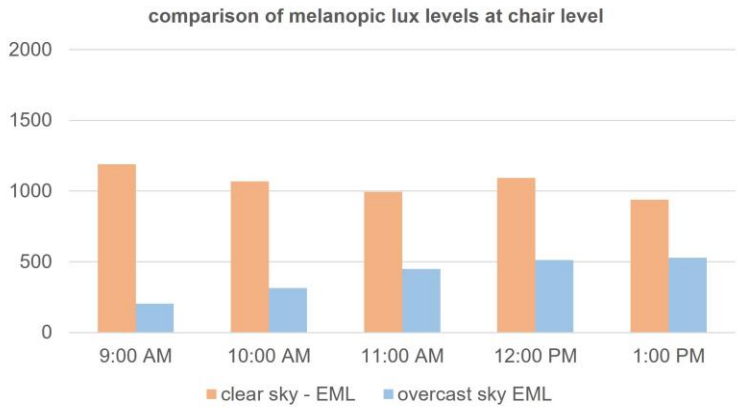


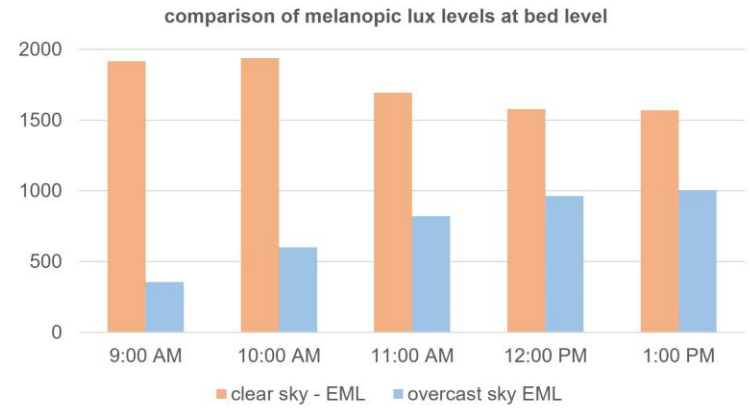
Figure 39: East Orientation – Circadian rhythm analysis Scene 2B and Scene 2C

Scene 2B: 10:00 am, overcast sky | melanopic lux values: avg. – 493 lux, bed – 601 lux, chair – 313 lux

Scene 2C: 11:00 am, overcast sky | melanopic lux values: avg. – 673 lux, bed – 820 lux, chair – 449 lux







Results Summary:

- **average melanopic lux level:**
  - Clear sky condition – marginal decrease in levels till 1:00 pm.
  - Overcast sky condition – marginal increase in levels till 1:00 pm.
- **melanopic lux levels at bed:**
  - Clear sky condition – decrease in levels observed between 10:00 am to 1:00 pm.
  - Overcast sky condition – marginal increase in levels till 1:00 pm..
- **melanopic lux levels at chair:**
  - Clear sky condition – marginal decrease in levels observed between 9:00 am to 1:00 pm with an exception at 12:00 pm where a slight gain is recorded.
  - Overcast sky condition – marginal increase in levels till 1:00 pm.

Figure 40: East Orientation – Circadian rhythm analysis summary

A comparative analysis and summary of the average melanopic lux levels and melanopic lux levels recorded at bed and chair during clear and overcast sky conditions.

4.4 Patient Room Orientation – West

4.4.1 Daylighting optimization

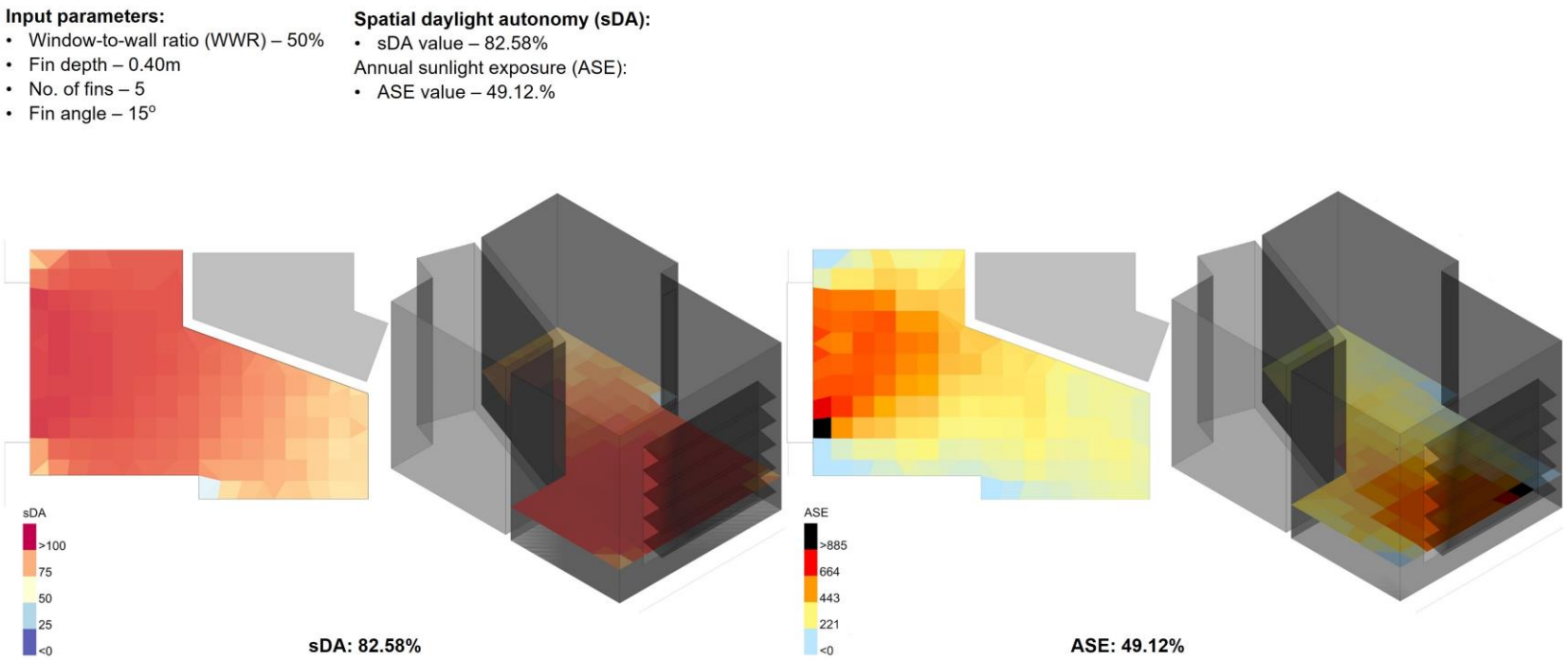
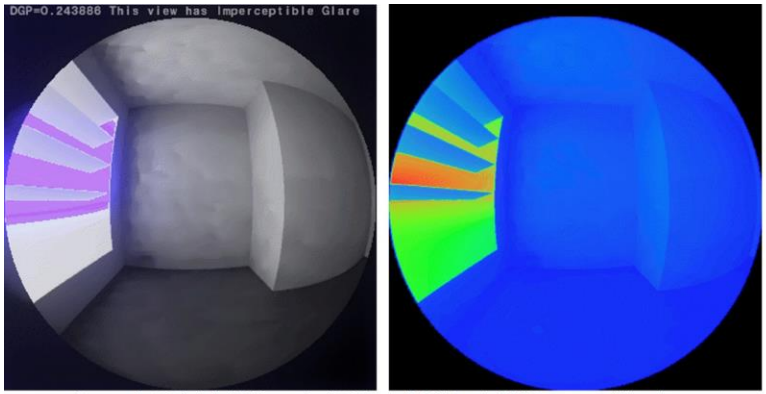
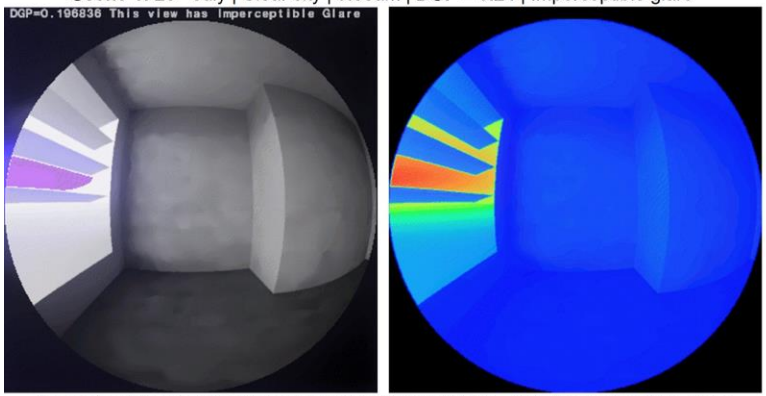


Figure 41: West Orientation – Shortlisted iteration for circadian rhythm analysis

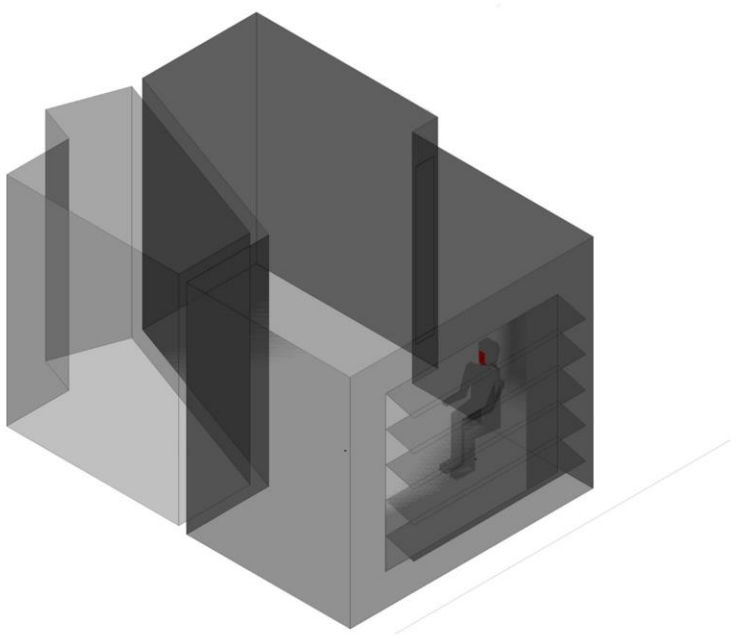
4.4.2 Glare Analysis



Scene 1: 23rd July | Clear sky | 9:00am | **DGP – 0.24** | Imperceptible glare



Scene 2: 24th February | Overcast sky | 9:00am | **DGP – 0.19** | Imperceptible glare



Patient room West: Glare analysis iso view

Figure 42: West Orientation – Patient room Glare Analysis

4.4.3 Circadian Rhythm analysis

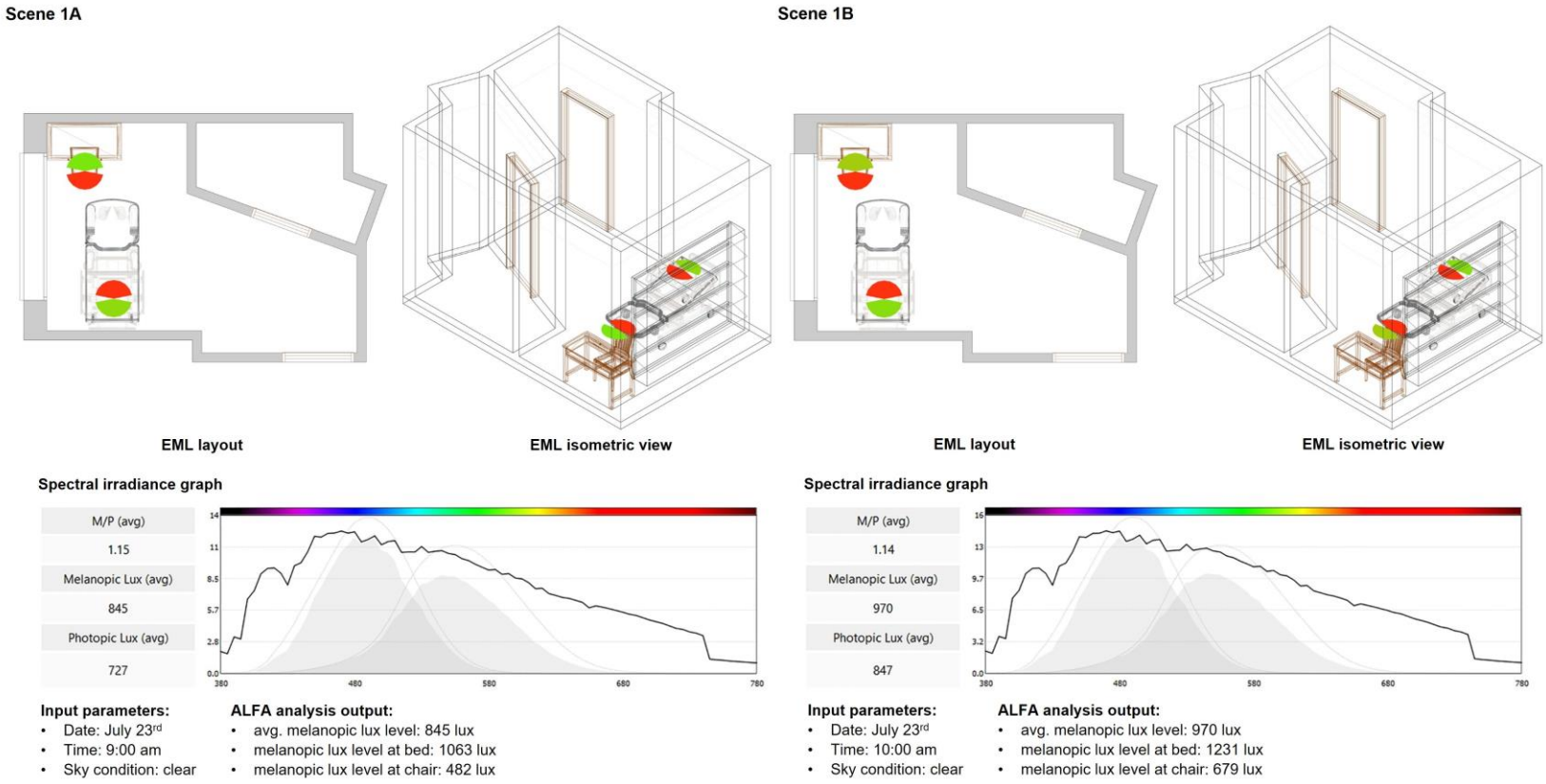


Figure 43: West Orientation – Circadian rhythm analysis Scene 1A and Scene 1B

Scene 1A: 9:00 am, clear sky | melanopic lux values: avg. – 845 lux, bed – 1063 lux, chair – 482 lux

Scene 1B: 10:00 am, clear sky | melanopic lux values: avg. – 970 lux, bed – 1231 lux, chair – 679 lux

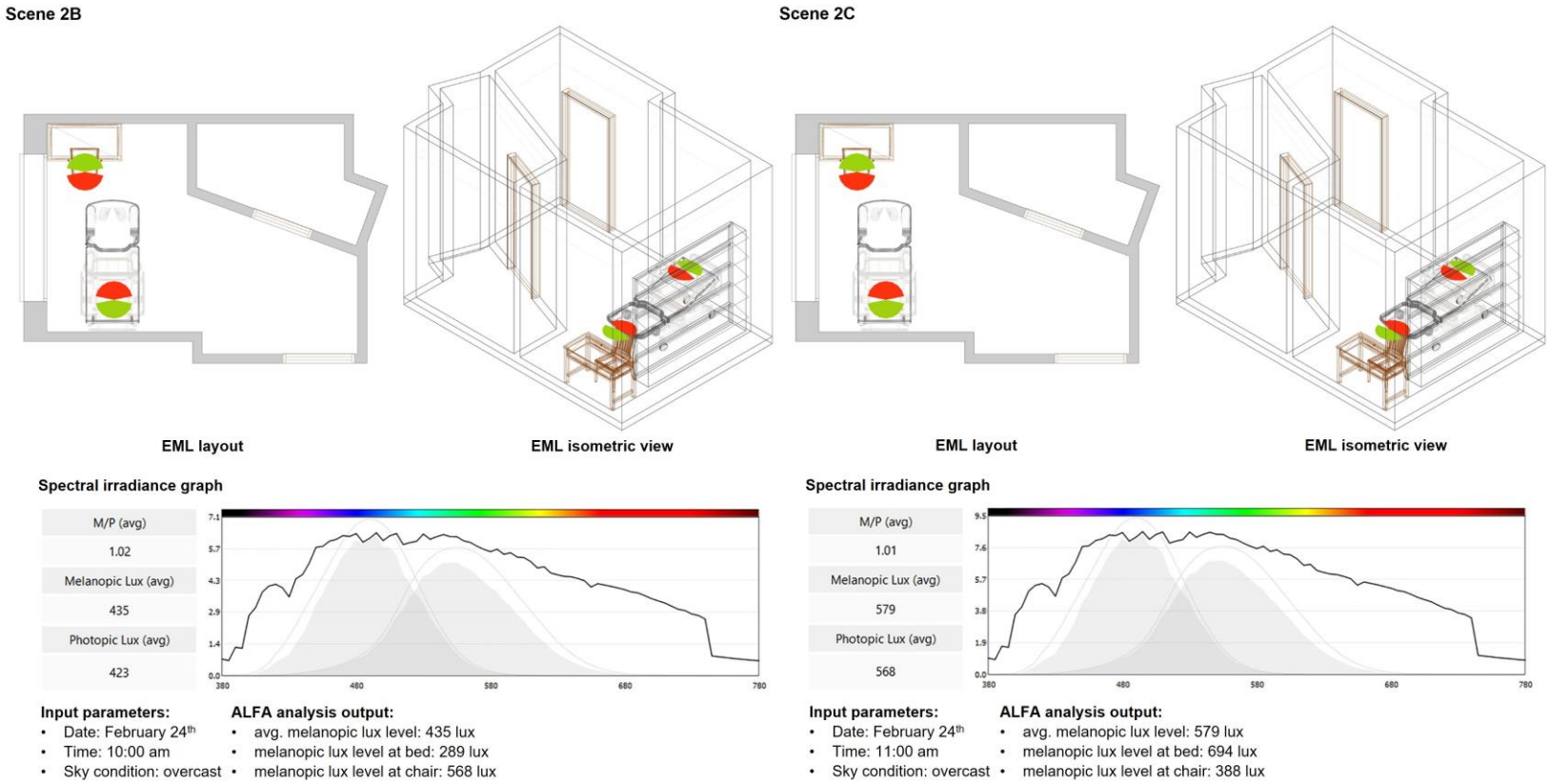
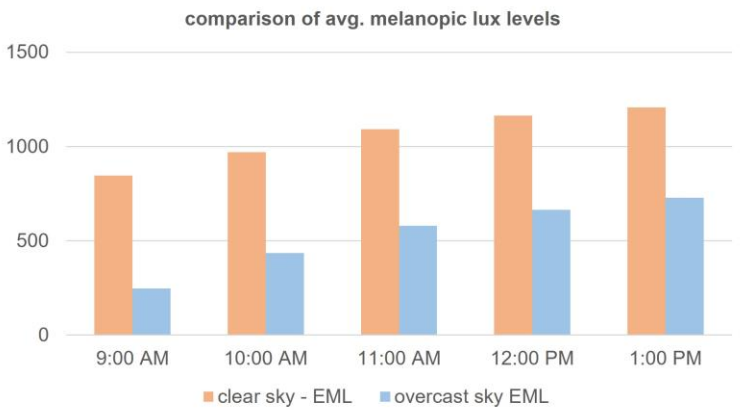
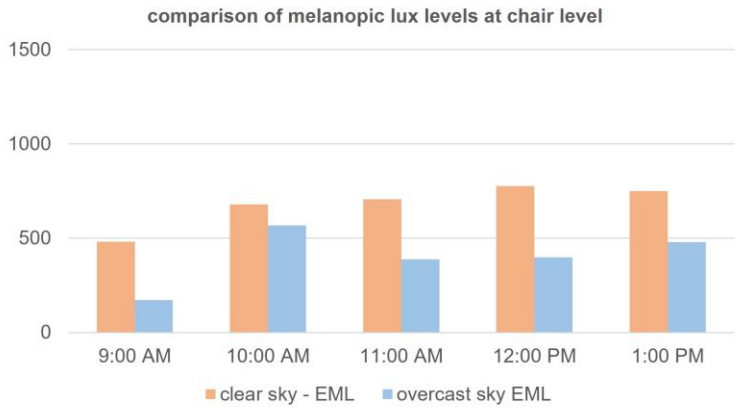


