BLIND AND LIGHTING CONTROLLER

-

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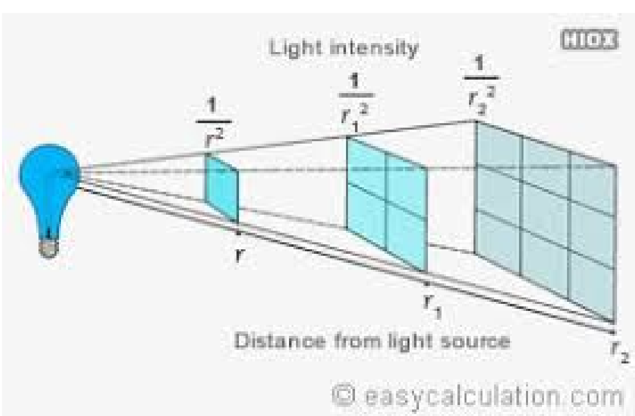
1. Objective:

This model focuses on simulating a possible approach for implementing a sustainable lighting system in a room which reduces the use of artificial lights and maximising the use of available ambient light by having a control over the blinds and the artificial lighting system.

2. Measuring the illuminance of sunlight at any point inside a room

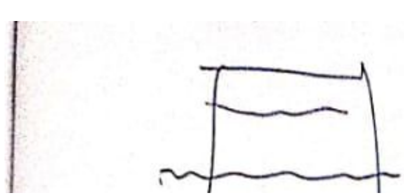
A. Assumptions:

1. There is only one window in the room that acts as the sole provider of light inside the room apart from ceiling lights.
2. The light coming inside the room is assumed to start from a point source located at the centre of the window.
3. The plane of movement of the sun and the plane of the window is exactly perpendicular, i.e, the vertical motion of the sun is not accounted for.
4. To ensure that places close to the window have illuminance that's almost the same as that at the centre of the window, we assume that for a semicircle of radius 1m centered at the middle of the window, the illuminance is constant and is equal to that at the centre of the window.



We have developed a model that finds the illuminance due to sunlight inside the room, with reasonable errors (With the above assumptions). The method followed is explained below.

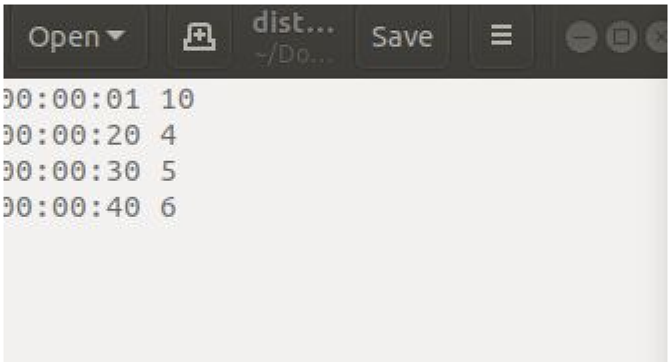
B. Working:



