A Biophilic Approach for Optimizing Daylighting Performance and Views-Out in Intensive Care Units Using Combined Light Shelf.

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Abstract

The application of biophilic design metrics in healthcare has positive impact on enhancing users' health and emotional wellbeing. Where, biophilic design elements especially daylighting and the views-out accelerate patients' recovery, decrease patients', family and staff stress and depression, and also increase patients' wellbeing (Watts, 2017). So, these metrics should be considered from the beginning in the design of intensive care units (ICUs), to promote patients' and staff's mood and health (Victoria. Department of Human Services).

This research aims at identifying the optimum design of parametric combined light shelf that will be installed over ICU patient room southern oriented window, located in Cairo, Egypt, considering the two biophilic design metrics performances, which are daylighting and the views-out. The main goal was to ensure adequate daylighting performance without discomfort glare inside the room, while maintaining patients' optimum upper vertical visual angle (in seating and sleeping positions) of the case study window unobstructed views-out.

Parametric modelling and daylighting simulation runs were performed using Grasshopper software, Diva plug-in for Grasshopper modeling software to interface with the simulation engines Radiance and Daysim software. Multi objective optimization was performed via Octopus plugin for Grasshopper. The generations of solutions formed in Octopus were studied one by one to clarify by how much there is development in optimization process and when the optimization is ended. In general most of the light shelf design variables have achieved the sDA objective (sDA value greater than or equal to 75%) and $\beta 1$ objective ($\beta 1$ angle be in the range of 2.5° - 50°), from the beginning of the optimization process, but without achieving ASE objective to be less than or equal to 10%, till the light shelf internal and external depths exceed 1m and it’s upward tilt angle seeks horizontality.

Keywords

Intensive Care Unit Single Patient Room, Biophilic Design, Combined Light shelf, Daylighting, Spatial Daylight Autonomy (sDA), Annual Sunlight Exposure (ASE), Un-obstructed Views-out, Upper Vertical Visual Angle.

1. Introduction

A health care design is considered complex design, as it depends on both physical and psychological aspects. Nevertheless, most designers care about the physical aspect (design requirements and codes provided by different authorities) and ignore the psychological one (the effect of the physical environment on the patient’s health). Although architecture in its physical aspects should provide a healing environment for patients (physically and psychologically) (Aripin, 2006). And even so, most of the intensive care units (ICUs) which are considered as a stressful space for workers, patients and their families (Heath, 2016) are designed in a way that provide a cold and sterile environment in which to receive specialized care, without taking into consideration the effect of this environment on patients and families health (Rubert, Long & L. Hutchinson, n.d.). Moreover, Many ICUs are also designed without windows or in a position that doesn't allow adequate daylighting and exposure to nature views-out (Roosmalen, 2010). So, how interventions in the design of ICU, can transform its built environment into a healing one that benefits patient, staff and their families.

This could be done through the biophilic design approach (positive environmental impact strategy), which is a design approach that promotes the benefits of human-nature connection in the built environment, through the application of it’s different patterns and dimensions in the design of the built environment (Kellert et al, 2008). It is also the design that monitors people (biological organism) health and well-being through respecting their mind-body systems. Therefore, It is considered as essential approach that creates healthy environments for human beings, improve their healing process, and decrease their stress. Research nowadays emphasizes the importance of the biophilic based design on enhancing human health and wellbeing, where it was found that; the presence of windows in ICUs might decrease symptoms of ICU phobia and enhance staff job satisfaction. Moreover, the presence of natural views might decrease patient’s length of stay, need for medications and stress levels. Furthermore, the presence of daylighting in ICUs might decrease patient’s perceived pain, consequently decreasing his request to pain killers (Shepley et al, 2012).

Numerous publications addressed also the positive impact of daylighting and external view on patients. Where, Ulrich (1984) studied the relation between the view through a window and the patient’s rate of recovery from a surgery, his psychological state and pain relief. And he found that; the gall bladder surgery patients with beds next to the external view (tree view), recover faster, have a better spirit, take a fewer moderate and strong analgesic doses, and had slightly lower scores for minor post-surgical complications, than those with a wall view, but this conclusion cannot be extended to all types of the built view or to other patient groups (long-term patients), as the built view in this study was monotonous one (large featureless brick wall). Another study was carried by Ulrich, et al. (1991) concerning the relationship between stress recovery and the exposure to the natural and urban environment, and it resulted in concluding that; different outdoor environments have different effects on stress recovery, where natural environment case leads to complete and faster recovery from stress, depending on both physical and physiological findings. Choi et al. (2012) investigated the effect of daylighting on the patient average length of stay (ALOS) in hospitals. Depending on the paper results, it was found that; patients in the brighter wards (more intense illuminance wards) have a shorter ALOS. Moreover, physiological benefits provided by the natural lighting may lead to faster recovery depending on the disease types. Furthermore, glare in these wards can be controlled by using manually controllable shading devices, such as; vertical or horizontal blinds.

A number of publications addressed the effect of using shading systems on day-lighting performance and views-out of typical hospital and intensive care unit patient room. Where, Shrief, et al. (2016) examined the shapes of patient room window horizontal blinds, in order to improve daylighting performance and the external view. According to the paper results, it was found that; blinds with flat or gently curved shapes were more efficient than the curved one, as they have better results for both daylighting (reflects sunlight into the room) and the external view, while it was expected that tilting it upwards will result in better daylighting performance. Shrief, et al. (2015) also examined Intensive Care Unit (ICU) window size (WWR) and the shading device, in order to reach sufficient daylighting performance, avoid glare and to improve energy performance, and he found that; ICU window proper orientation can positively affect both daylighting and thermal performance, where north oriented windows provide the biggest numbers of successful window configuration possibilities at different WWRs, while windows facing south enjoyed a reasonable number of configuration options as well. Moreover, shading systems especially sunscreens and the horizontal sun breakers are considered as the most successful alternatives in a wide range of WWR. Wagdy, et al. (2017) tested the effect of cut off angle and the corresponding tilt angle of sun-breakers fixed on a southern elevation window of both inboard and outboard bathroom patient rooms, at different window to wall ratios, under a clear desert sky condition on the daylighting performance. And he found that; the number of accepted sun-breaker cases increased with higher window to wall ratios for both patient room designs, moreover, bigger range of accepted tilt angles was for inboard bathroom patient rooms. Furthermore, both the inboard and outboard bathroom designs had the same range of accepted cut off angles. It was observed that efficient daylighting performance was achieved in all tested WWRs for the two patient room layouts with cut off angles between 50° and 54° with the wall. Moreover, horizontal sun-breakers achieved successful results in all tested WWRs for the two patient room layouts. It was also noted that the cut off angles were more influential in providing adequate daylighting performance in comparison with tilt angles.