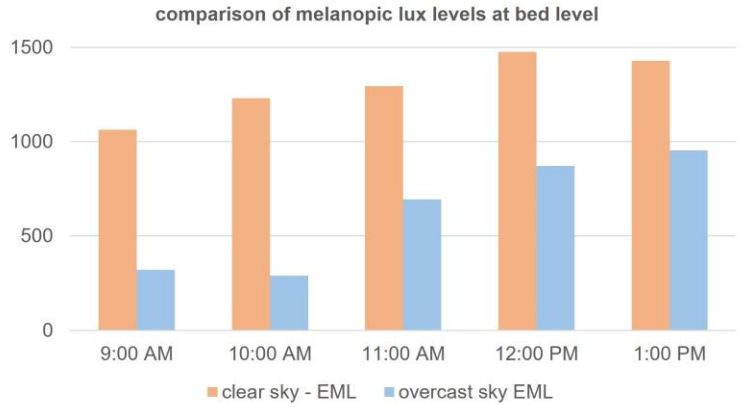
Figure 44: West Orientation – Circadian rhythm analysis Scene 2B and Scene 2C

Scene 2B: 10:00 am, overcast sky | melanopic lux values: avg. – 435 lux, bed – 289 lux, chair – 568 lux

Scene 2C: 11:00 am, overcast sky | melanopic lux values: avg. – 579 lux, bed – 694 lux, chair – 388 lux







Results Summary:

- **average melanopic lux level:**
  - Clear sky condition – marginal increase in levels till 1:00 pm.
  - Overcast sky condition – marginal increase in levels till 1:00 pm.
- **melanopic lux levels at bed:**
  - Clear sky condition – increase in levels observed between 9:00 am to 12:00 pm.
  - Overcast sky condition – increase levels observed between 9:00 am to 1:00 pm with an exception of 10:00 am where a slight dip is recorded.
- **melanopic lux levels at chair:**
  - Clear sky condition – marginal increase in levels observed between 9:00 am to 12:00 pm with a slight dip recorded at 1:00 pm.
  - Overcast sky condition – marginal increase in levels observed between 9:00 am to 1:00 pm with an exception at 10:00 am where a significant gain is recorded.

Figure 45: West Orientation – Circadian rhythm analysis summary

A comparative analysis and summary of the average melanopic lux levels and melanopic lux levels recorded at bed and chair during clear and overcast sky conditions.

CHAPTER 5: DISCUSSION, LIMITATIONS, FUTURE RESEARCH, AND CONCLUSION

This chapter reviews the implications of the findings and results of the thesis. It gives a context of the results generated for each patient room orientation, the limitations of the research, raises questions for future research, and concludes the work done on this thesis.

5.1 Discussion on the simulation results

The Optimization results provide an insight into the varying levels of permutations possible for the building envelope in regulating daylighting inside patient rooms. There is a significant impact of the envelope parameters like window-to-wall ratio and shading mechanisms on the sDA and ASE values. In terms of selecting the shading mechanisms, the DGP or Daylight Glare Probability value became a critical factor especially for the South, East and West orientations.

Apart from the primary envelope parameters, the VT or visible transmittance value of the glass also played an important role in regulating the sDA and melanopic lux values. The VT level for the existing patient rooms is 40% which resulted in sDA levels below 50% for all orientations except South which recorded inside the interior built environment. an sDA value of 63% owing to the longer façade of the building in a North-South orientation.

An increase in the VT value of the glazing from 40% to 65% while conducting the optimization permutations resulted in a significant increase in the sDA values while balancing the ASE values by the virtue of shading mechanisms. The North and South orientations recorded sDA values of 94.35% and 89.49% respectively. Although the East and West orientations recorded sDA values higher than 80% they also recorded higher ASE

values than the North and South orientations. However, to understand occupant comfort with reference to high ASE values, a glare analysis for both East and West orientations recorded imperceptible glare for patients in both clear and overcast sky conditions.

The circadian rhythm analysis of the patient rooms focused on a more occupant-centric approach by placing the analysis sensor nodes on the bed and chair. This resulted in the recording of melanopic lux levels anticipating patient behavior inside the room during daytime hours of 9:00 am to 1:00 pm on both clear and overcast sky conditions. A comparative analysis of the melanopic lux levels during the clear and overcast sky conditions resulted in evaluating the performance of the building envelope during varying climatic conditions.

The results indicate that in the North orientation the average melanopic lux levels showed moderate variation in clear sky conditions whereas the levels increased with each passing hour in overcast sky condition. The melanopic lux levels at bed stay above 3000 lux in clear sky conditions whereas the levels increase with each passing hour in overcast sky condition. The melanopic lux levels at chair showed marginal increase in levels till 1pm whereas the levels increased with each passing hour in overcast sky conditions.

In the South orientation, the average melanopic lux levels increase till 12:00 pm and then a slight dip is observed at 1:00 pm for both clear and overcast sky conditions. The melanopic lux levels stay above 1500 lux between 10:00 am and 1:00 pm in clear sky conditions whereas in the overcast sky condition there is a marginal increase in levels till 12:00 pm and then a slight dip is observed at 1:00 pm. The melanopic lux levels at the chair indicated a marginal increase in levels 1ill 11:00 am in clear sky condition whereas in the

overcast sky condition, there was a marginal increase in levels till 12:00 pm and then a slight dip is observed at 1:00 pm.

In the East orientation, the average melanopic lux levels decrease marginally till 1:00 pm for clear sky conditions, whereas the levels increase till 1:00 pm for overcast sky conditions. The melanopic lux levels at bed decrease between 10:00 am to 1:00 pm in clear sky conditions whereas the levels marginally increase till 1:00 pm in overcast sky conditions. The melanopic lux levels at the chair decrease between 9:00 am to 1:00 pm, except at 12:00 pm, where a slight gain in the levels is recorded. Whereas a marginal increase in levels is observed till 1:00 pm in overcast sky conditions.

In the West orientation, the average melanopic lux levels increase marginally till 1:00 pm for both clear and overcast sky conditions. The melanopic lux levels at bed increase between 9:00 am to 12:00 pm for clear sky conditions, whereas in overcast sky conditions, an increase in levels is observed between 9:00 am to 1:00 pm with an exception at 10:00 am where a slip dip is recorded. The melanopic lux levels at chair increase marginally between 9:00 am to 12:00 pm with a slight dip recorded at 1:00 pm in clear sky conditions whereas in overcast sky conditions a marginal increase in levels is observed between 9:00 am to 1:00 pm with an exception at 10:00 am where a significant gain is recorded.

A comparative analysis of the values for the existing and optimized conditions indicates the percentage of improvement in the sDA and melanopic lux levels for the different orientations. The tables on the next page indicate the percentage of improvement in values thereby indicating the implications of the simulation experiment on the performance of the building envelope.

Table 2: Comparative analysis of sDA values

Sr.no	Patient room Orientation	sDA (%)		% improvement
		existing condition	optimized condition	
1	North Orientation	26.39	94.48	258.01
2	South Orientation	63.23	89.49	41.53
3	East Orientation	42.41	87.94	107.36
4	West Orientation	36.74	82.58	124.77

Table 3: Comparative analysis of melanopic lux values at 9:00 am, clear sky condition

Sr.no	Patient room Orientation	melanopic lux level at bed (lux)		% improvement	melanopic lux level at chair (lux)		% improvement
		existing condition	optimized condition		existing condition	optimized condition	
1	North Orientation	96	3336	3375.00	295	1920	550.85
2	South Orientation	157	1309	733.76	425	718	68.94
3	East Orientation	488	1915	292.42	1512	1190	-21.30
4	West Orientation	125	1063	750.40	183	482	163.39

Table 4: Comparative analysis of melanopic lux values at 9:00 am, overcast sky condition

Sr.no	Patient room Orientation	melanopic lux level at bed (lux)		% improvement	melanopic lux level at chair (lux)		% improvement
		existing condition	optimized condition		existing condition	optimized condition	
1	North Orientation	32	1117	3390.63	141	764	441.84
2	South Orientation	108	283	162.04	37	183	394.59
3	East Orientation	49	356	626.53	169	203	20.12
4	West Orientation	50	320	540.00	79	171	116.46

The baseline threshold levels set by LEED for sDA – 55% and WELLv2, Q3 2022 standard for living environments is 275 EML or equivalent melanopic lux are considered for the comparative analysis. From the above tables, it is evident that optimization of the building envelope in different orientations resulted in a significant gain in both sDA and melanopic lux values. Amongst the different orientations, the North orientation showcased the highest percentage of improvement followed by the West orientation.

5.2 Limitations

The simulation experiment was conducted in Salt Lake City which has a semi-arid, temperate climate. As the study was conducted in a specific climate zone, there is a wide scope to explore other climate zones and subsequent climatic conditions specific to daylighting. The experiment conducted on the ASU level had its longer facade oriented on

a north-south axis. As a result, most of the patient rooms were oriented north-south as compared to east-west orientations. However, the intercardinal directions like north-east, north-west, south-east, and south-west were not explored as a part of the simulation experiment. Another limitation of the study was the urban context surrounding the built form. The facility was in a semi-urban context with very few buildings located distant blocks away from the healthcare facility. Healthcare facilities in dense urban settings and rural settings with dense vegetation and trees will pose challenges with regards to daylighting penetration. In this simulation experiment, the material of the shading mechanism was opaque in nature. The nature of the transparency of shading mechanisms can impact the daylighting quality and levels within the interior built environment in a significant manner. Although the study adopted an occupant-centric approach in collecting melanopic lux data, it is difficult to anticipate occupant behavior inside a patient room. This is mainly due to the nature of illness, immunity, and treatment response levels and the overall response to a healthcare setting which differs from patient to patient.

5.3 Future Research

This research established an integral relationship between the building envelope and its impact on the circadian rhythms of occupants within an interior built environment with reference to a healthcare context focusing on patients. Apart from patients, healthcare staff experiences heavy working loads in treating patients physically and psychologically. Along with patients, the scope of the simulation-based workflow for daylighting analysis can be expanded to cater to the overall health and well-being of the healthcare staff. Recent technological improvements have resulted in establishing a balance between ambient daylighting and tunable electrical lighting which can aid in designing healthcare facilities,

especially in dense urban contexts. With the aid of automated shading devices integrated with the building envelope, an equilibrium can be achieved in daylighting penetration and providing quality views, especially those integrating nature. Further research can be conducted on the performance of the transparent and translucent nature of building materials used in developing shading mechanisms with regards to facilitating daylighting balancing glare and providing quality views of nature. Apart from ALFA, Lark spectral lighting tool can be used to gain deeper insights into circadian entrainment with its nine-channel method for daylit scenes and prediction of indoor daylight. Collaborating with the healthcare staff, a time-integrated metric dose of daylighting for the patients can be worked out to further evaluate the performance of the building envelope. In terms of validating the simulation experiment, the light levels can be measured in one patient room in each orientation with a lux meter over different times of the year to analyze the difference in the levels between clear and overcast sky conditions.

5.4 Conclusion

This research provided some valuable insights between the building envelope and its impact on the non-visual effects and circadian entrainment of occupants inside a patient room setting through daylighting. Focusing primarily on window-to-wall ratios and shading mechanisms, the research indicated a potential scope to further investigate different aspects related to the material specifications and economics in implementing such interventions in physical projects. The outcome of this research is to provide designers, planners, and healthcare staff with a simulation-based framework for designing healthcare environments with a focus on daylighting simulation.

APPENDIX

This section consists of the remainder results derived from the Optimization and Circadian rhythm analysis stages for the South, East, and West patient room orientations which have not been discussed in Chapter 4.

South Orientation – Daylighting Optimization results

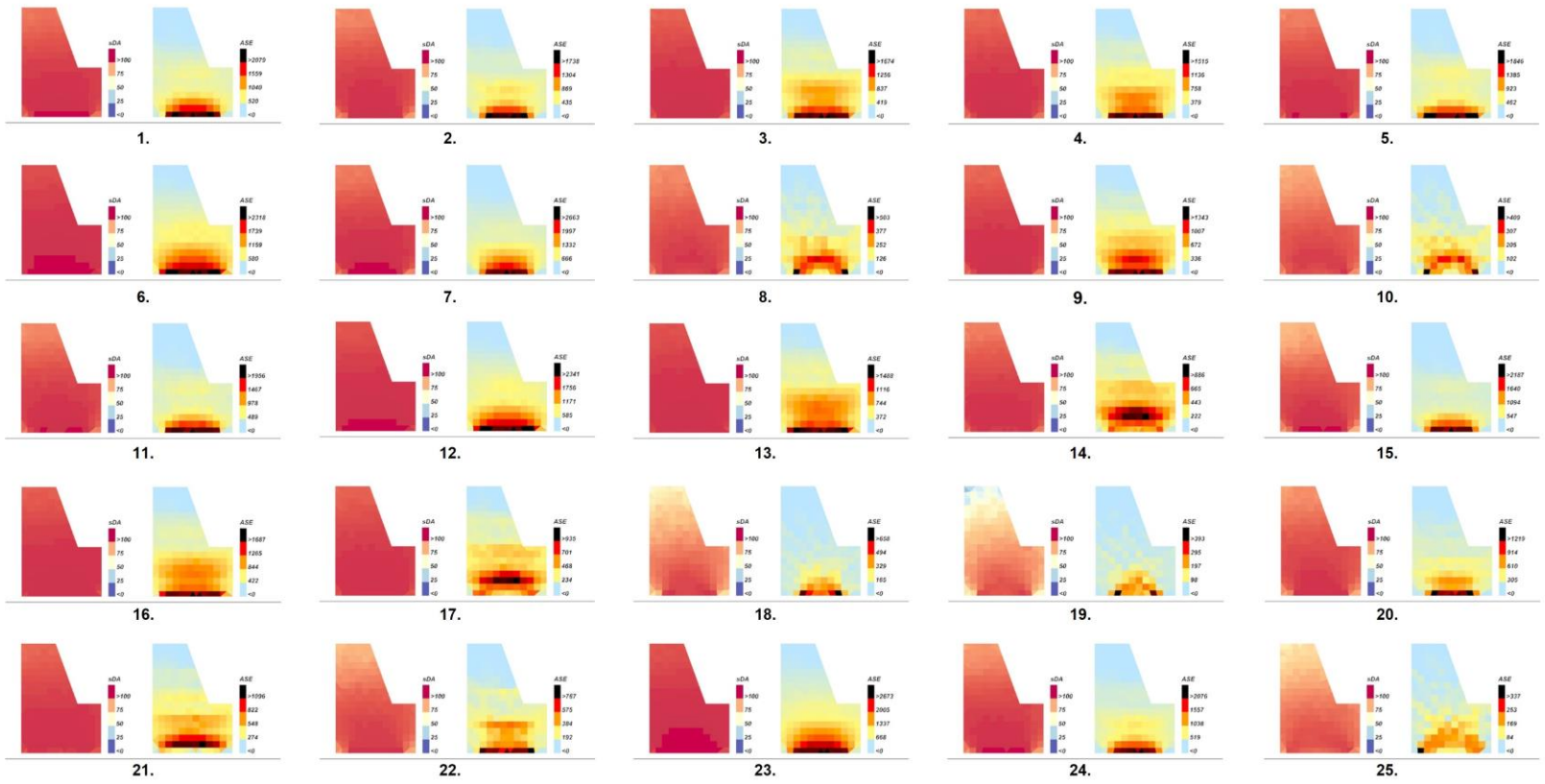


Figure 46: South Orientation - Daylighting optimization iterations using louvers as shading mechanism