C. RESULTS FROM SIMULATION

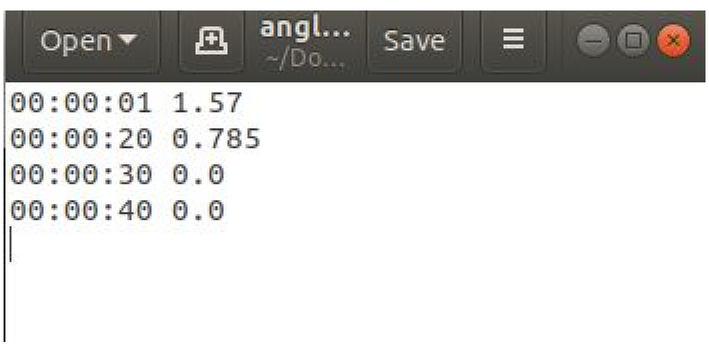
Input -

1. Distance from the centre of window



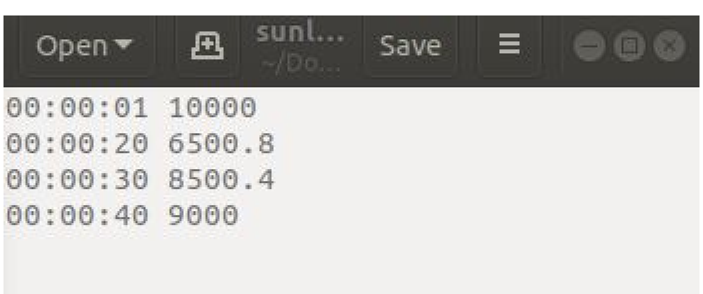
00:00:01 10
00:00:20 4
00:00:30 5
00:00:40 6

2. Angle of incidence of sun rays



00:00:01 1.57
00:00:20 0.785
00:00:30 0.0
00:00:40 0.0

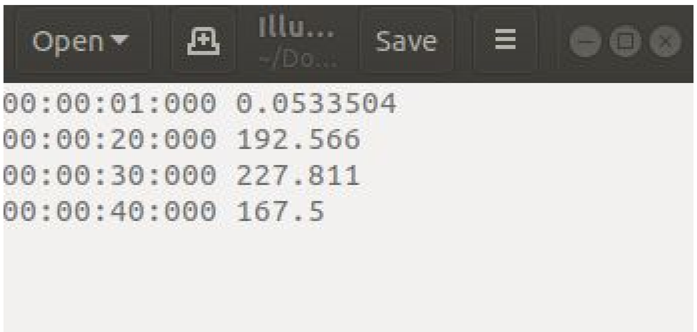
3. Illuminance of Sun's rays at the corresponding instant



00:00:01 10000
00:00:20 6500.8
00:00:30 8500.4
00:00:40 9000

Output -

1. Illumination inside the room at the required distance from the centre of window



D. Comparisons and development

We measured sunlight inside the room (VSIM Room number 3220) at 4.45 PM on 26.6.2019 with the help of a lux meter. The following data was collected and it was compared with the simulation results.

For working with simulation, we assumed that 622 lx is present at the distance 214.89 cm from centre and accordingly sunlight illuminance was calculated -

Angle of incidence of sunlight = 0

Sunlight intensity = 4287 lx

Calculations:-

$I = 622 * 2.1489^2 / 0.67 = 4287$ lx

This is done because the first few values near the window and with a range of 1.5m produce out of range results when compared with the rest. Hence we neglect the first few values near the window.

Distance from the Centre of window(cm)	Data from Simulation(lx)	Data from Lux Meter(lx)
214.89	622	622
244.3	481.26	532
274.41	381.442	458
305	308.765	385
335.96	254.48	321
367.18	213.044	272
398.6	180.781	237
430.19	155.206	197
461.91	134.621	173
493.72	117.833	157
525.6	103.972	142
557.59	92.384	128
589.62	82.61	115
621.69	74.3157	106
653.81	67.1932	97

This simulation was conducted based on the fact that the illuminance inside the room changes with distance as the inverse square of distance from the centre (1/x*2). This provides results with reasonable levels of errors in illuminance.

However, when curve fitting is applied to the data obtained from lux meter, the following results were obtained -