Within the relevant literature there many publications concerning the impact of daylighting and external view on patients, and the effect of using shading systems on day-lighting performance and views-out, but there aren’t any concerning the application techniques of both biophilic metrics, which are daylighting and views-out in ICUs, moreover methodologies usually tackle one of the two biophilic metrics either, daylighting metric or the views-out.

2. Objectives

This paper is considered a part of a more comprehensive research aiming at enhancing the quality of views-out and daylighting performance in ICU patient rooms without influencing quality of their medical process, and that is through the biophilic design approach that improves patients’ health and wellbeing. The aim of this paper is to identify the optimal design of parametric combined light shelf that is installed over an Intensive Care Unit (ICU) patient room southern oriented window of 63% window to wall ratio (WWR) located in Cairo, Egypt, considering the two biophilic design metrics performances, which are daylighting and the views out, in order to improve patients’ health and wellbeing.

3. Methodology

ICU single patient room with a decentralized nurse station was chosen to be the tested case study, where it’s window design has various objectives to fulfil. Which are; ensuring adequate daylighting without causing discomfort glare (through filtered, diffused, and reflected light), providing warm light (through southern orientation) (Kellert et al., 2008), and providing un-obstructed natural views-out at distance that is visible to the patient in more than one position (Ex: seating and sleeping positions) (Browning et al., 2014). These design objectives are based on the studies that have been carried out on the effect of applying biophilic design metrics especially daylighting and views out, on enhancing patient’s health, wellbeing and rate of recovery. Thus, in order to achieve these objectives, parametric combined light shelf was chosen from the different shading devices to be installed on ICU patient room case study southern window, since it is considered as one of the most efficient shading devices that is capable of controlling direct sunlight, redistributing incoming daylight and pushing daylight deeper into the space through reflecting it on its upper surface and the ceiling plane, while maintaining un-obstructed views outside (Kontadakis et al. , 2017), as shown in Table 1.

Table 1: Biophilic Design Metrics Proposed Application Techniques in ICU Patient Room Case Study

	Metrics Application	Proposed Techniques in ICU Patient Room	
Daylighting	**Warm Light** (makes interior spaces more welcoming and makes people feel secure) (Kellert et al., 2008)	**Southern Oriented Windows** in ICU Patient Room Case Study	Phase 1
	Filtered or Diffused Sunlight (to decrease glare, and to encourage the feeling of the connection to the outside) (Kellert et al., 2008)	**Installation of Combined Light Shelf over The ICU Single Patient Room Southern Elevation Window and Selecting its Best Internal and External Depths and Inclination Angle** which: 1.Control direct sunlight, redistribute incoming daylight, and push it deeper into the space through reflecting it on its upper surface and the ceiling plane (Kontadakis et al., 2017).	Phase 2
	Reflected Natural Light Off Light-Colored Walls, Ceilings, And Water Surface (to decreases glare and delivers light into the interior spaces) (Kellert et al., 2008)		
	Difference in Light Distribution (without causing visual discomfort will improve the quality of the user experience) (Browning et al., 2014)		
	Movement of Light and Shadows (Dynamic Lighting) Along A Surface (attract attention) (Browning et al., 2014)		
Views - Out	**Un-Obstructed Views at Distance** (views of elements of nature, living systems and natural processes) (Browning et al., 2014)	2.Maintain un-obstructed views-out and make it visible to the patient in different positions (seating and sleeping positions) (Kontadakis et al., 2017).	
	Natural Views Visible to Users in More Than One Position (seating and sleeping positions) (Browning et al., 2014)		

This will be carried out through two sequential phases. The first phase will begin with creating ICU single patient room case study model, with all its parameters and configurations. Then, the daylighting simulation settings will be set for this base case. The second phase will encompass the setup of the whole parametric based optimization workflow of the light shelf.

3.1 Phase One: Base Case Daylighting Simulation

3.1.1 ICU Patient Room Parameters & Configuration

Analysis of daylighting and views out performances was carried out for the chosen ICU patient room layout design, which is; ICU single patient room with decentralized nurse station and a private outboard bath room. The room has modular dimension of 7.5m * 4.8 m * 3.3 m (L * W * H). It's designed to include a zone for family and visitors to sit/ stay over near the patient without intersecting with the staff, through dividing it into three zones (family zone, patient zone, staff zone), where family area is on one side of the patient zone (located on the external perimeter overlooking the view), while the staff zone (medical area) is on the other side, as shown in Figure

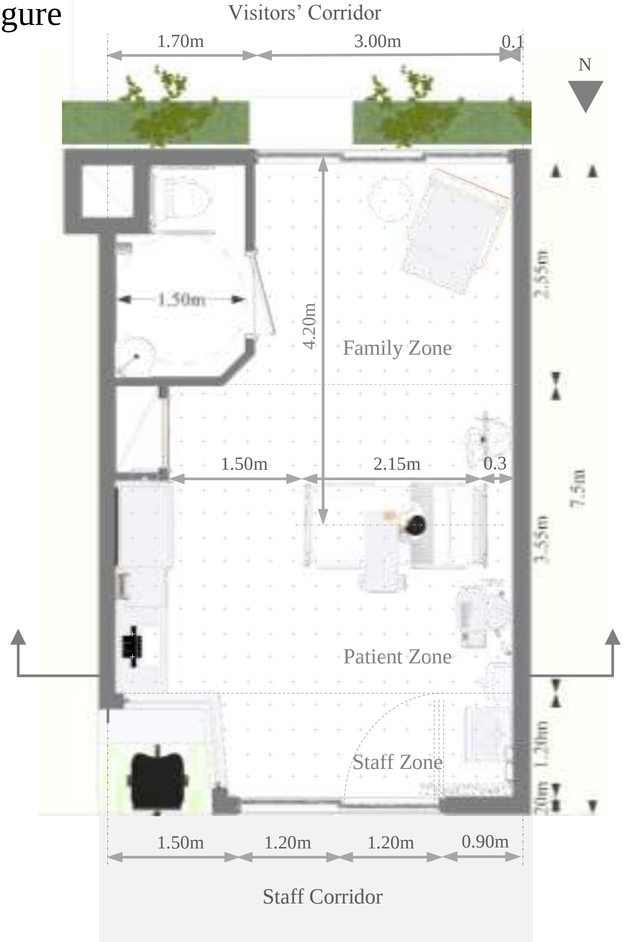


Figure 1: ICU Single Patient Room with Decentralized Nurse Station Layout

The patient bed located in the room is oriented such that the patient can see the views out and can see the staff (and vice versa). It's located at a distance of 4.2m from the external perimeter of the room (4.2m from the bed axis to the internal face of the external wall). Its height from the ground varies between 0.44 - 0.82 m, moreover its maximum backrest angle is 70 degrees (Multicare, 2015). The medical device used in the room is overhead Ponta Beam Medical System that allows continuous access to the patient's head, and multiple bed locations and orientations, moreover it allows un-obstructed views out for the patient and allows less obstruction between patients and their visitors and patients and the staff.