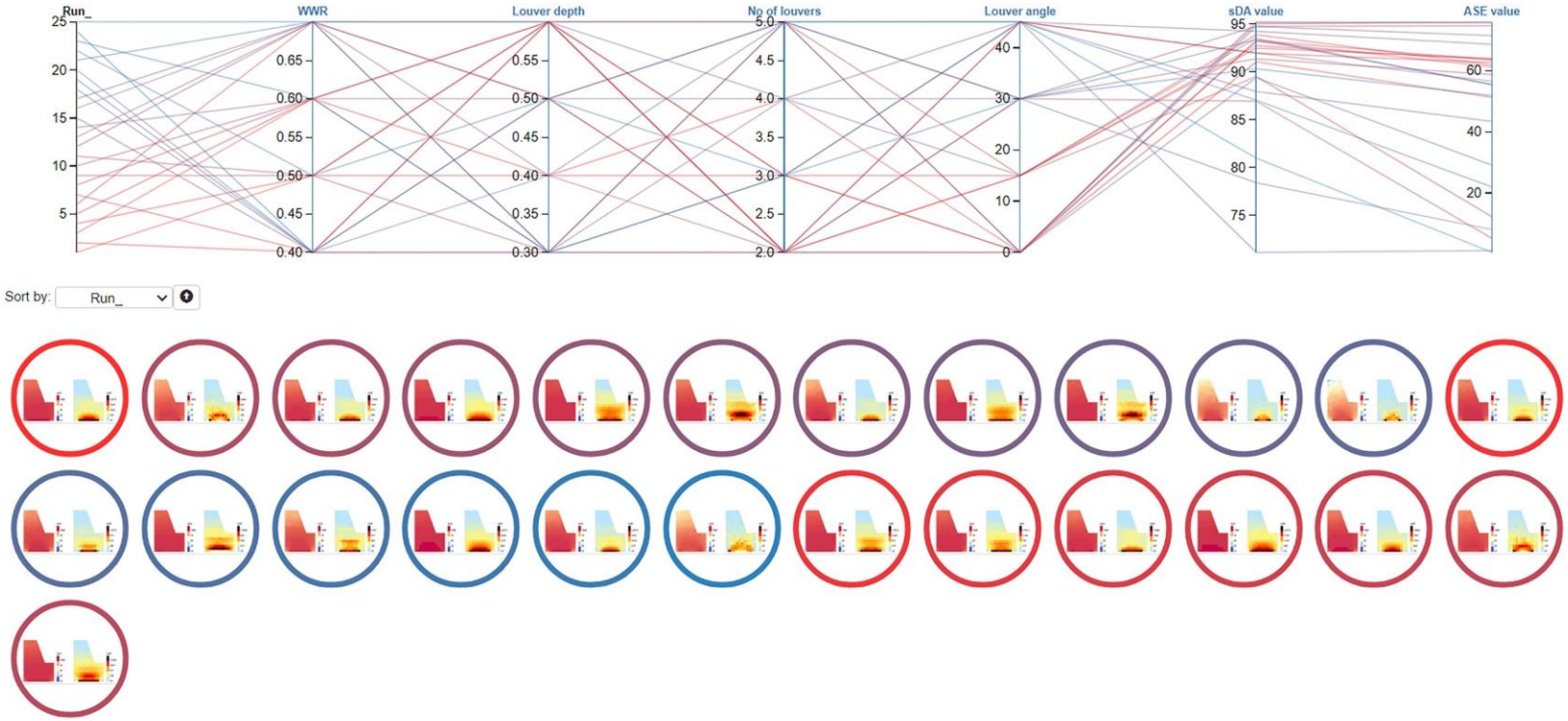
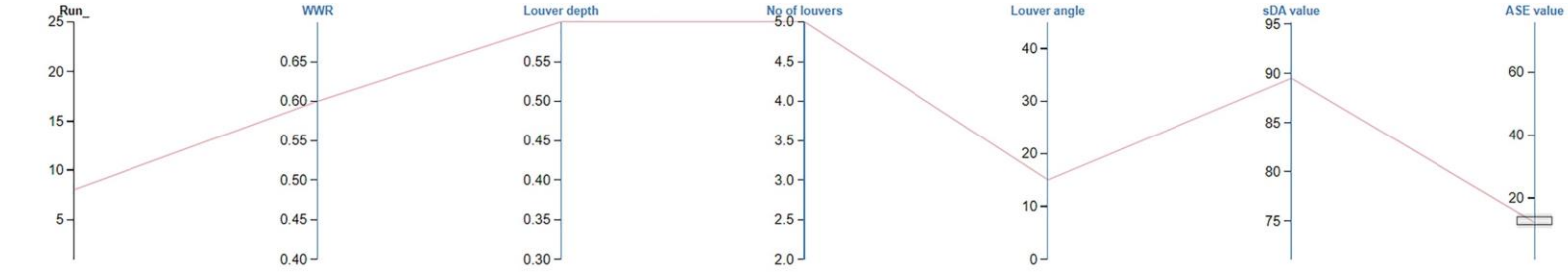
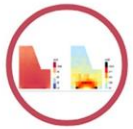


Figure 47: South Orientation – Comparative analysis of louvers iterations using Design Explorer





Run_	WWR	Louver depth	No of louvers	Louver angle	sDA value	ASE value	img	Rating	scid
8	0.6	0.6	5	15	89.499162	12.14655	Run_8.png	0	7

- Based on the comparative analysis **iteration no. 08** provides a better balance of sDA and ASE values as compared to other iterations.

Sensitivity Analysis:

- From the sensitivity analysis, it can be observed that No. of louvers as a parameter considerably impacts the sDA and ASE values followed by Louver angle.

Source	LogWorth	PValue
No of louvers	6.328	0.00000
Louver angle	3.528	0.00030
Louver depth	3.480	0.00033
WWR	2.804	0.00157

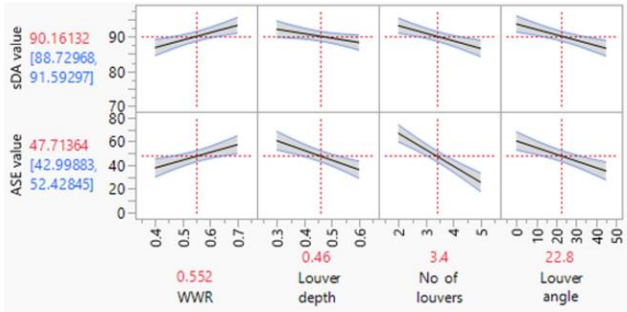


Figure 48: South Orientation – Selection of optimum louvers iteration

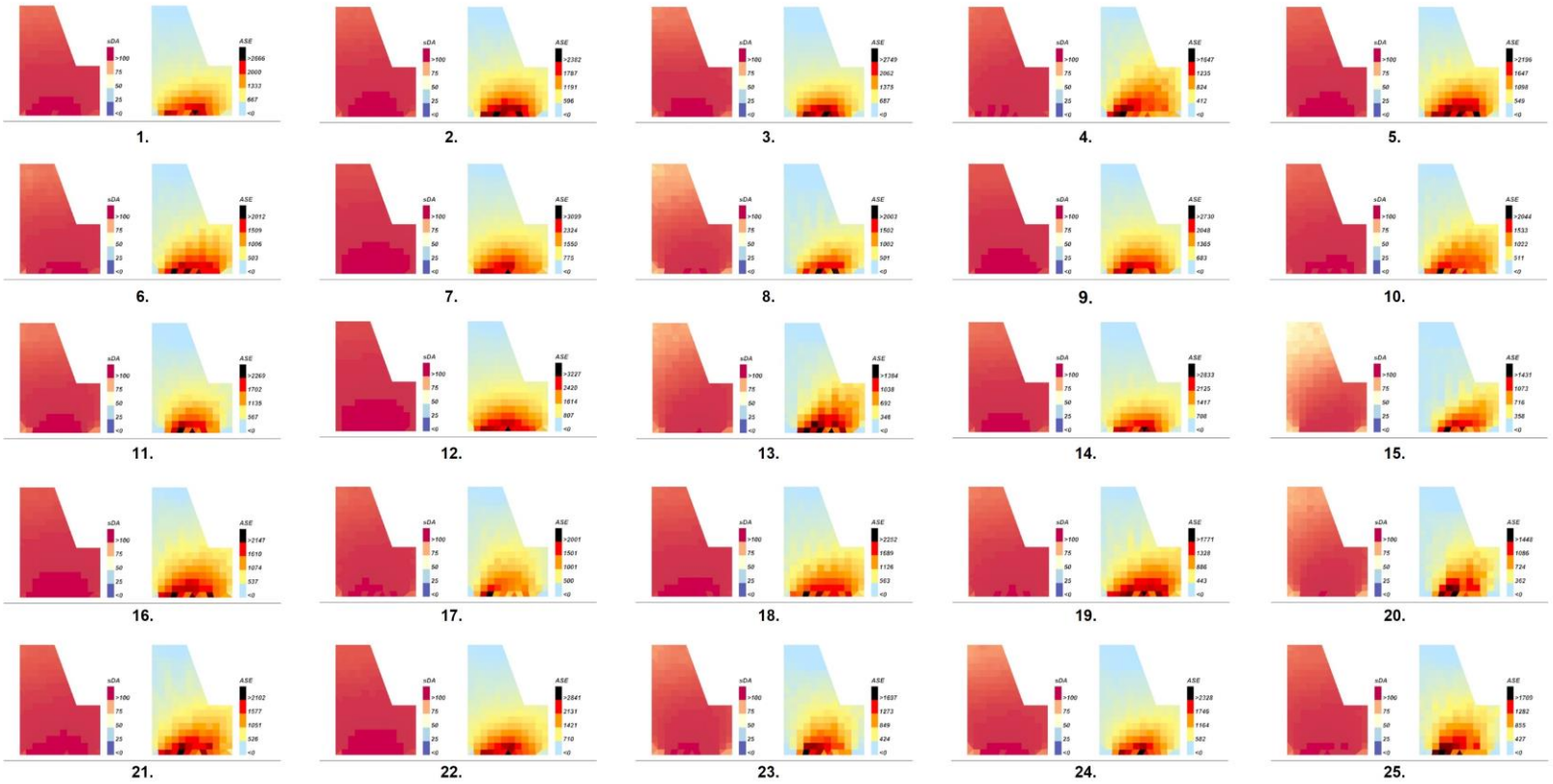


Figure 49: South Orientation - Daylighting optimization iterations using fins as shading mechanism

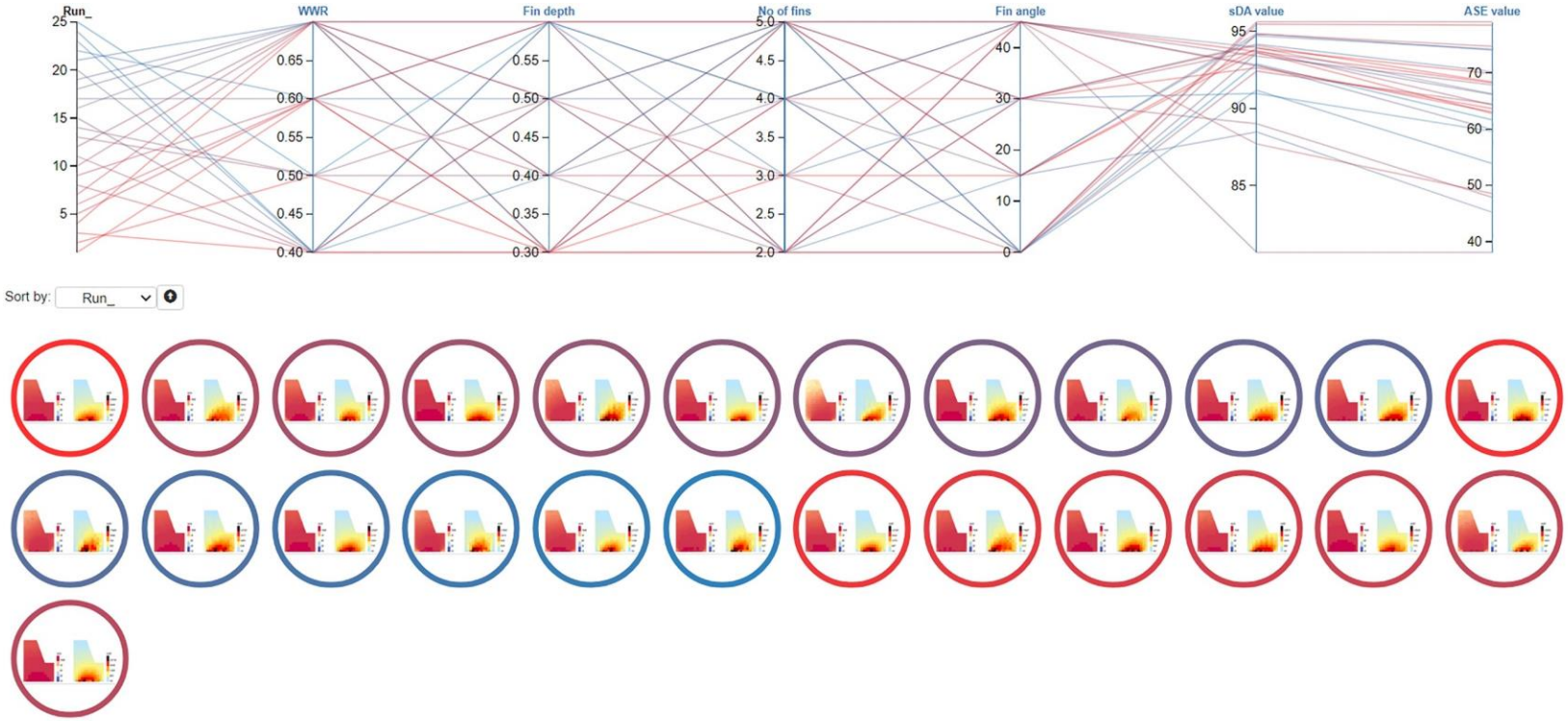
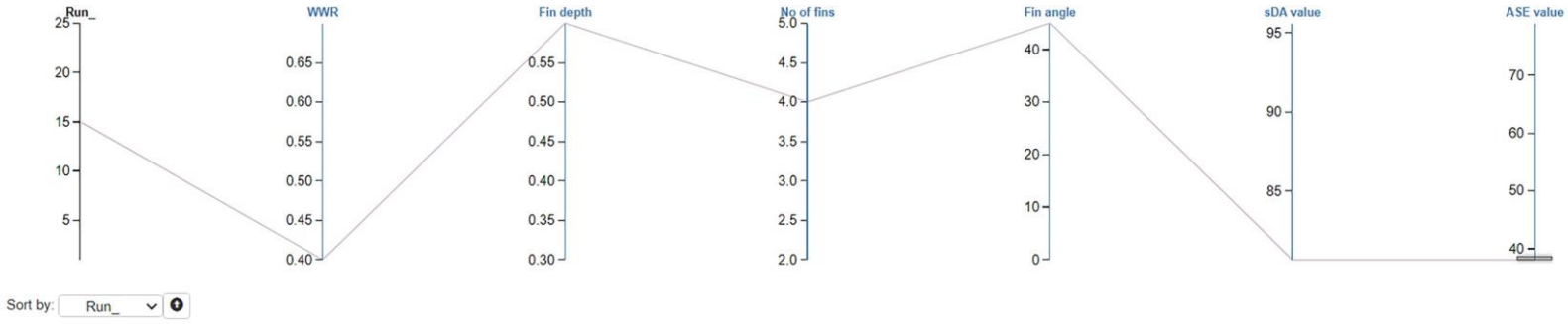


Figure 50: South Orientation – Comparative analysis of fins iterations using Design Explorer



Run_	WWR	Fin depth	No of fins	Fin angle	sDA value	ASE value	img	Rating	scid
15	0.4	0.6	4	45	80.672408	38.107643	Run_15.png	0	14

- Based on the comparative analysis **iteration no. 15** provides a better balance of sDA and ASE values as compared to other iterations.

Sensitivity Analysis:

- From the sensitivity analysis, it can be observed that window-to-wall ratio as a parameter considerably impacts the sDA and ASE values followed by No. of fins.

Source	LogWorth	PValue
WWR	7.699	0.00000
No of fins	5.979	0.00000
Fin angle	3.869	0.00014
Fin depth	3.232	0.00059

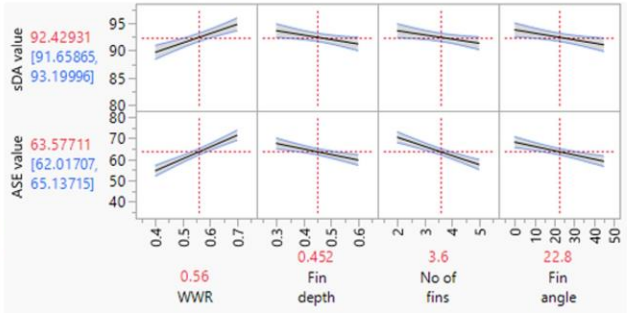
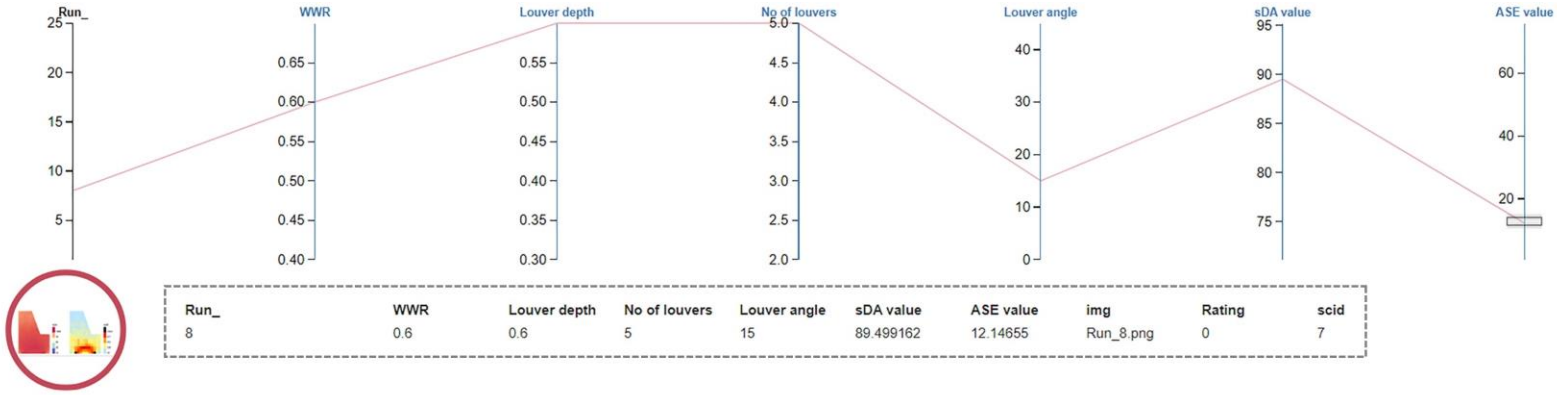
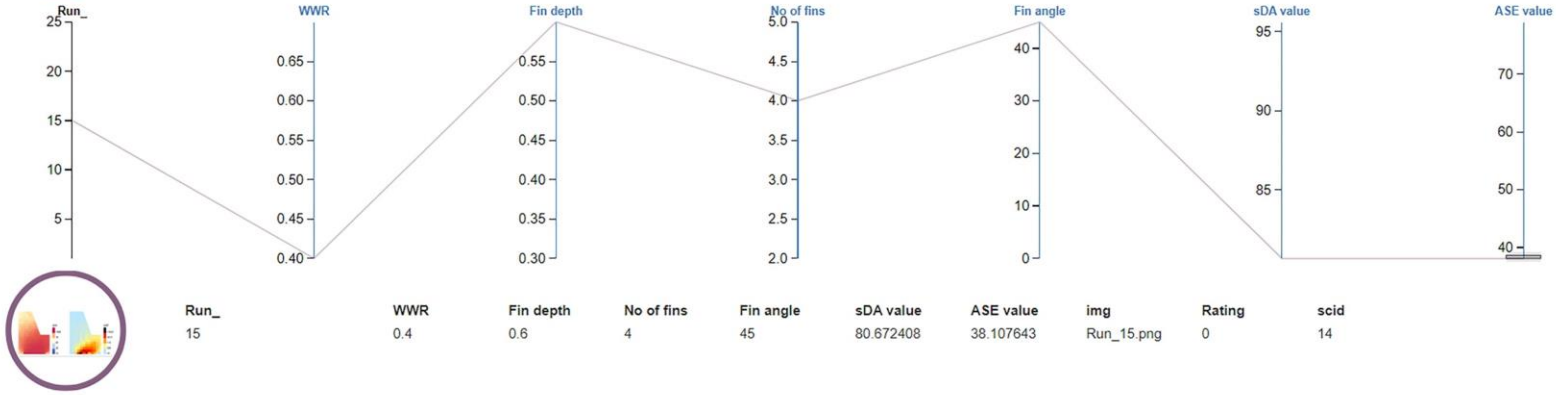