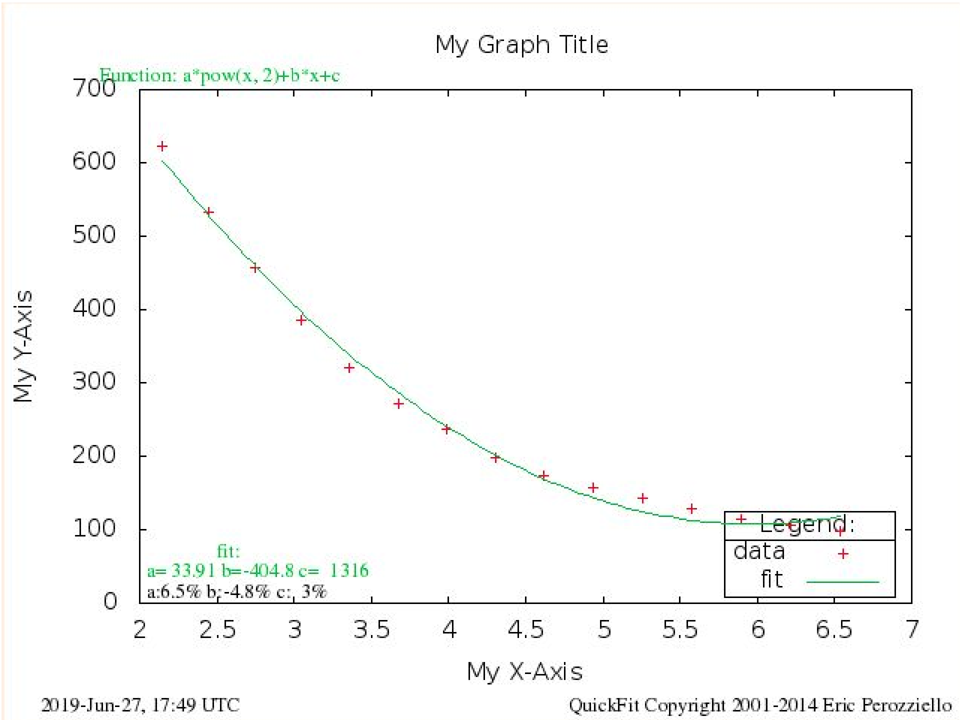
Y = a + bx + cx^2 + dx^3 , where a = 178.456, b = -7.4597, c = 0.0117 and d = -0.00006 fits all the points exactly (between distance from centre and data from lux meter)

Y = a + bx + cx^2, where a = 1315.847, b = -4.04845 and c = 0.00339 has more error than the cubic equation.

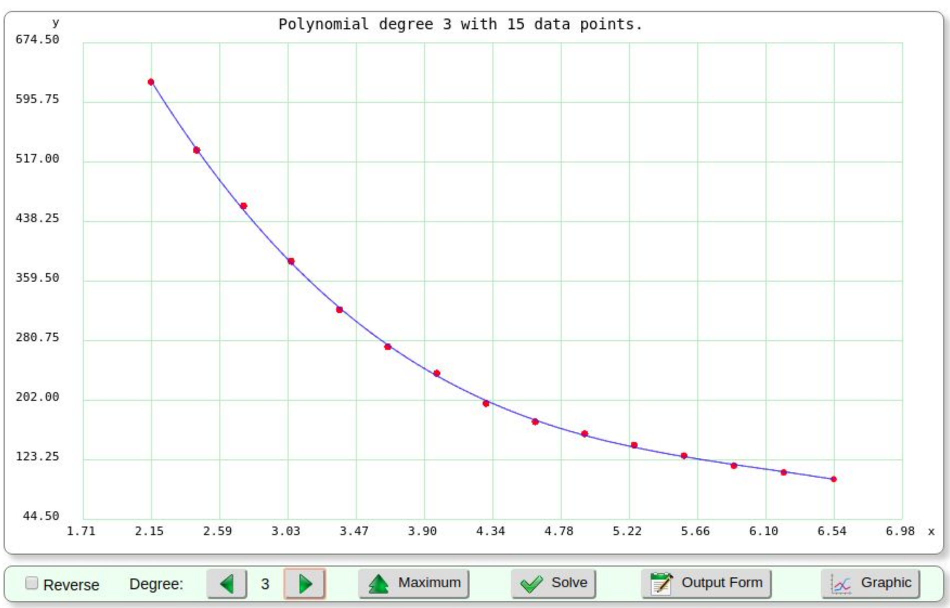
(x is in cm in these equations).