ICU patient room has a 9.9 m2 (3 m * 3.3 m) window with a maximum Window-to-Wall Ratio (WWR= ((3*3.3) / (4.8*3.3)) *100 = 63%) facing the south (to provide warm white light which creates more homely and warm atmosphere). The window condition is assumed to be floor to ceiling operable window, which is divided into three white painted aluminum frames with anti-glare clear double glass panels with a visible light transmission rate of 70%, as shown in Table 2.

3.1.2 Base Case Daylighting Simulation Parameters and Evaluation Criteria

Simulations were conducted using the climatic data of the city of Cairo, Egypt (30°60N, 31°240E, alt.75 m) that enjoys an almost year-round desert clear-sky, and characterized by a hot-arid desert climate, according to ("World Maps of Köppen-Geiger climate classification", 2019). The tested ICU patient room was assumed to be located on the second-floor level of a hospital building, where windows were facing south. The patient bed level plane (0.75 m height) was used as a reference plane on which daylighting performance was simulated. The analysis points were set at a 0.3 m * 0.3 m grid. Accordingly, the total number of the analysis points were three hundred and sixty-four 364 points for the tested ICU patient room. These are illustrated in Figure 1, and other simulation parameters are summarized in Table 2.

Table 2: Simulation Model Parameters

Simulation Model Parameters	ICU Patient Room Parameters	
	Room Location	Cairo, Egypt
	Floor Level	Second Floor
	Room Floor Area (m^2)	36 m^2
	Room Modular Dimension of (L*W*H)	7.5m * 4.8 m * 3.3 m
	ICU Window Parameters	
	Window Orientation	South
	Window Area (m^2)	9.9 m^2 (3 m * 3.3 m)
	WWR	63%
	Internal Surfaces Materials and Reflectance	
	Walls	White Paint of Reflectance 81%
	Floors	Light Brown Epoxy of Reflectance 58%
	Ceiling	White Gypsum Board Tiles of Reflectance 85%
	Medical Devices	White Coated Stainless Steel of Reflectance 50%
	ICU Door Glass	Anti-Glare Clear Double Glass of Transmittance 30%
	Toilet & Wardrobe Door	Light Brown Wooden Material of Reflectance 42%
	Table and Chair	Light Brown Wooden Material of Reflectance 32%
	Furniture Cloth	White Cloth of Reflectance 79.5%
	Working Counter	White Epoxy Resin Material of Reflectance 70%
	White Board	White Board of Reflectance 87%
	Window Materials and Transmittance	
	ICU Window and Door Frame	White Coated Aluminum of Reflectance 92%
	ICU Window Glass	Anti-Glare Clear Double Glass of Transmittance 70%

Rhinoceros modelling software was used to generate the model of ICU patient room, while Diva plugin for Grasshopper which uses Radiance software, was used in the daylighting simulation. The metrics applied in this study were the Spatial Daylight Autonomy (sDA300/50%) and the Annual Sunlight Exposure (ASE1000/250h). The Spatial Daylight Autonomy describes how much of the space receives sufficient daylight. Specifically, sDA describes the percentage of floor area that receives at least 300 lux for at least 50% of the annual occupied hours. While the Annual Sunlight Exposure describes how much of the space receives too much direct sunlight, which can cause visual discomfort (glare). Specifically, ASE measures the percentage of floor area that receives at least 1000 lux for at least 250 occupied hours per year. These metrics give an indication about daylighting adequacy and visual comfort. Radiance parameters for sDA and ASE were based on those defined by IESNA (2012). These are presented in Table 3.

Table 3: Radiance Simulation Parameters

	Ambient Bounces	Ambient Divisions	Ambient Sampling	Ambient Accuracy	Ambient Resolution
sDA	6	1000	20	0.1	300
ASE	6	1000	20	0.1	200

For evaluating the adequacy of base case daylighting performance, one acceptance criteria was introduced, which is: the percentage of sDA should meet a minimum requirement of 75% of the whole room area, under the condition that the percentage of the Annual Sunlight Exposure (ASE) would not exceed 10%, and this is based on the USGBC (2019) LEED v.4 requirements.

3.2 Phase Two: Case Study Multi-Objective Optimisation

3.2.1 Parametric Light Shelf Variables and Modelling

A combined light shelf was chosen to be installed over the case study southern window to restrict direct sun light, redistribute incoming daylight and push it deeper into the space while maintaining the un-obstructed views outside. It is placed above patient standard eye level (in standing, seating and sleeping positions), where it divides the window into two parts; an upper part (clerestory area) which can be considered as daylight provider and a lower one which is a view area window. It's paced at height of 1.1 m from the ceiling of the room, in order to divide the window with a ratio of 1:3. The chosen material for the light shelf is white coated aluminium of reflectance 92%, as light shelf reflectance should be as high as possible (Kontadakis Et al, 2017).

A. Problem Formulation

Three variables were chosen to define the window's light shelf, which are: it's internal depth (X), it's external depth (Y), and its upward tilt angle (Θ) (The angle between the light shelf horizontal centre line and the window vertical axis), where;

It's internal depth (X) ranges from 0 to 1.2m, with increments of 0.1m
$\therefore$ 0m $\leq$variable (X) $\leq$ 1.2m
It's external depth (Y) ranges from 0 to 1.5m, with increments of 0.1m
$\therefore$ 0m $\leq$variable (y) $\leq$ 1.5m
It's upward tilt angle (Θ) ranges from 45° to 90°, with increments of 5°
$\therefore$ 45° $\leq$variable (Θ) $\leq$ 90°

The following Table 4 and Figure 2 describe the parametric light shelf variables, and their maximum and minimum value limits for performance evaluation. While, the ICU patient room case study window parameters and room configuration stated before are considered as constants.