Figure 51: South Orientation – Selection of optimum fins iteration



Run_	WWR	Louver depth	No of louvers	Louver angle	sDA value	ASE value	img	Rating	scid
8	0.6	0.6	5	15	89.499162	12.14655	Run_8.png	0	7



Run_	WWR	Fin depth	No of fins	Fin angle	sDA value	ASE value	img	Rating	scid
15	0.4	0.6	4	45	80.672408	38.107643	Run_15.png	0	14

- After analyzing the results, it can be inferred that **louvers iteration in the South orientation provides a better balance between the sDA & ASE values compared to fins iteration.**

Figure 52: South Orientation – Comparative analysis of shortlisted louvers and fins iterations

South Orientation – Circadian rhythm analysis results

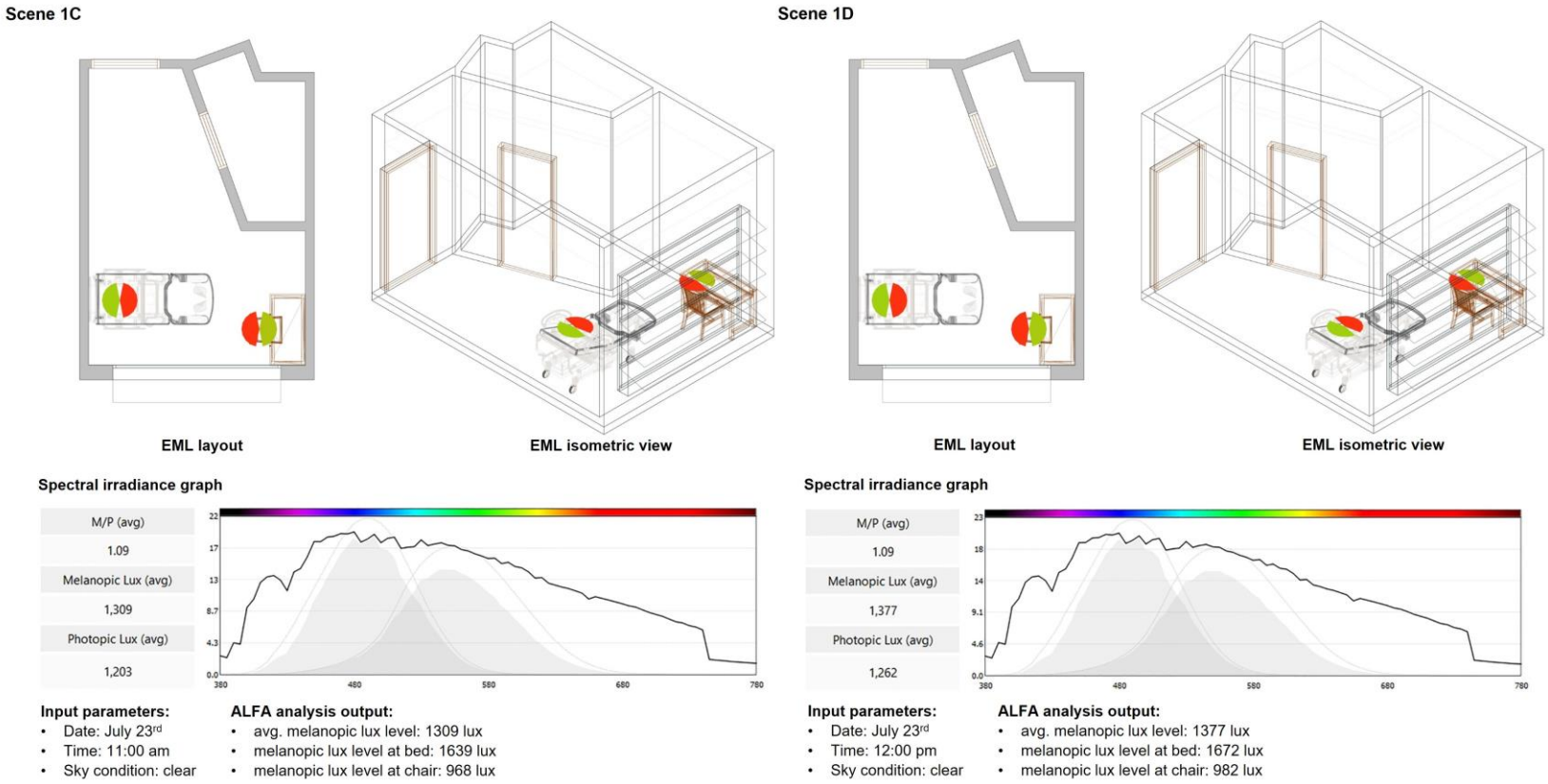


Figure 53: South Orientation – Circadian rhythm analysis Scene 1C and Scene 1D

Scene 1C: 11:00 am, clear sky | melanopic lux values: avg. – 1309 lux, bed – 1639 lux, chair – 968 lux

Scene 1D: 12:00 pm, clear sky | melanopic lux values: avg. – 1377 lux, bed – 1672 lux, chair – 982 lux

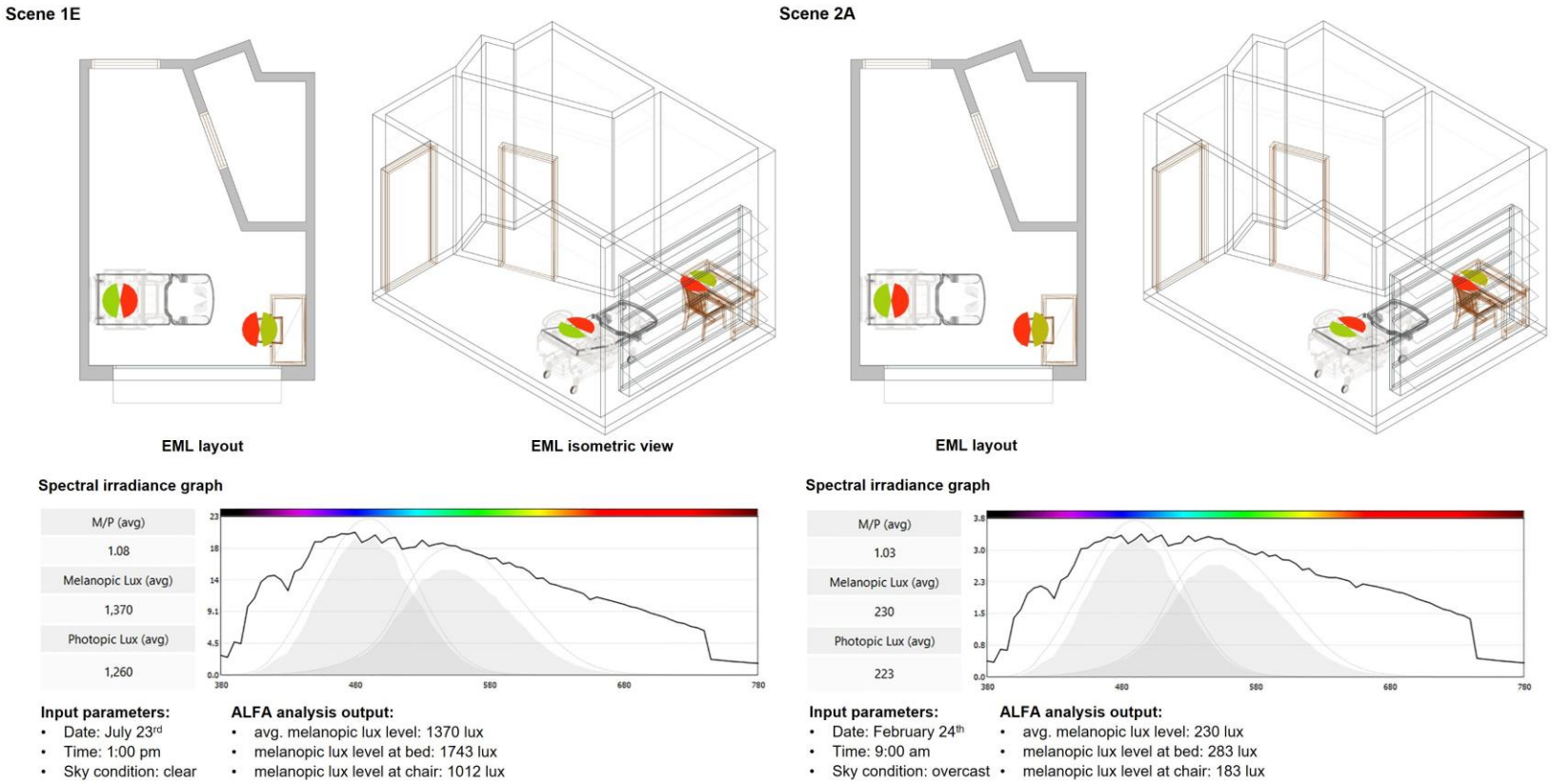


Figure 54: South Orientation – Circadian rhythm analysis Scene 1E and Scene 2A

Scene 1E: 1:00 pm, clear sky | melanopic lux values: avg. – 1370 lux, bed – 1743 lux, chair – 1012 lux

Scene 2A: 9:00 am, overcast sky | melanopic lux values: avg. – 230 lux, bed – 283 lux, chair – 183 lux

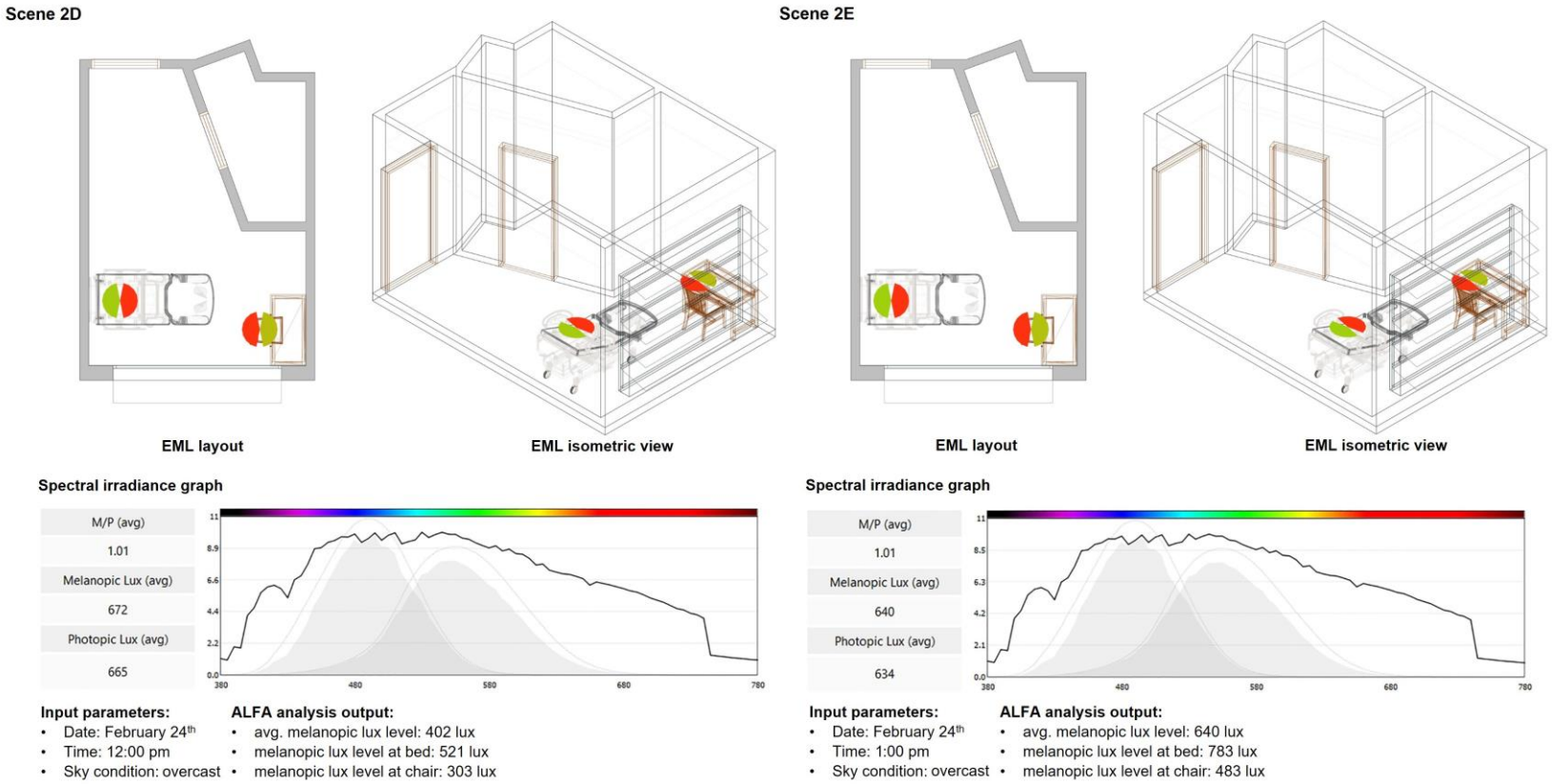


Figure 55: South Orientation – Circadian rhythm analysis Scene 2D and Scene 2E

Scene 2D: 12:00 pm, overcast sky | melanopic lux values: avg. – 402 lux, bed – 521 lux, chair – 303 lux

Scene 2E: 1:00 pm, overcast sky | melanopic lux values: avg. – 640 lux, bed – 783 lux, chair – 483 lux

East Orientation – Daylighting Optimization results

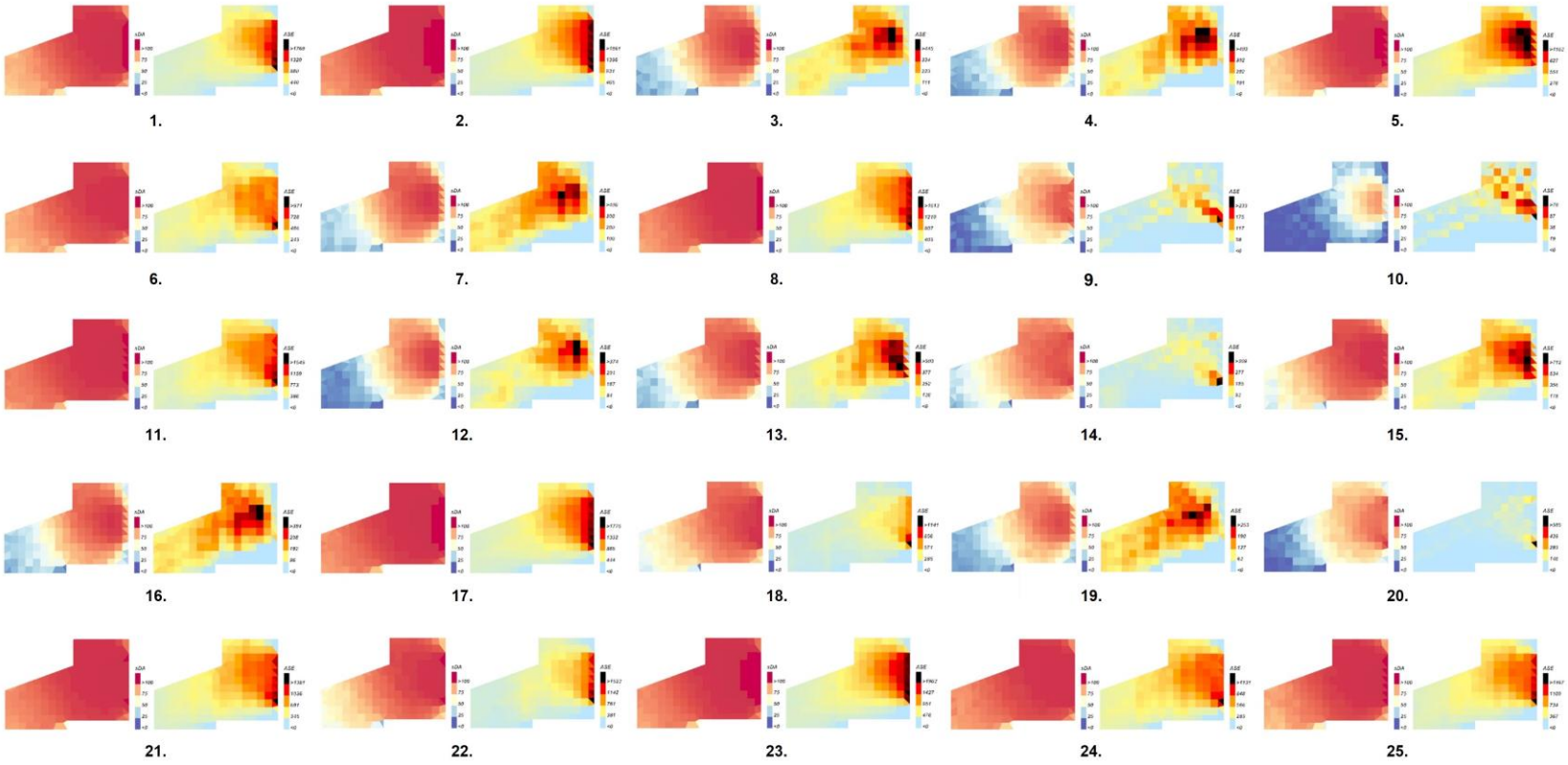


Figure 56: East Orientation - Daylighting optimization iterations using louvers as shading mechanism