Table 4: Parametric Light Shelf Variables

	Variable	Symbol	Definition	Minimum - Maximum Value
Parametric Light Shelf	Internal depth	**X**	The distance from the window vertical axis to the internal end point of the light shelf.	**X**= 0 - 1.2 m, with increments 0.1m
	External depth	**Y**	The distance from the window vertical axis to the external end point of the light shelf.	**Y**= 0 - 1.5 m, with increments 0.1m
	Upward tilt angle	**Θ**	The angle between the light shelf horizontal centre line and the window vertical axis	**Θ**= 45°- 90°, with increments 5°

Note that: X and Y should always be on the same straight line.

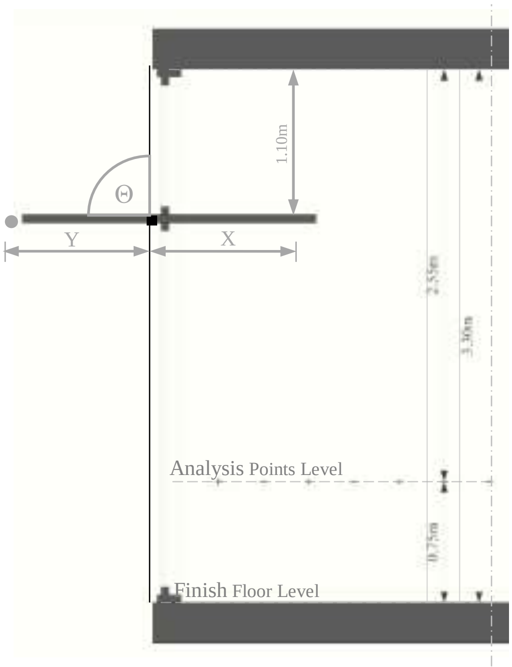


Figure 2: Parametric Light Shelf Variables

Grasshopper software which is a graphical algorithm editor and a plug-in for Rhinoceros, that allows parametric design generation ("Grasshopper", 2019), was used to generate the model of the light shelf, where it's three parameters where set as three sliders in the grasshopper software.

3.2.2 Patient's Upper Visual Angle Parameters and Modeling

Patient's eye points location and standard sight line levels in both seating and sleeping positions, in the ICU patient room case study were located based on; the proposed ICU bed location in this room (where, bed axis is about 4.2 meters away from the external south window wall, it's back is 0.3m away from the room's west wall), ICU bed height from the finish floor level (which varies from 0.44m to 0.82m, but the selected height for this study is 0.75m, which is the height of the working plane), and it's backrest angle (which varies from 0 to70 degrees, where 0 degree resembles patient's sleeping angle, while 70 degrees resembles patient's seating angle). Therefore, In this case study patient's standard line of sight level in the sleeping position is about 0.95m from the finish floor level and his eye point is about 0.5 m from the tested room’s west wall, while patient’s standard line of sight level in the seating position is about 1.45m from the finish floor level and his eye point about 1.1 m from the tested room’s west wall, as shown in the Figure 3.

Figure 3: Case Study Southern Oriented Window Height, Work Plane and Patient Eye Level in Seating and Sleeping Positions

A. Problem Formulation

The optimization of views out in this case study, would be carried out through maximizing patient’s upper vertical visual angles of the unobstructed case study window views out (the view area window) in both seating and sleeping positions, as the lower vertical visual angle and horizontal visual angle of the unobstructed case study window views out (the view area window) are constants, due to the fixed dimensions of the room window (width and height), that is based on the maximum WWR that can be achieved in the chosen case study room configuration, as shown in Figure 4. While the upper visual angles can vary based on the parametric light shelf variables (internal depth (X), external depth (Y), and its upward tilt angle (Θ)), as shown in Figure 5.

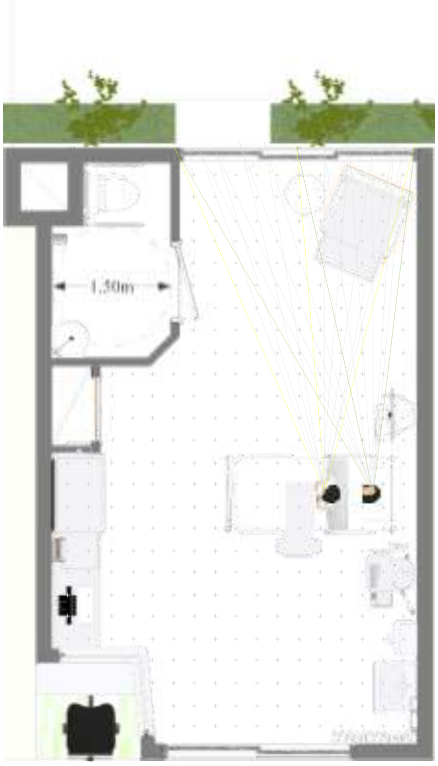


Figure 4: Patient's Constant Horizontal visual angles in seating and sleeping Positions

Grasshopper software was used to model patient's eye points, patient standard sight line levels and to define his/her upper vertical visual angles of the unobstructed case study window views out (the view area window) in both seating (β1) and sleeping positions (β2). One more angle was defined as a constraint angle (α ≥ 0°) that prevent the parametric light shelf to get into the upper vertical visual angles during the light shelf optimization process, as shown in Figure 5.

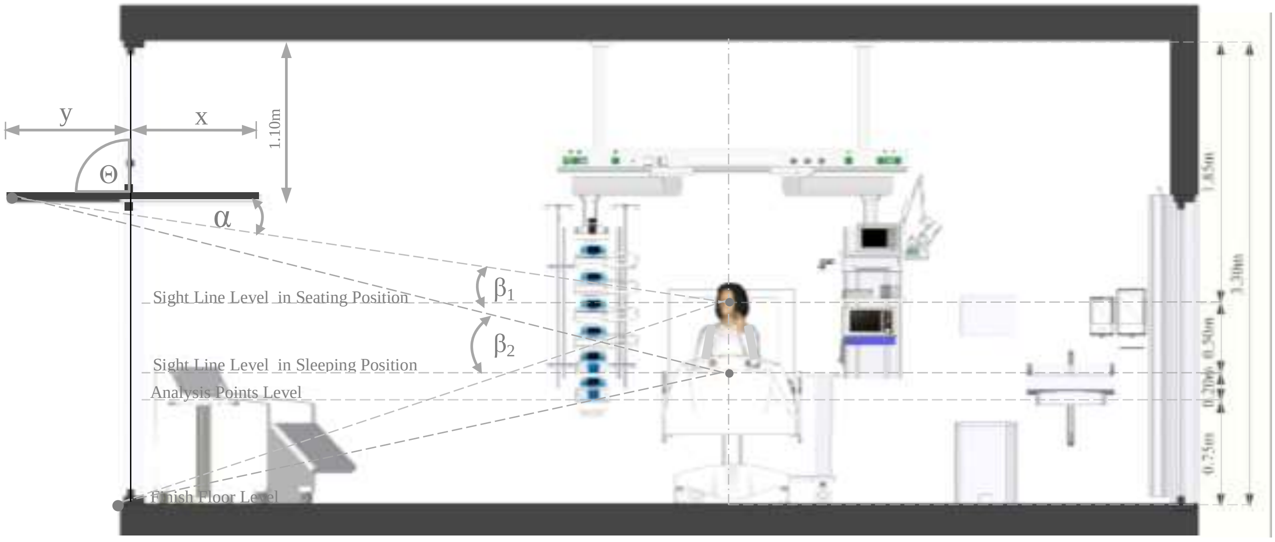


Figure 5: Patient's Eye Points, Patient Standard Sight Line Levels and His Upper Vertical Visual Angles in both Seating and Sleeping Positions.

3.2.3 Multi Objective Optimization and Evaluation Criteria

Multi-objective optimisation methodology was used to identify the optimal design of the combined light shelf installed over the chosen case study southern window, that optimises both the ICU patient room daylighting performance and patient’s upper vertical visual angle of the unobstructed case study window views out (the view area window) in the seating position only (as it’s considered more critical case than the sleeping position angle, moreover patient visual angle in sleeping position will consequently be optimized following his/her visual angle optimisation in seating position), as shown in Figure 5.

The light shelf performance was evaluated based on the following criteria;

- Maximizing the percentage of Spatial Daylight Autonomy (sDA), where it should meet a minimum requirement of 75% of the whole room area and this is based on the USGBC (2019) LEED v.4 requirements.
- Minimizing the percentage of the Annual Sunlight Exposure (ASE), where it should not exceed 10%, and this is based on the USGBC (2019) LEED v.4 requirements.
- Maximizing patient’s upper vertical visual angles of the unobstructed case study window views out (the view area window) in the seating position (β1), which will consequently maximize patient’s upper vertical visual angles in the sleeping position (β2), where it should be in the range of (2.5° - 50°), based on human central field of vision (binocular field of vision) which covers an angle of between 50° and 60°, within this field images are sharp, depth perception occurs, and color discrimination is possible (Environment Protection Department, 2011), as shown in Figure 6.

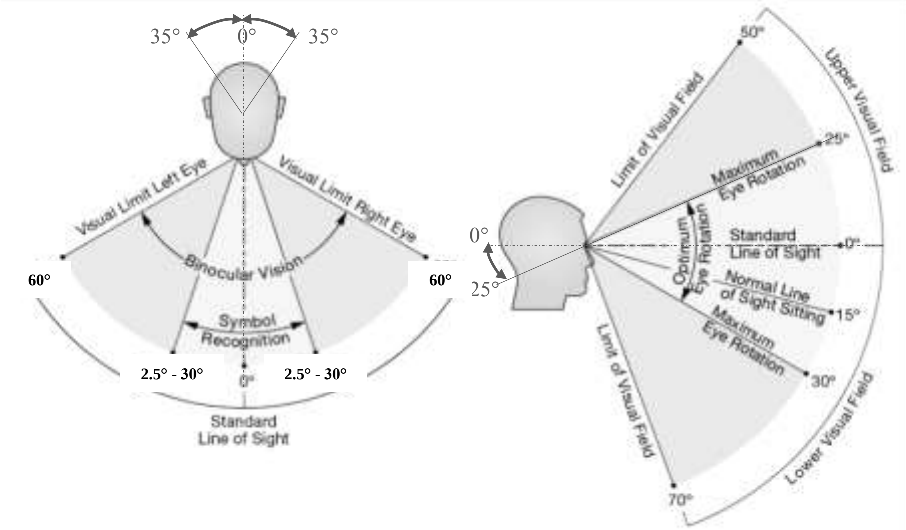


Figure 6: Horizontal and Vertical Fields of View of Human Eye (Environment Protection Department, 2011)

The optimization framework used in this phase is a self-automated, as model, simulation and the optimization evaluation would be performed automatically on one canvas. This parametric framework is held mainly in Grasshopper plug-in for Rhinoceros. Many software and simulation engines have a role in this process, as Grasshopper will be responsible for parametric modelling, Diva plugin for Grasshopper will be responsible for daylighting performance simulation, while genetic algorithms (GAs) will be ready to optimize solutions via Octopus plug-in which can perform multi-objective optimization, as shown in Figure 7.