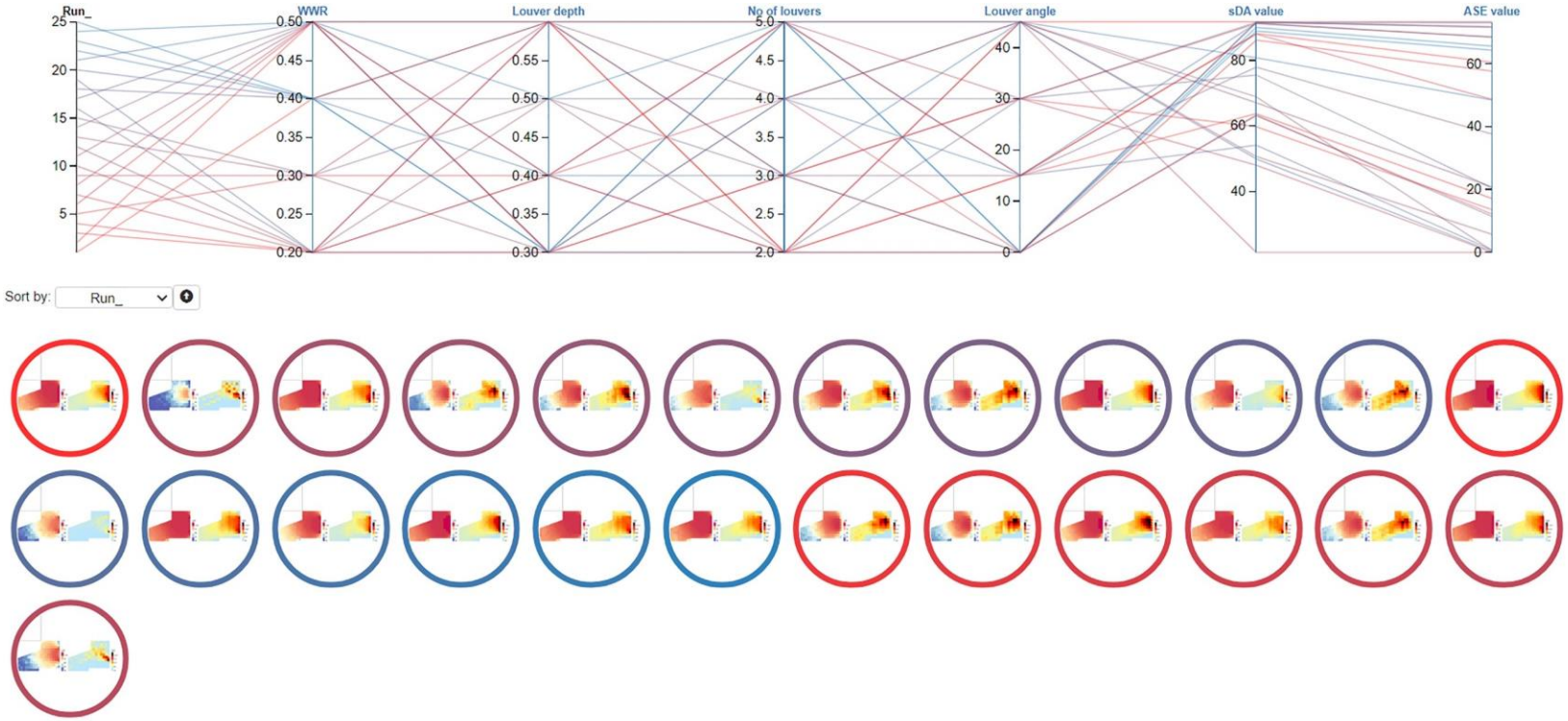
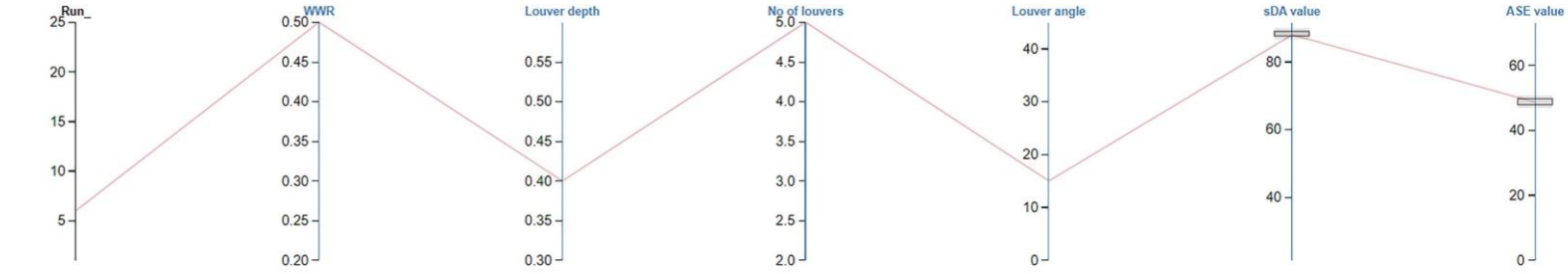


Figure 57: East Orientation - Comparative analysis of louvers iterations using Design Explorer



Run_	WWR	Louver depth	No of louvers	Louver angle	sDA value	ASE value	img	Rating	scid
6	0.5	0.4	5	15	87.919494	48.626656	Run_6.png	0	5

- Based on the comparative analysis **iteration no. 06** provides a better balance of sDA and ASE values as compared to other iterations.

- From the sensitivity analysis, it can be observed that window-to-wall ratio (WWR) as a parameter considerably impacts the sDA and ASE values followed by Louver angle.

Source	LogWorth	PValue
WWR	9.387	0.00000
Louver angle	5.652	0.00000
No of louvers	4.802	0.00002
Louver depth	3.688	0.00020

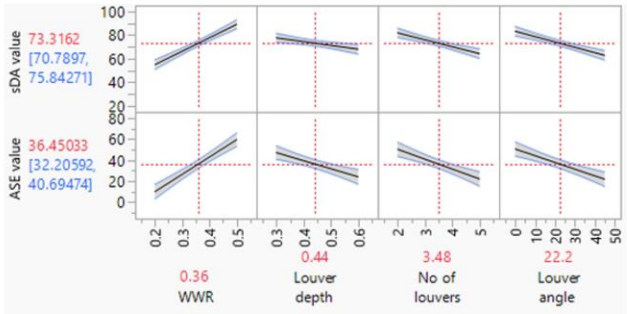


Figure 58: East Orientation - Selection of optimum louvers iteration

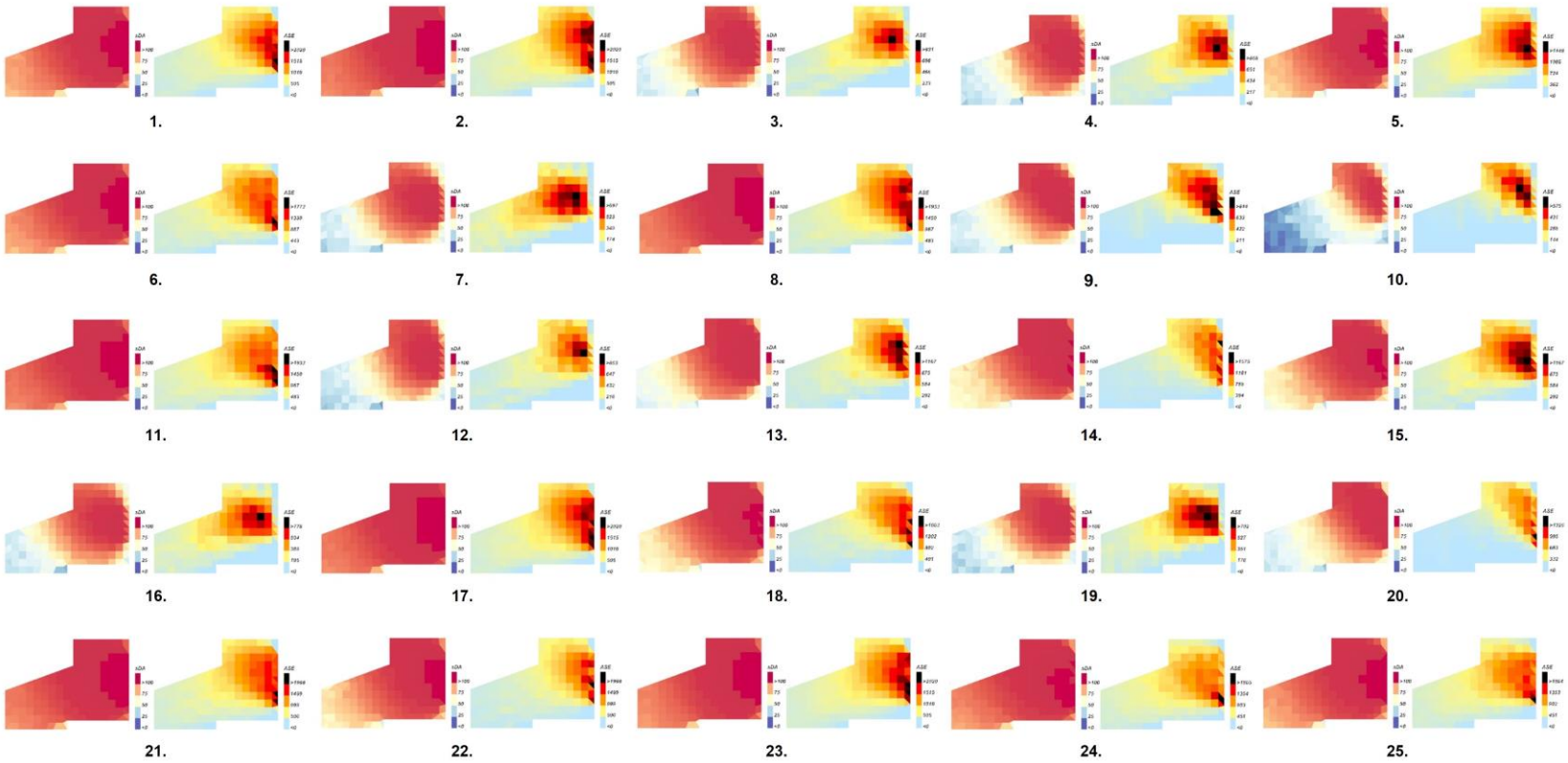


Figure 59: East Orientation - Daylighting optimization iterations using fins as shading mechanism

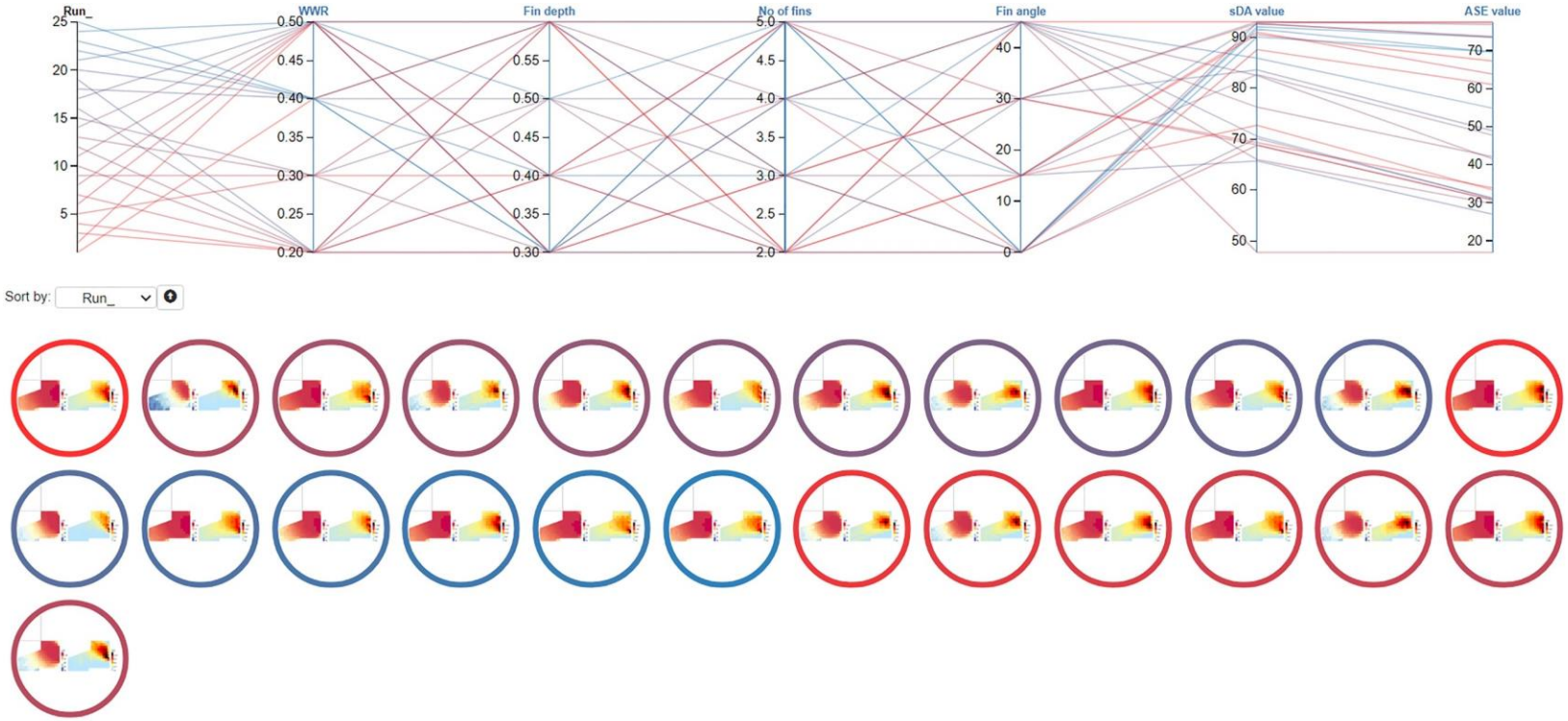
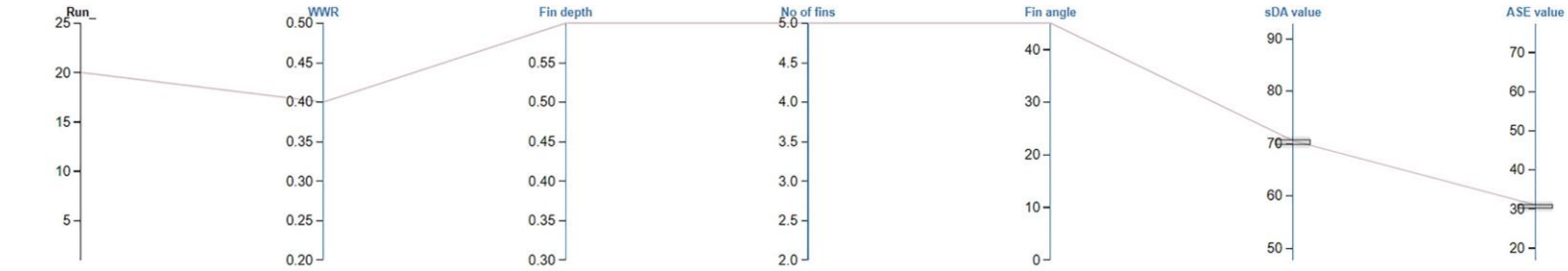


Figure 60: East Orientation - Comparative analysis of fins iterations using Design Explorer



Run_	WWR	Fin depth	No of fins	Fin angle	sDA value	ASE value	img	Rating	scid
20	0.4	0.6	5	45	70.510506	31.065488	Run_20.png	0	19

- Based on the comparative analysis **iteration no. 20** provides a better balance of sDA and ASE values as compared to other iterations.

Sensitivity Analysis:

- From the sensitivity analysis, it can be observed that window-to-wall ratio as a parameter considerably impacts the sDA and ASE values followed by No. of fins.