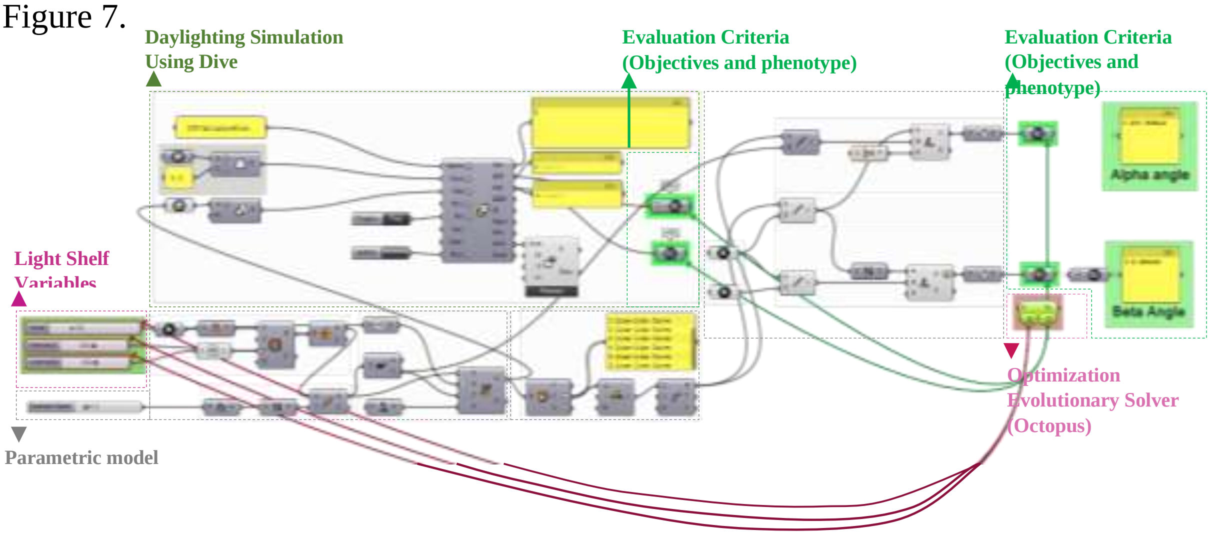
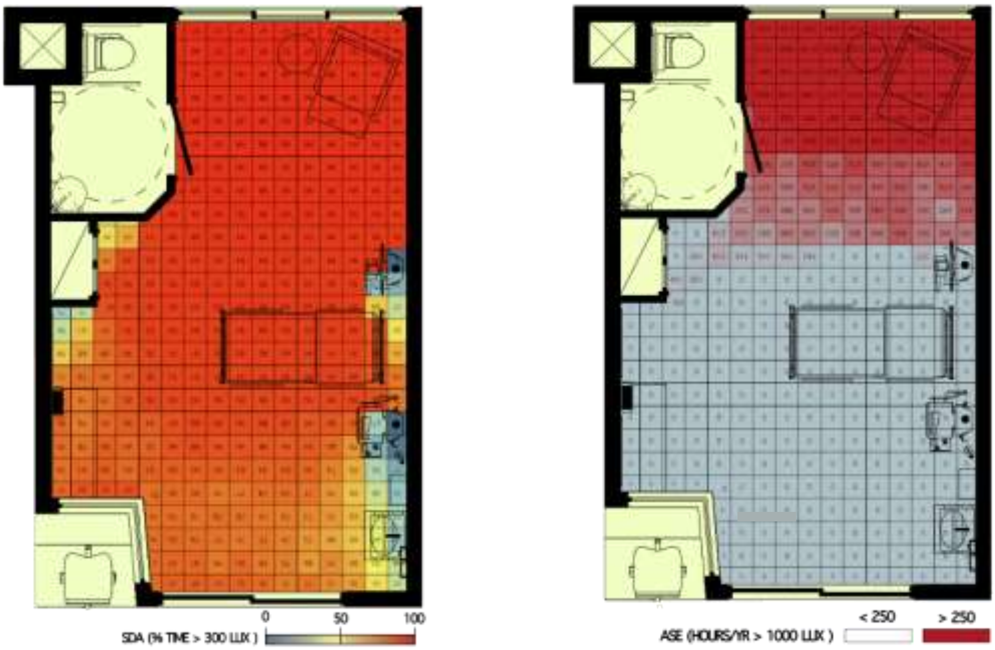


Figure 7: Multi Objective Optimisation Definition

4. Results

4.1 Phase One: Base Case Daylighting Simulation Results

The current state of design (base case) is simulated (without the portable furniture and light shelf) and analyzed, then it was found that: more than half of the case study floor area received at least 300 lux for at least 50% of the annual occupied hours (sDA300/50% = 89.3 %), but 32.2 % of its floor area exceeds 1000 lux for more than 250 occupied hours per year (ASE1000/250h = 32.2 %) , as shown in Figure 8. Therefore, the required percentage of Spatial Daylight Autonomy (sDA) which should meet a minimum requirement of 75% of the whole room area, under the condition that the percentage of the Annual Sunlight Exposure (ASE) would not exceed 10% (based on USGBC (2019) LEED v.4 requirements) was not achieved. Moreover, the daylighting metrics of the biophilic design approach wasn’t adequately applied, as the quality of daylight in interior spaces isn’t sufficient and the space received too much direct sunlight, which caused visual discomfort (glare), as shown in Figure 8. This is because there are not any shading devices in the southern elevation. The only parameter side with sDA and ASE calculations is the anti-glare clear double glass panels with a visible light transmission rate of 70%, which permits the majority of direct and reflected sun rays to penetrate the space, as shown in Figure 9.



$sDA_{300/50\%}$ = 89.3 % **$ASE_{1000/250h}$ = 32.2 %**

Figure 8: Base Case Daylighting Simulation Results

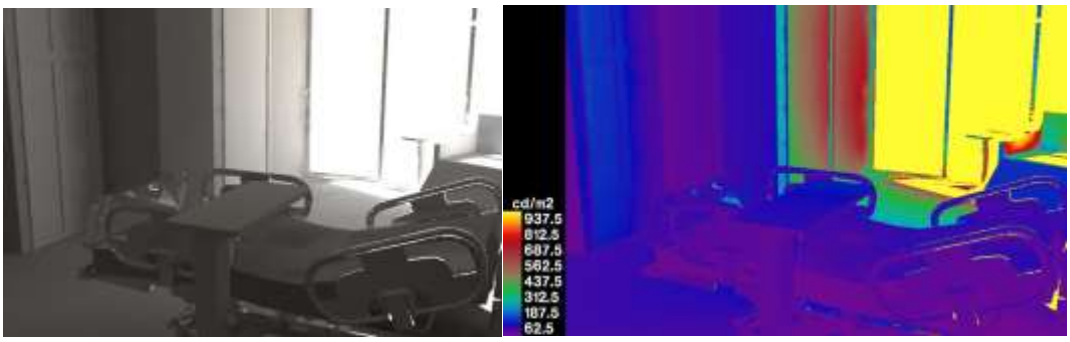


Figure 9: Southern Window Radiance Rendering

4.2 Phase Two: Case Study Multi-Objective Optimisation Results

There are many conflicting parameters which are interactive with each other in the process of optimizing both case study daylighting performance and patient's upper vertical visual angle of the unobstructed case study window views out (the view area window) in the seating position. So, the whole optimization process was performed via Octopus plug-in for grasshopper, which was running for about 168 h on a computer with (Intel(R) Core (TM) i7-3770 CPU @ 3.40 GHz, ~3.90 GHz) processor and 8.00 GB Ram, in order to find the logical balance in between these conflicting parameters. During this period, about 350 daylighting simulations and upper vertical visual angle calculations were run to form 70 generations of 5 iterations each.

The 350 operations were arranged and scheduled in tables, charts, and graphs to find the relationship between different parameters and their influence on daylighting performance and patient's upper vertical visual angle of the unobstructed case study window views out (the view area window) in the seating position, in addition, to reach to the optimum light shelf design. By analyzing them it was found that, there are many solutions which have high performance in one objective but don't have any effective results in the other objectives and so on, till the generation number (65) was reached. Then the convergence of GAs in reaching near optimal solution for sDA, ASE and patient's upper vertical visual angle of the unobstructed case study window views out (β1), occurs starting from generation number (66), as shown in Figure 10.

By analyzing Figure 10 it was found that, trying to minimize solution (iteration) ASE value and to maximize sDA value of the whole room area in each generation, leads to decreasing β1 angle (But it still in the acceptable range of 2.5° - 50°). This is because the light shelf internal depth (X) and external depth (Y) increase while it's upward tilt angle (Θ) seeks horizontality, in order to block direct sun light, redistribute and redirect sunlight, to fulfill daylighting adequacy and to avoid glare. It was also found that all the light shelf design variables have achieved the sDA objective (sDA value greater than or equal to 75%) and β1 objective (β1 angle be in the range of 2.5° - 50°), from the beginning of the optimization process, but without achieving ASE objective to be less than or equal to 10%, till the light shelf internal depth (X) and external depth (Y) dimensions exceed 1m and it's upward tilt angle (Θ) seeks horizontality (Θ = 90°or 85°or 80°) starting from generation number (66), as shown in Table 5.

Table 5: Fitness Function Values of Varied Solutions

Fitness Function Values of Varied Solutions	**Generations**	**Iterations**	**Optimization Variables**			**Optimization Constraint**	**Optimization Objectives**		
	Generation No.	**Iteration No.**	**Theta (θ) °**	**X value (m)**	**Y value (m)**	**Alpha (α) °**	**Beta (β1)°**	**sDA %**	**ASE %**
	Generation 66	**1**	**85**	**1**	**1.3**	**3.689**	**9**	**94**	**8.7**
		2	85	1	1.3	3.689	9	93.9	8.7
		3	**85**	**1.2**	**1.3**	**3.778**	**9**	**94**	**7.3**
		4	80	0.9	0.8	0.067	10	94	20.9
		5	80	1	0.4	0.597	11	94	23.3
	Generation 67	**1**	**80**	**1.2**	**1.2**	**359.9**	**10**	**94**	**9.3**
		2	**90**	**1.1**	**1.4**	**7.540**	**8**	**93.4**	**7.15**
		3	**85**	**1.1**	**1.2**	**3.846**	**9**	**94**	**8.9**
		4	**90**	**1.2**	**1.5**	**7.410**	**7**	**93.3**	**7**
		5	85	1	0.4	4.860	10	93.6	21
	Generation 68	1	85	1.2	1.4	3.668	9	94	7.3
		2	90	1.1	1.4	7.540	8	93.4	7.15
		3	85	1.2	1.3	3.778	9	94	7.3
		4	80	1.2	1.2	359.9	10	94	9.3
		5	85	1.1	1.2	3.846	9	94	8.9
	Generation 69	**1**	**85**	**1.2**	**1.2**	**3.891**	**9**	**93.7**	**7.5**
		2	85	1.2	1.4	3.668	9	94	7.3
		3	85	1.2	1.4	3.668	9	93.7	7.3
		4	90	1.1	1.4	7.540	8	93.4	7.15
		5	85	1.1	1.2	3.846	9	94	8.9
	Generation 70	1	85	1.2	1.3	3.778	9	93.9	7.3
		2	90	1.1	1.4	7.540	8	93.4	7.15
		3	85	1.2	1.2	3.891	9	93.7	7.5
		4	85	1.2	1.4	3.668	9	94	7.3
		5	**90**	**1.2**	**1.1**	**7.410**	**7**	**92.8**	**7**

Note

🟩 Top Nine Solutions ▣ Optimum Solution ▨ Refused Solutions

*The optimum solution is selected from the operated iterations, as it achieved a realistic logical balance between the different case study objectives