Source	LogWorth	PValue
WWR	13.090	0.00000
No of fins	6.254	0.00000
Fin angle	6.184	0.00000
Fin depth	4.576	0.00003

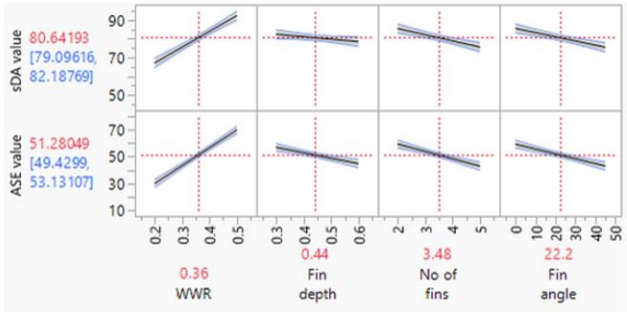
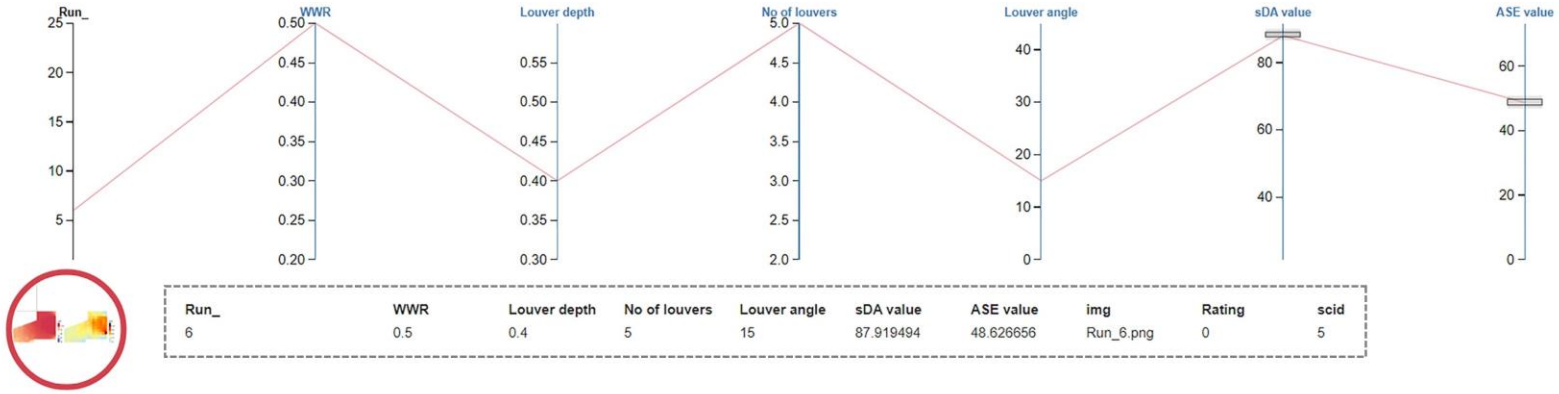
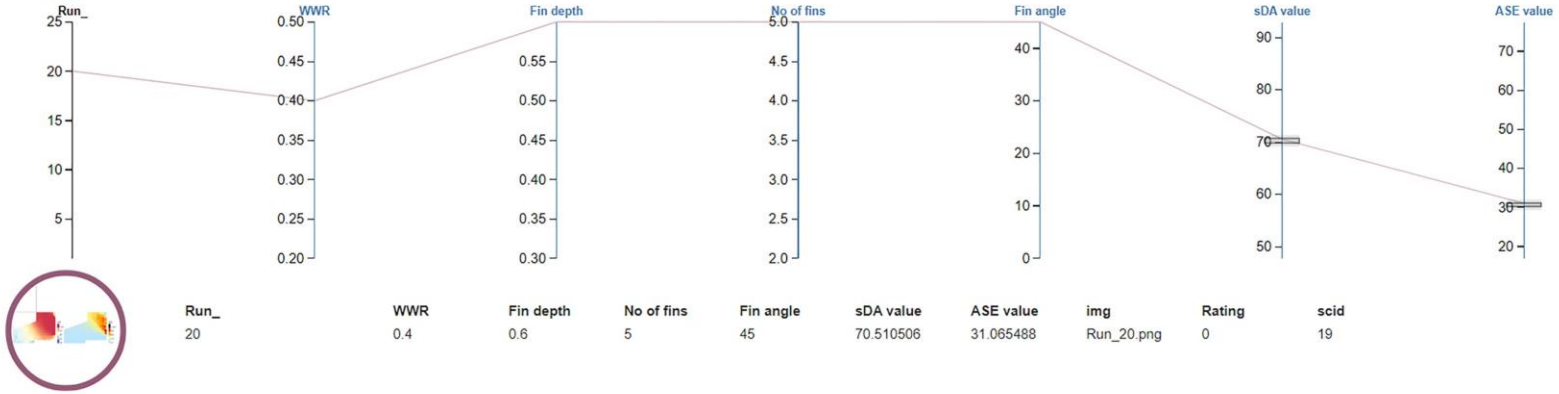


Figure 61: East Orientation – Selection of optimum fins iteration



Run_	WWR	Louver depth	No of louvers	Louver angle	sDA value	ASE value	img	Rating	scid
6	0.5	0.4	5	15	87.919494	48.626656	Run_6.png	0	5



Run_	WWR	Fin depth	No of fins	Fin angle	sDA value	ASE value	img	Rating	scid
20	0.4	0.6	5	45	70.510506	31.065488	Run_20.png	0	19

- After analyzing the results, it can be inferred that **louvers iteration in the East orientation provides a better balance between the sDA & ASE values compared to fins iteration.**

Figure 62: East Orientation – Comparative analysis of shortlisted louvers and fins iterations

East Orientation – Circadian rhythm analysis results

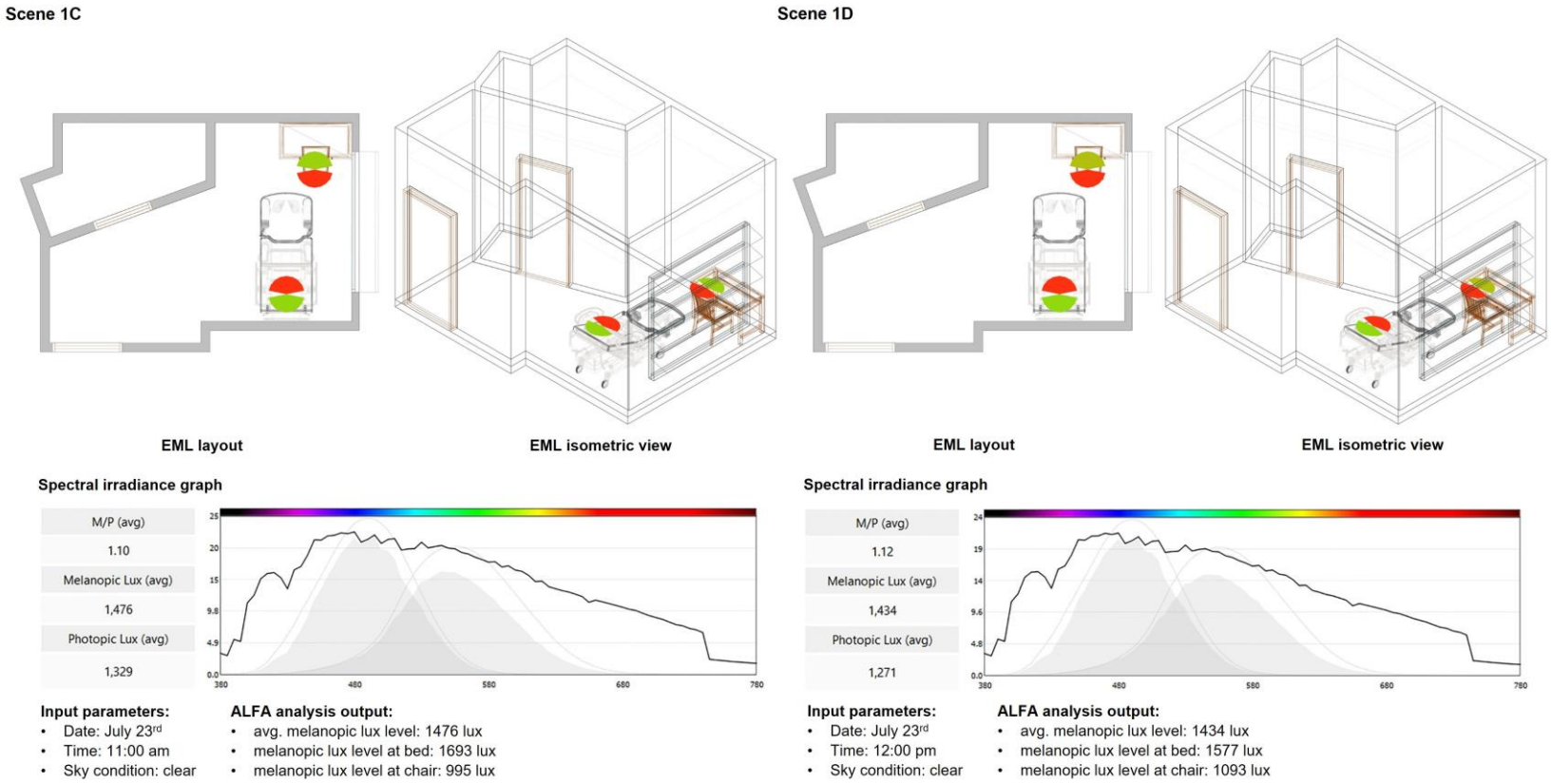


Figure 63: East Orientation – Circadian rhythm analysis Scene 1C and Scene 1D

Scene 1C: 11:00 am, clear sky | melanopic lux values: avg. – 1476 lux, bed – 1693 lux, chair – 995 lux

Scene 1D: 12:00 pm, clear sky | melanopic lux values: avg. – 1434 lux, bed – 1577 lux, chair – 1093 lux

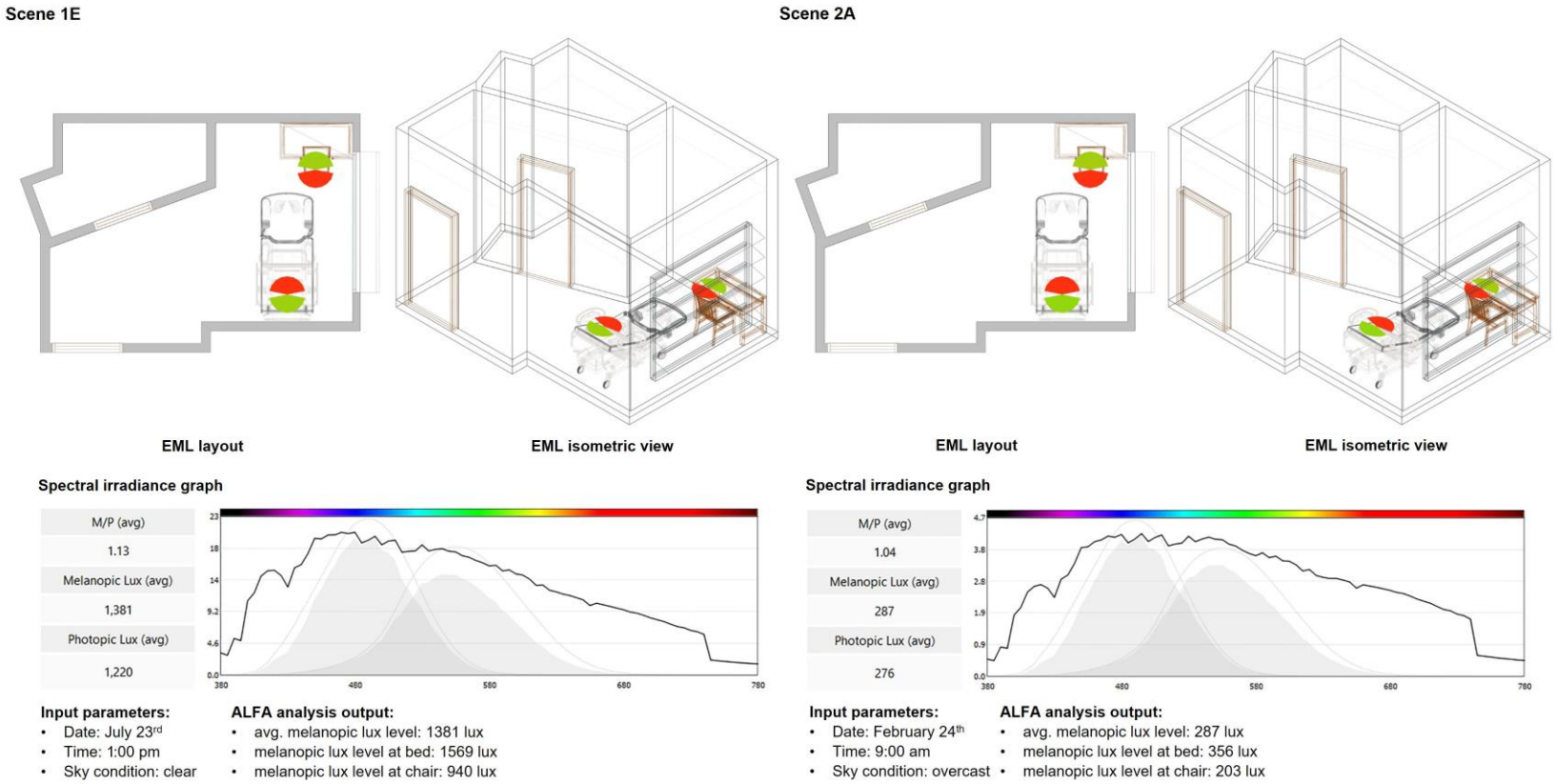


Figure 64: East Orientation – Circadian rhythm analysis Scene 1E and Scene 2A

Scene 1E: 1:00 pm, clear sky | melanopic lux values: avg. – 1381 lux, bed – 1569 lux, chair – 940 lux

Scene 2A: 9:00 am, overcast sky | melanopic lux values: avg. – 287 lux, bed – 356 lux, chair – 203 lux

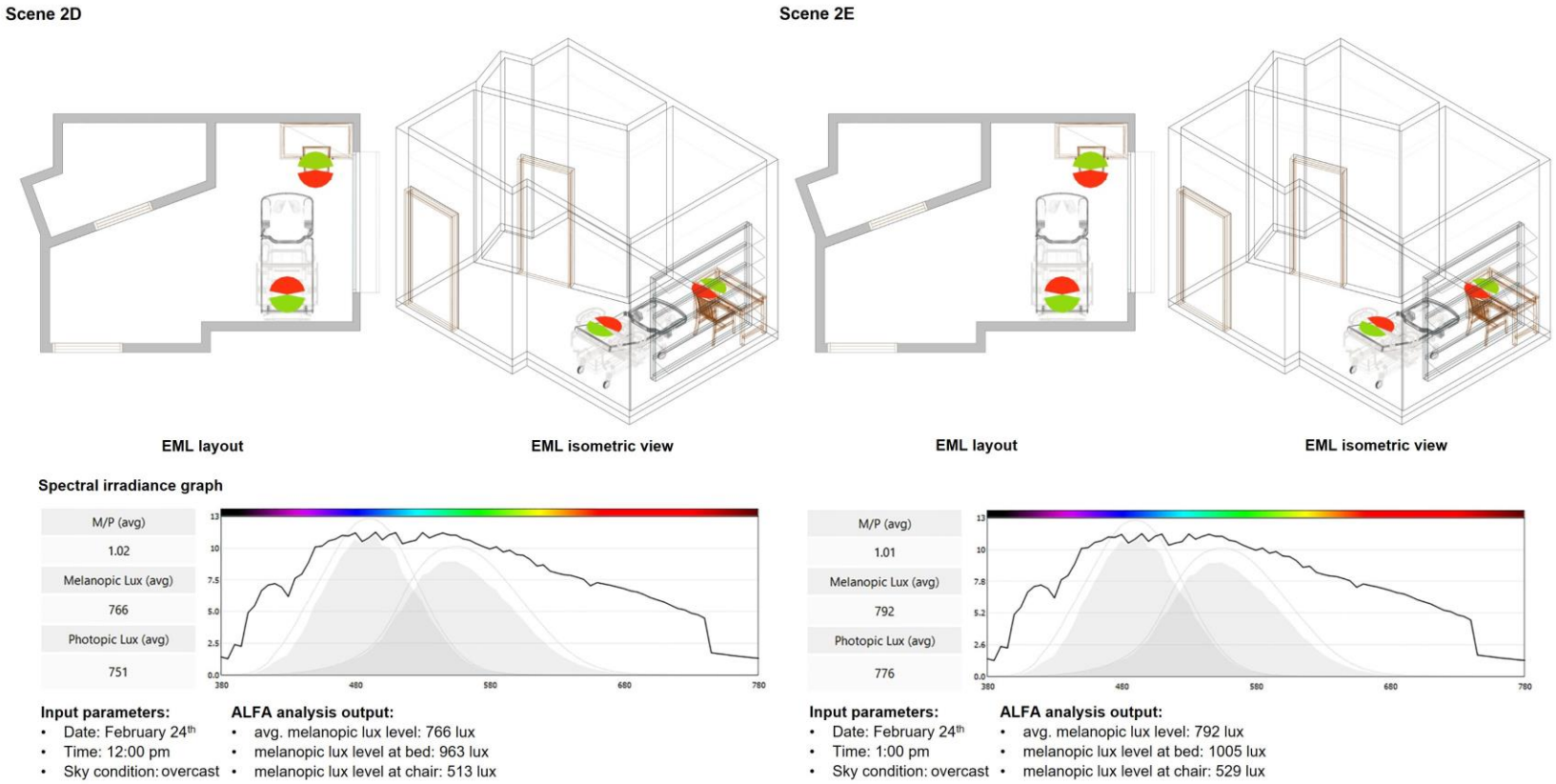


Figure 65: East Orientation – Circadian rhythm analysis Scene 2D and Scene 2E

Scene 2D: 12:00 pm, overcast sky | melanopic lux values: avg. – 766 lux, bed – 963 lux, chair – 513 lux

Scene 2E: 1:00 pm, overcast sky | melanopic lux values: avg. – 792 lux, bed – 1005 lux, chair – 529 lux

West Orientation – Daylighting Optimization results

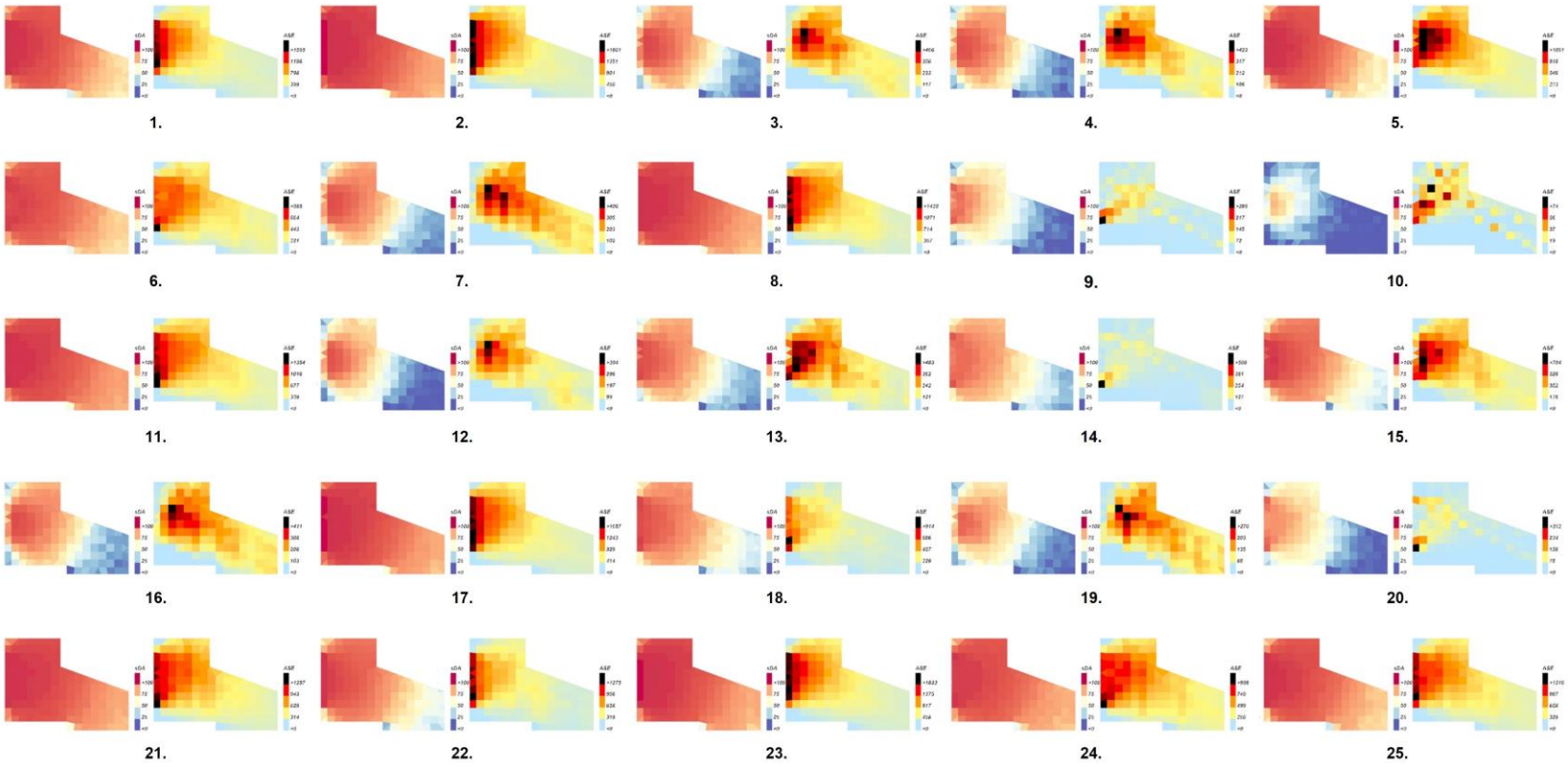


Figure 66: West Orientation - Daylighting optimization iterations using louvers as shading mechanism

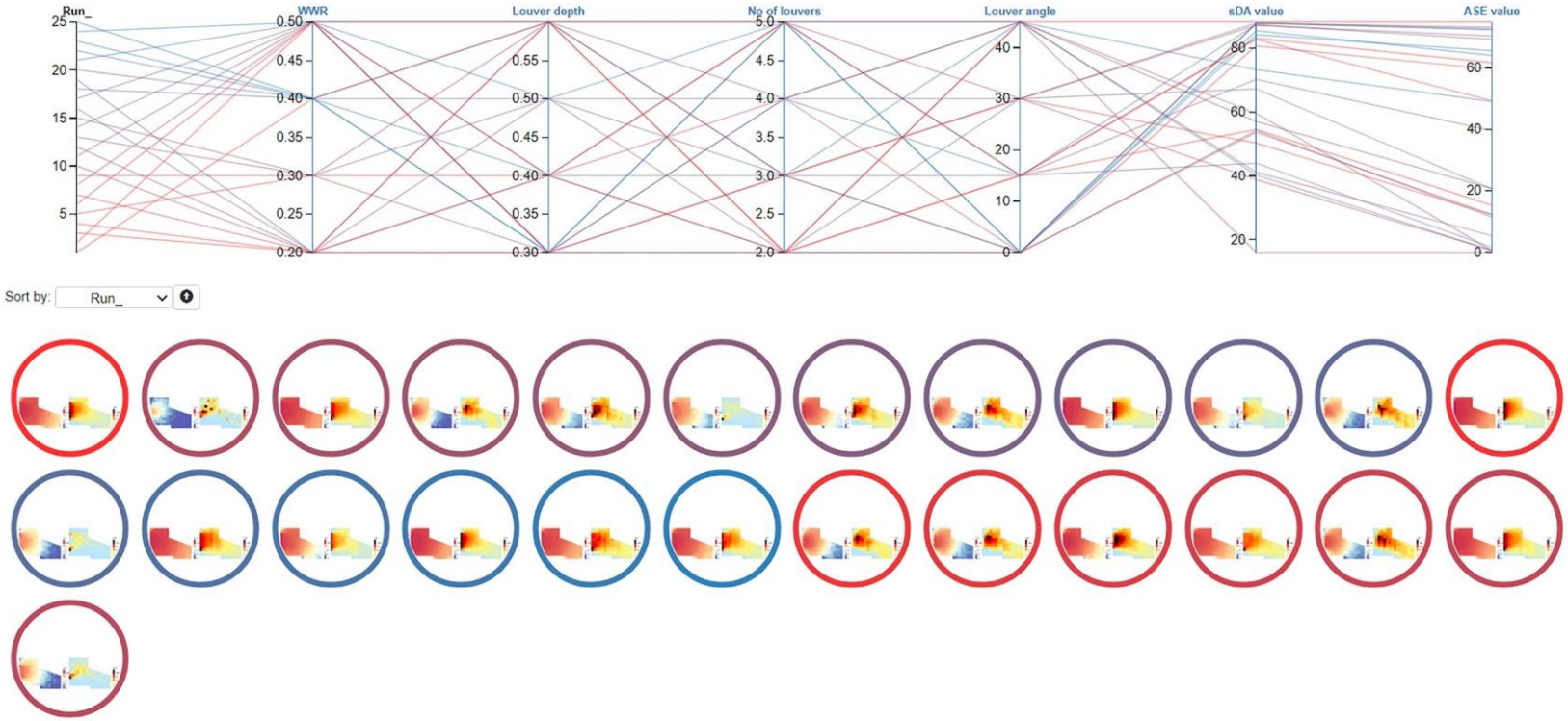
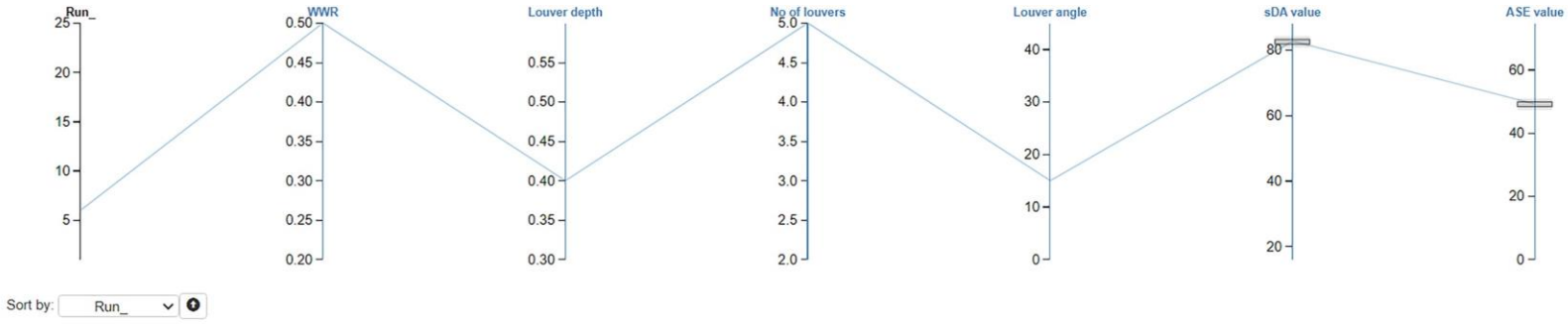


Figure 67: West Orientation - Comparative analysis of louvers iterations using Design Explorer



Run_	WWR	Louver depth	No of louvers	Louver angle	sDA value	ASE value	img	Rating	scid
6	0.5	0.4	5	15	82.580848	49.126248	Run_6.png	0	5

- Based on the comparative analysis **iteration no. 06** provides a better balance of sDA and ASE values as compared to other iterations.

Sensitivity Analysis:

- From the sensitivity analysis, it can be observed that window-to-wall ratio (WWR) as a parameter considerably impacts the sDA and ASE values followed by Louver angle.

Source	LogWorth	PValue
WWR	11.345	0.00000
Louver angle	7.123	0.00000
No of louvers	6.097	0.00000
Louver depth	3.644	0.00023

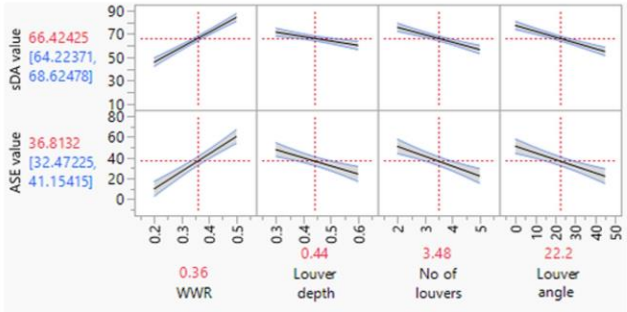


Figure 68: West Orientation - Selection of optimum louvers iteration

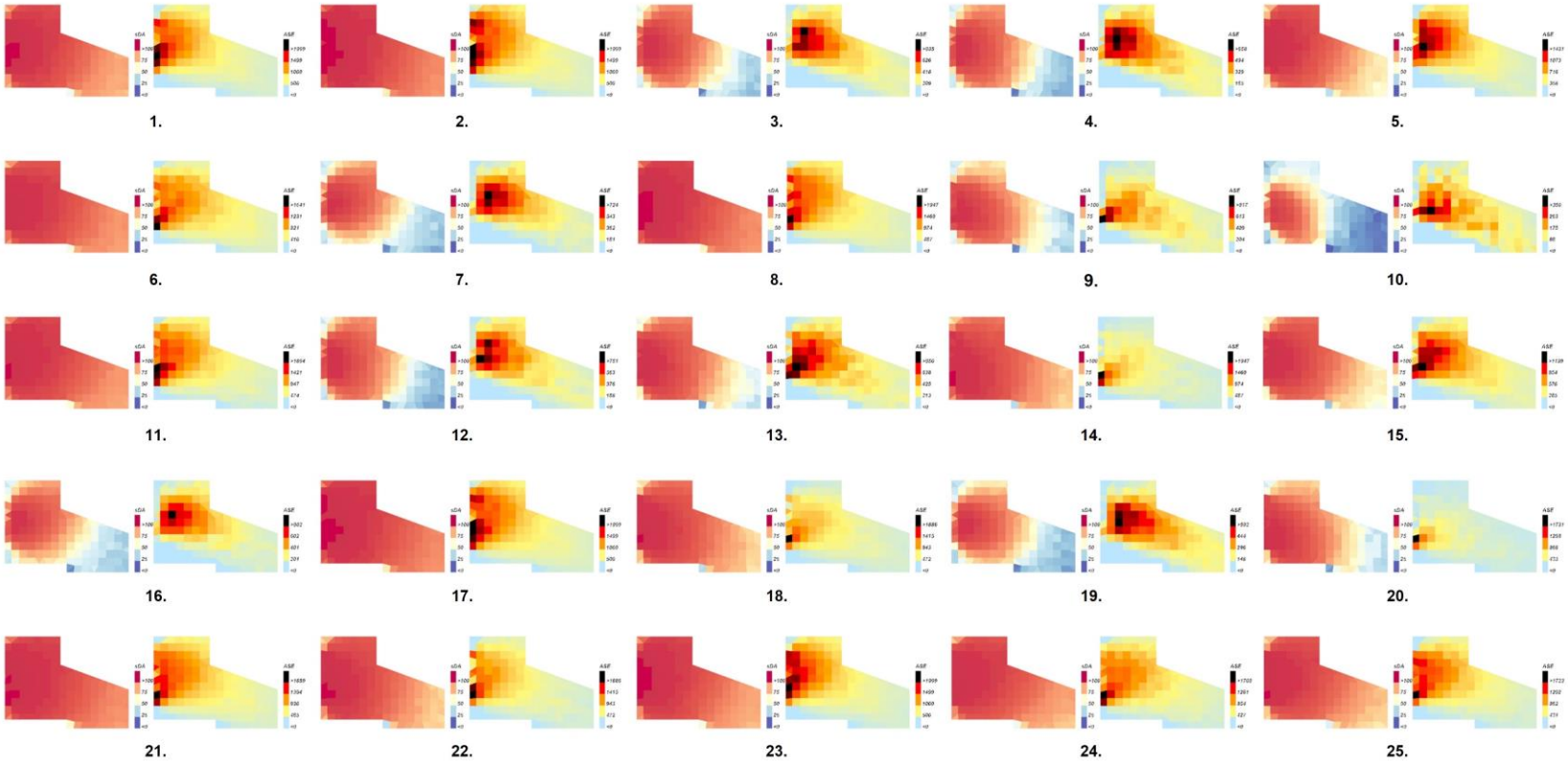


Figure 69: West Orientation - Daylighting optimization iterations using fins as shading mechanism

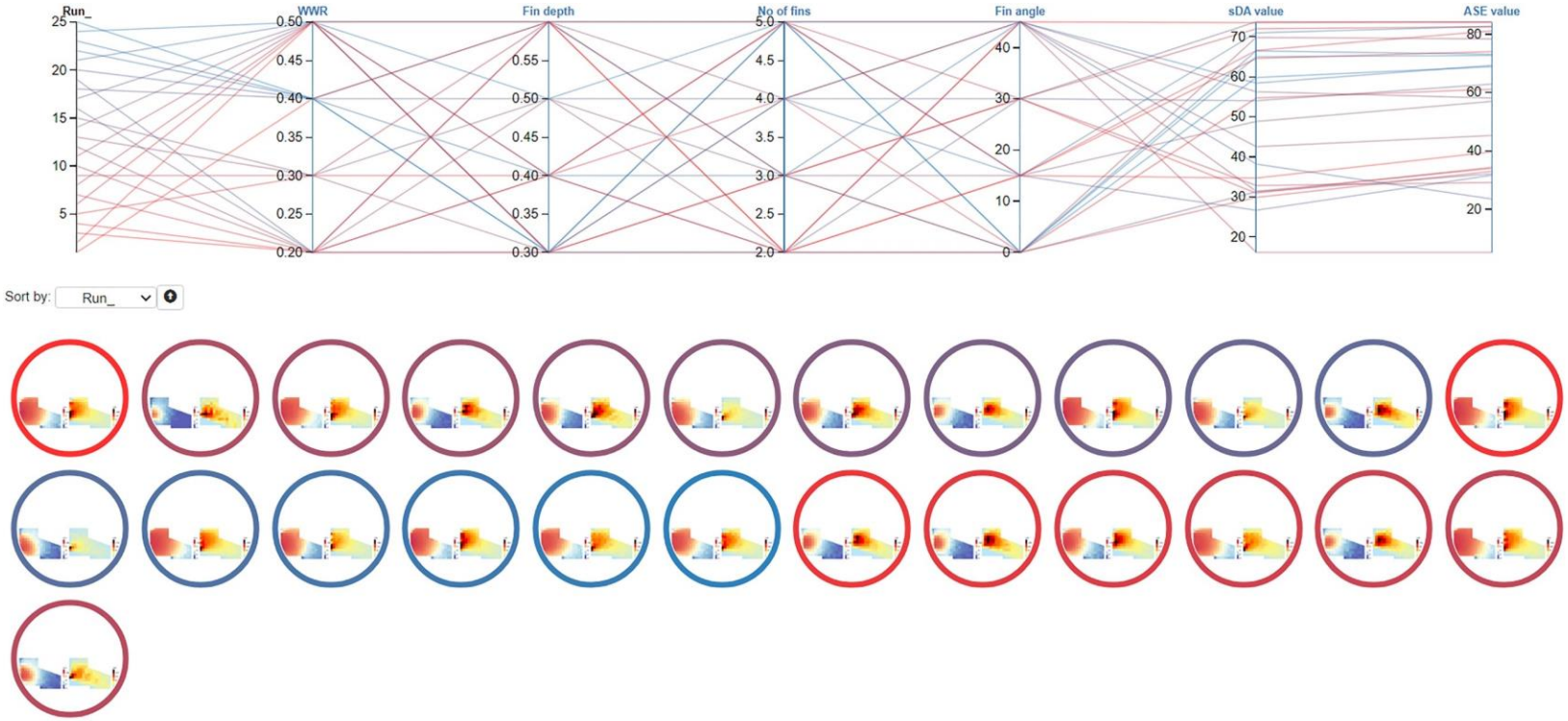
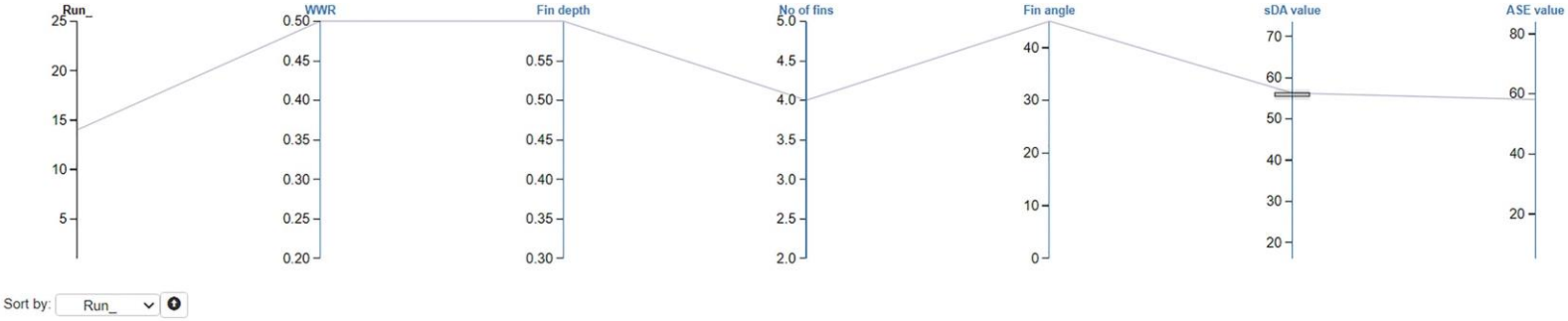


Figure 70: West Orientation – Comparative analysis of fins iterations using Design Explorer



Run_	WWR	Fin depth	No of fins	Fin angle	sDA value	ASE value	img	Rating	scid
14	0.5	0.6	4	45	56.216303	58.053828	Run_14.png	0	13

- Based on the comparative analysis **iteration no. 14** provides a better balance of sDA and ASE values as compared to other iterations.