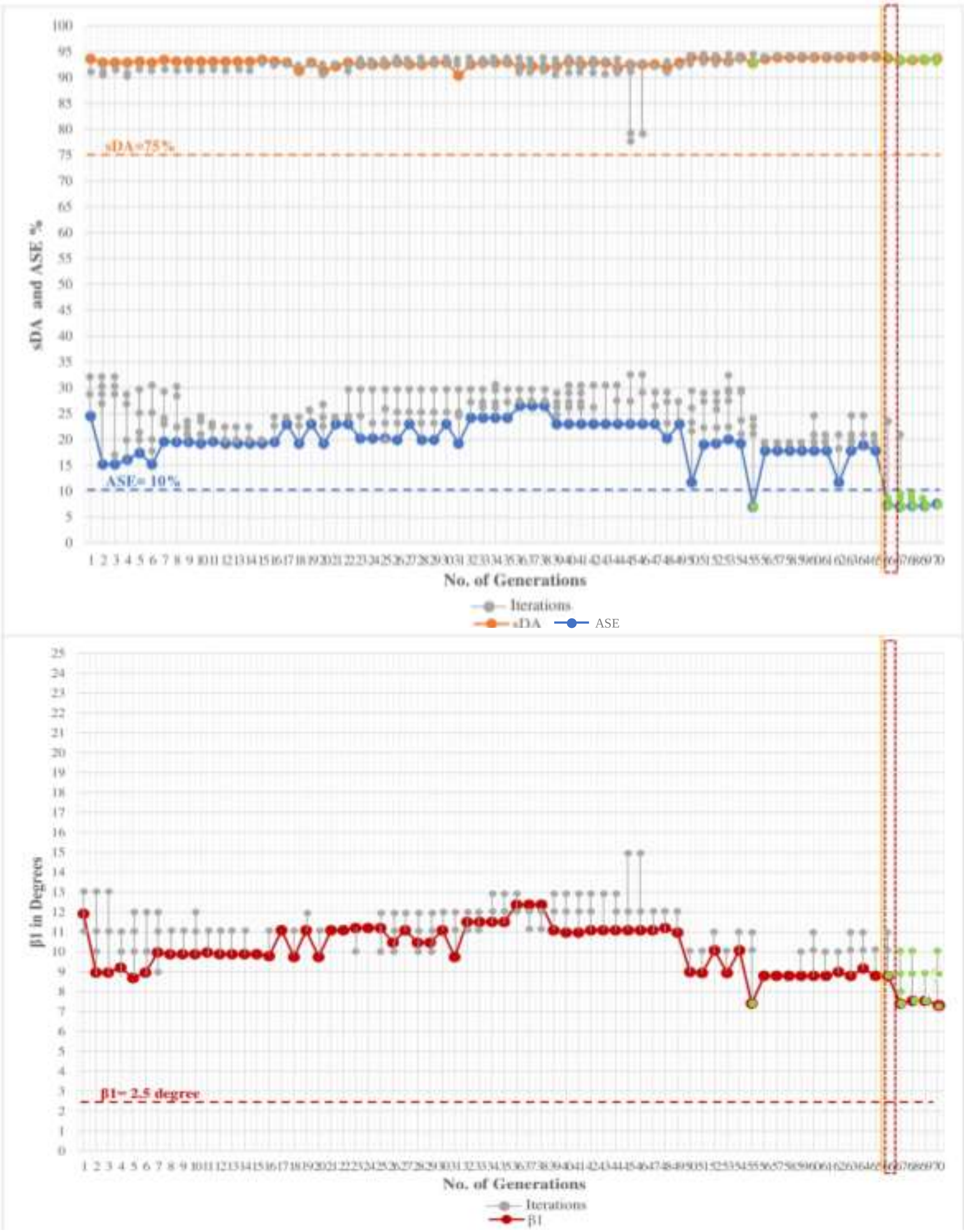


Figure 10: sDA, ASE and β1 Values Along 70 Generations are Represented as Grey Dots, The Blue Dots Represents The Lowest ASE Value in Each Generation and Their Correspondent sDA Value (orange dots) and β1 Value (red dots), While, The Green Dots are The Solution Which Passed The Benchmarks for The Three Objectives

As shown in Table 5, the top nine solutions are characterized by the balance in the performance of the three objectives, which are maximizing sDA to be greater than or equal 75%, minimizing ASE to be smaller than or equal to 10 and maximizing patient’s upper vertical visual angle of the unobstructed window views-out (β1) to be in range of 2.5° - 50°.

Moreover, in the optimum solution (which is selected from the operated iterations, as it achieved a realistic logical balance between the different case study objectives), the percentage of Spatial Daylight Autonomy (sDA) achieved a value of 94% of the whole room area which exceeds the sDA value for the base case, while the percentage of the Annual Sunlight Exposure (ASE) became of a value of 7.3%, and patient’s upper vertical visual angle of the unobstructed case study window views out (β1) became of value of 9°, as shown in Table 5 and Figures 11, 12. Therefore, the quality of daylight in case study interior spaces became sufficient, so the daylighting metrics of the biophilic design approach was adequately applied, while maintaining maximizing patient’s upper vertical visual angle of the unobstructed case study window views-out, in both positions (seating and sleeping), as shown in Figures 12.

$sDA_{300/50\%}$ = 94 %

$ASE_{1000/250h}$ = 7.3 %

Figure 11: Optimum Solution Daylighting Simulation Results

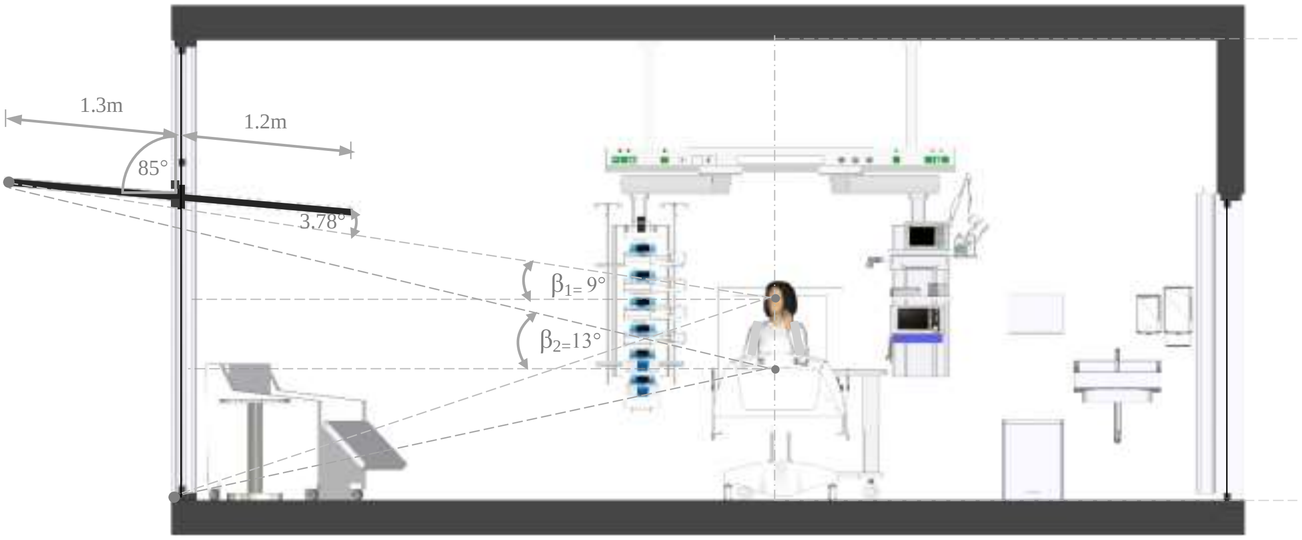


Figure 12: Optimum Solution Section

5. Discussion and conclusion

The outcomes of this study revealed that, in general, the conflicting parameters which are interactive with each other in the process of optimizing both case study daylighting performance and patient's upper vertical visual angle of the unobstructed case study window views out (the view area window) in the seating position, resulted in the presence of many solutions which have high performance in one objective but don't have any effective results in the other objectives. Where, it was found that all the light shelf design variables have achieved the sDA objective (sDA value greater than or equal to 75%) and β1 objective (β1 angle be in the range of 2.5° - 50°), from the beginning of the optimization process, but without achieving ASE objective to be less than or equal to 10%. So, trying to balance between the Fitness Function Values (the three objectives values), through minimizing solution (iteration) ASE value and to maximizing sDA value of the whole room area, leads to decreasing β1 angle (But it is still in the acceptable range of 2.5° - 50°). This is because the light shelf internal depth (X) and external depth (Y) increase while it's upward tilt angle (Θ) seeks horizontality, in order to block direct sun light, redistribute and redirect sunlight, to fulfill daylighting adequacy and avoid glare.

So, in order to recommend common combined light shelf parameters (internal and external depths and upward tilt angle) that could be used by designers to achieve acceptable performance (balancing between optimizing both base case daylighting performance and patient's upper vertical visual angle of the unobstructed case study window views-out in seating and sleeping positions) in similar cases to the tested case study, the range of commonly accepted solutions were identified. Where it was found that the light shelf internal depth (X) ranges from 1-1.2m, it's external depth (Y) ranges from 1.2-1.5m and it's upward tilt angle (Θ) seeks horizontality (Θ = 90°or 85°or 80°).

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