Sensitivity Analysis:

- From the sensitivity analysis, it can be observed that window-to-wall ratio as a parameter considerably impacts the sDA and ASE values followed by No. of fins.

Source	LogWorth	PValue
WWR	10.997	0.00000
No of fins	4.745	0.00002
Fin angle	3.286	0.00052
Fin depth	2.616	0.00242

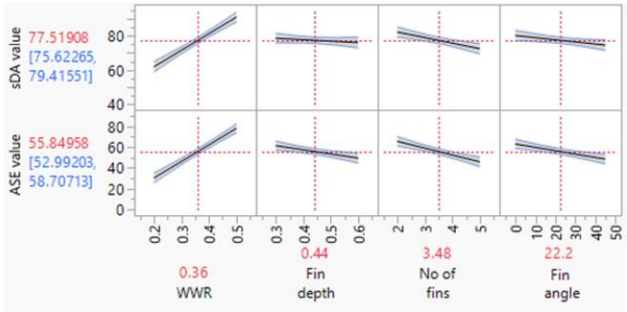
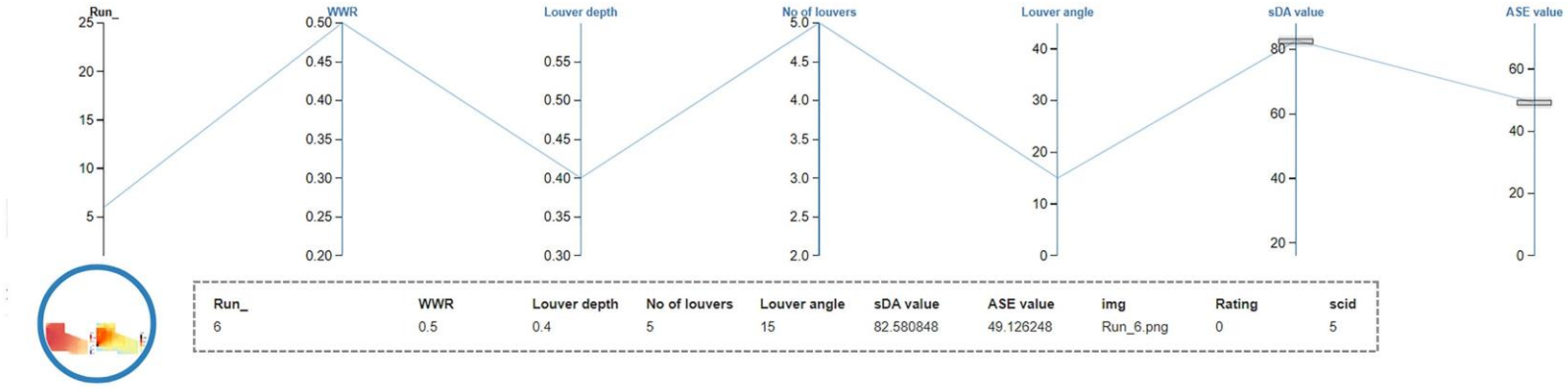
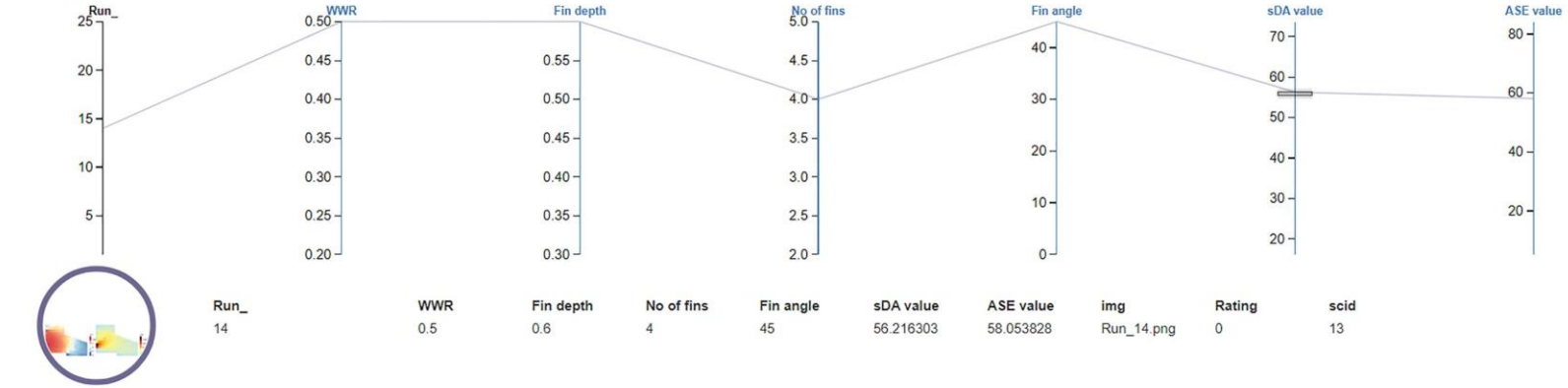


Figure 71: West Orientation – Selection of optimum fins iteration



Run_	WWR	Louver depth	No of louvers	Louver angle	sDA value	ASE value	img	Rating	scid
6	0.5	0.4	5	15	82.580848	49.126248	Run_6.png	0	5



Run_	WWR	Fin depth	No of fins	Fin angle	sDA value	ASE value	img	Rating	scid
14	0.5	0.6	4	45	56.216303	58.053828	Run_14.png	0	13

- After analyzing the results, it can be inferred that **louvers iteration in the West orientation provides a better balance between the sDA & ASE values compared to fins iteration.**

Figure 72: West Orientation – Comparative analysis of shortlisted louvers and fins iterations

West Orientation – Circadian rhythm results

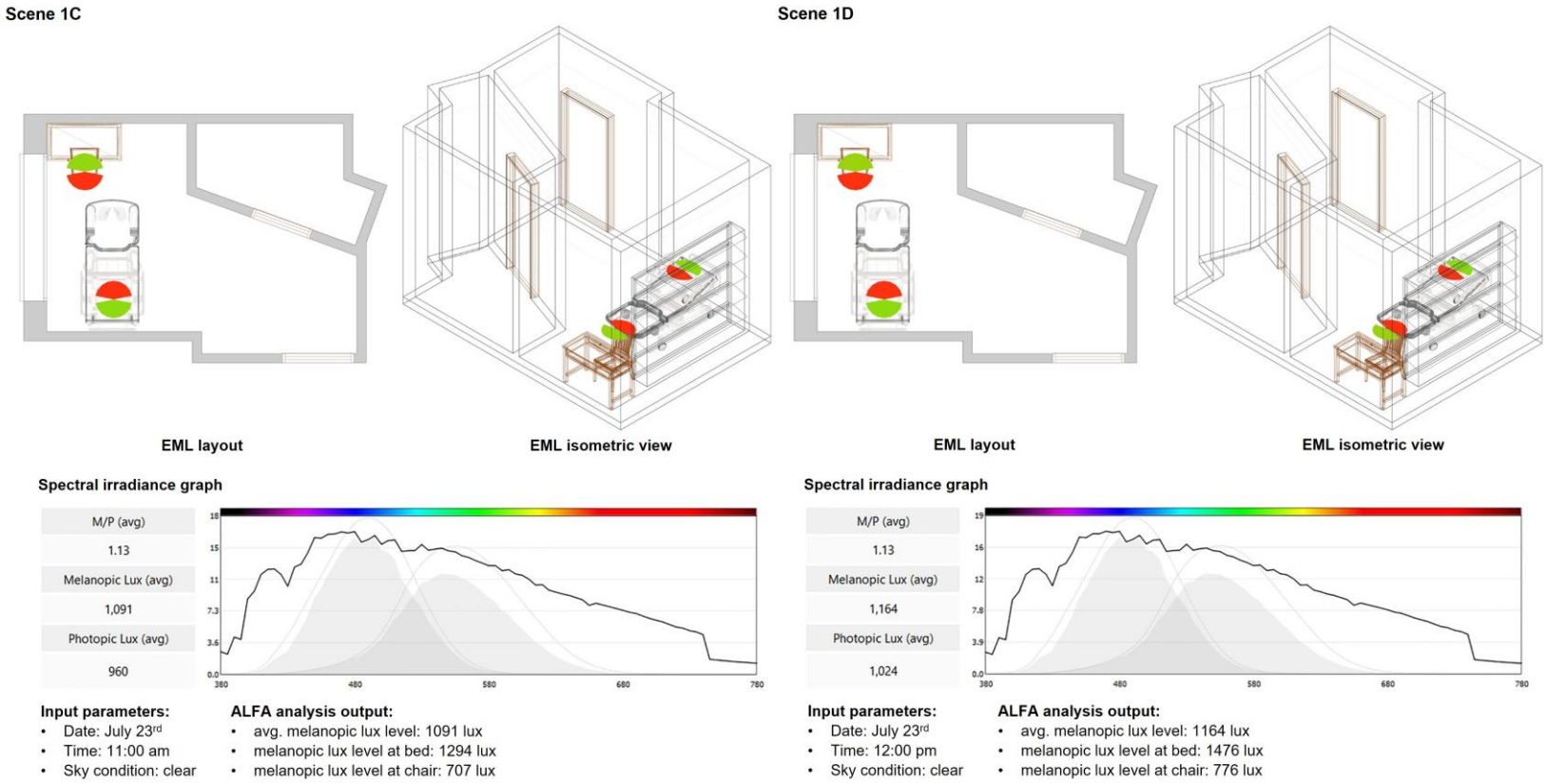


Figure 73: West Orientation – Circadian rhythm analysis Scene 1C and Scene 1D

Scene 1C: 11:00 am, clear sky | melanopic lux values: avg. – 1091 lux, bed – 1294 lux, chair – 707 lux

Scene 1D: 12:00 pm, overcast sky | melanopic lux values: avg. – 1164 lux, bed – 1476 lux, chair – 776 lux

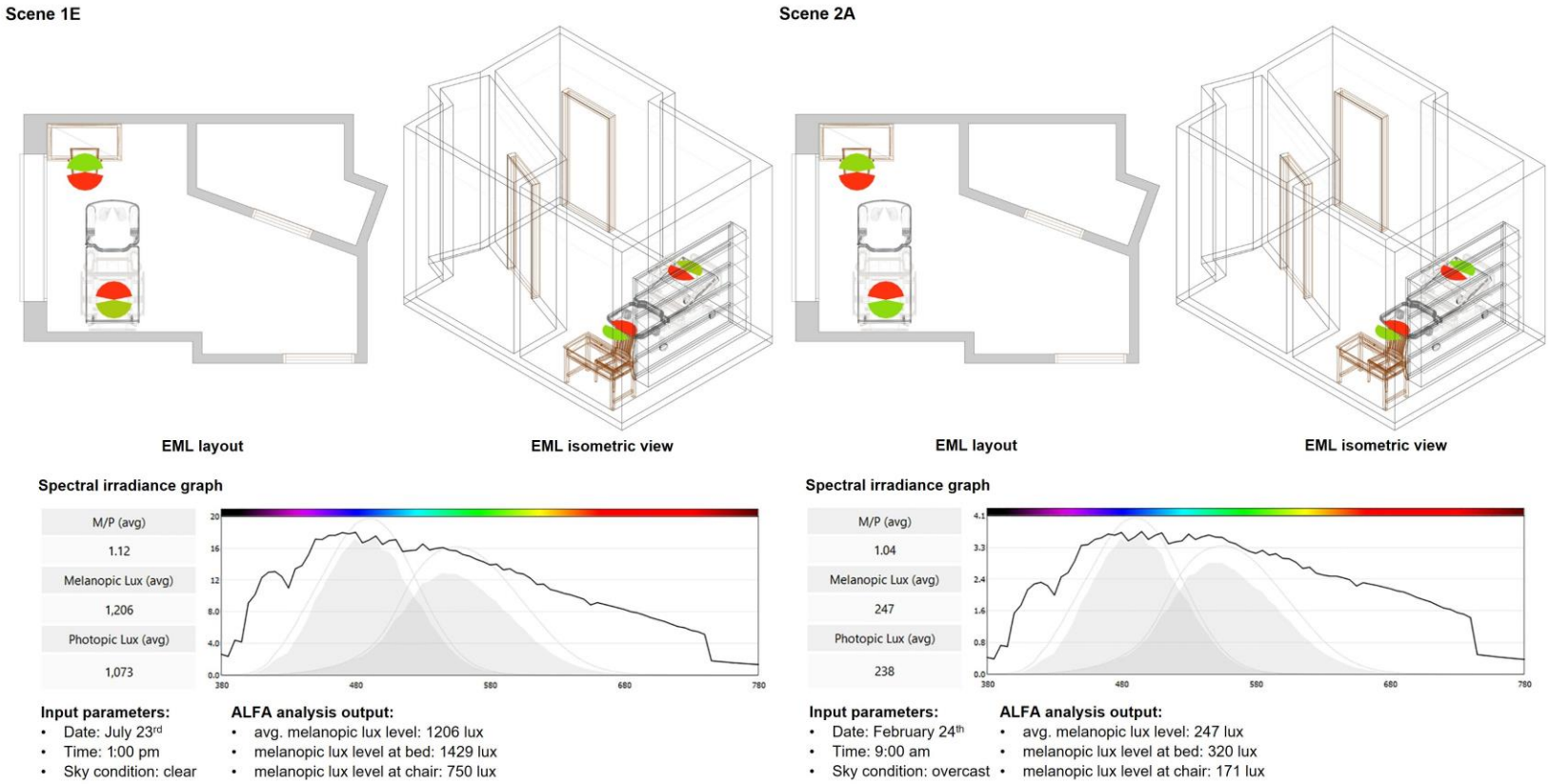


Figure 74: West Orientation – Circadian rhythm analysis Scene 1E and Scene

Scene 1E: 1:00 pm, clear sky | melanopic lux values: avg. – 1206 lux, bed – 1429 lux, chair – 750 lux

Scene 2A: 9:00 am, overcast sky | melanopic lux values: avg. – 247 lux, bed – 320 lux, chair – 171 lux

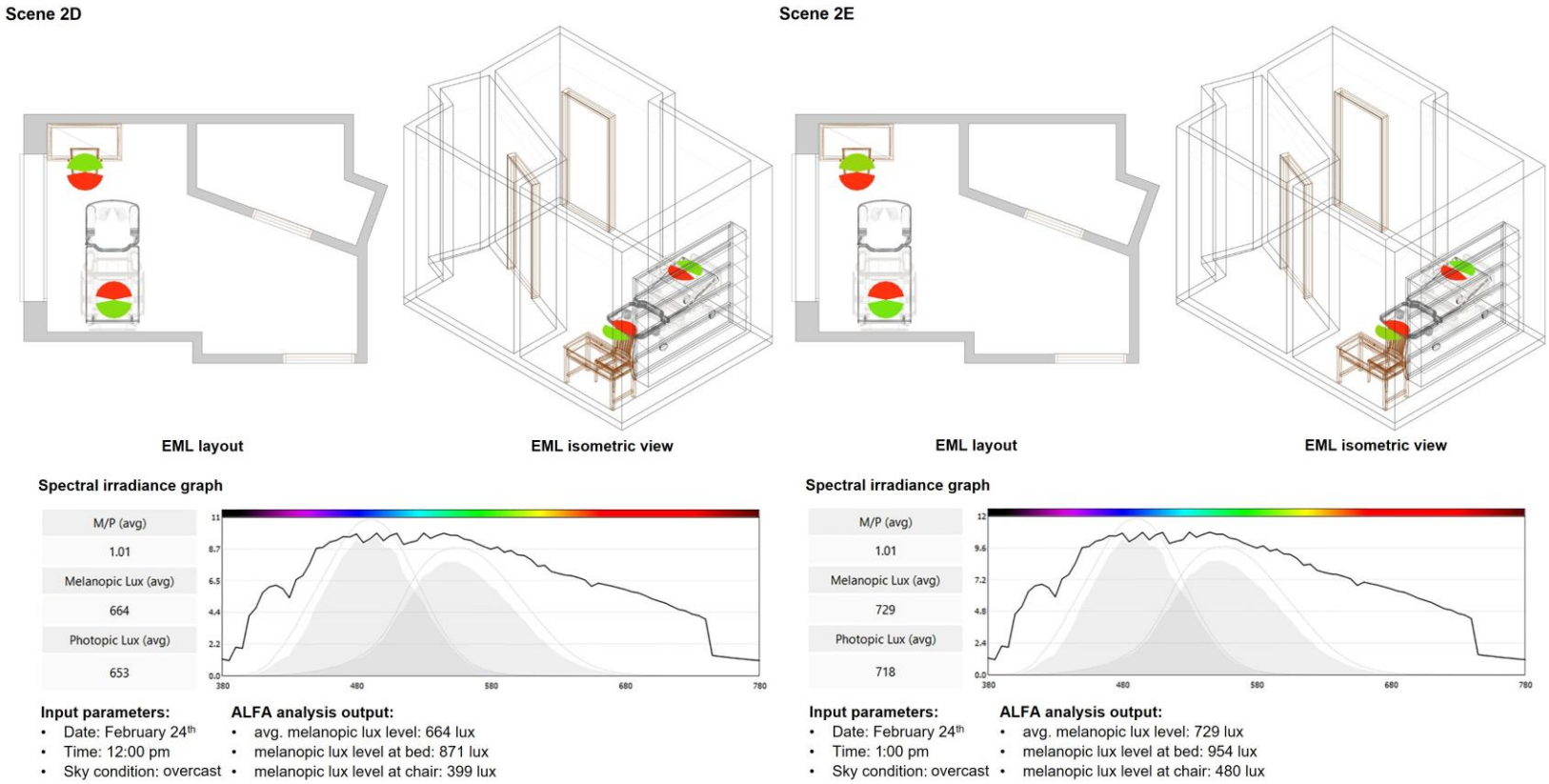


Figure 75: West Orientation – Circadian rhythm analysis Scene 2D and Scene 2E

Scene 2D: 12:00 pm, overcast sky | melanopic lux values: avg. – 664 lux, bed – 871 lux, chair – 399 lux

Scene 2E: 1:00 pm, overcast sky | melanopic lux values: avg. – 729 lux, bed – 954 lux, chair – 480 lux

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