These can be chosen as an alternative to predict sunlight because 1/x^2 closely resembles these equations for the required distance intervals of a room.

Second order polynomial curve fitting (x in m)



Third degree polynomial curve fitting (x in m)



Select: Ctrl+A | Copy: Ctrl+C | Paste: Ctrl+V

Results Area:

```
Mode: normal x,y analysis
Polynomial degree 3, 15 x,y data pairs.
Correlation coefficient (r^2) = 0.9997500385716739
Standard error = 2.7346719391833587
Coefficient output form: simple list (ordered x^0 to x^n):

 1.7484561614143104e+003
-7.4597751558208893e+002
 1.1736494672563440e+002
-6.4094963711519171e+000
```

Data fed into the online graph plotter

Distance from Centre of window	Illuminance measured (from lux meter)
2.1489	622
2.443	532
2.7441	458
3.05	385
3.3596	321
3.6718	272
3.986	237
4.3019	197
4.6191	173
4.9372	157
5.256	142
5.5759	128
5.8962	115
6.2169	106
6.5381	97

Data taken from lux meter on a different day at a different time at the same venue gave readings that follow similar trends.

Ways to improve the simulated results:
1. Fit different curves at different time to map more points accurately
2. Change function according to distance from centre to fit curves accurately

Data measured on 27/06/19 on 12.25 PM and 3.30 PM at the same location

Distance	12.25 PM (lx)	3.30 PM (lx)
2.1489	608	820
2.443	512	691
2.7441	458	590
3.05	400	482
3.3596	374	438
3.6718	328	372
3.986	277	298
4.3019	249	261
4.6191	225	220
4.9372	202	196
5.256	183	170
5.5759	167	152
5.8962	149	136
6.2169	135	122
6.5381	126	108

3. Control of blinds to adjust illuminance inside the room

We have also accommodated the control system for controlling the blinds in the windows. We find the average illuminance inside the room by calculating the illuminance at various distances from the centre and finding the average of them. We have set a threshold of 300 lx. When the average light inside the room crosses this threshold, the blinds act to reduce the amount of sunlight entering the room. The percentage of blinds that should come up is proportional to the difference between the average lux and threshold lux levels. This would reduce the amount of sunlight entering the room and increase comfortability of occupants inside the room. The blinds will be fully open if the average lux levels is below the threshold lux level.

a. **Simulation Results**

Threshold illuminance inside room = 300 lx

Average illuminance calculated at 5 points - 2.25m, 2.5m, 2.75m, 3m, 3.25m from the centre of the window.

Inputs:

1. Sunlight Illuminance (lx)

```
00:00:01 4287
00:00:20 4900
00:00:30 5200
00:00:40 6000
00:00:50 6800
00:00:55 7500
00:01:30 8600
00:01:40 9500
00:02:01 10000
00:02:20 8900
00:02:30 7625
00:02:40 7000
00:03:01 6887
00:03:20 6666
00:03:30 5000
```

2. Angle of Incidence of sunlight (radians)

```
00:00:01 1.5
00:00:20 1.4
00:00:30 1.3
00:00:40 0.8
00:00:50 0.6
00:00:55 0.4
00:01:30 0.2
00:01:40 0.1
00:02:01 0
00:02:20 0.1
00:02:30 0.2
00:02:40 0.5
00:03:01 0.9
00:03:20 1.1
00:03:30 1.2
```

3. Distance from the centre of window where illuminance is to be measured (m)

(Distance is same to relate between illuminance when the blind on the window is put up)

```
00:00:01 2.986
00:00:20 2.986
00:00:30 2.986
00:00:40 2.986
00:00:50 2.986
00:00:55 2.986
00:01:30 2.986
00:01:40 2.986
00:02:01 2.986
00:02:20 2.986
00:02:30 2.986
00:02:40 2.986
00:03:01 2.986
00:03:20 2.986
00:03:30 2.986
```

Outputs:

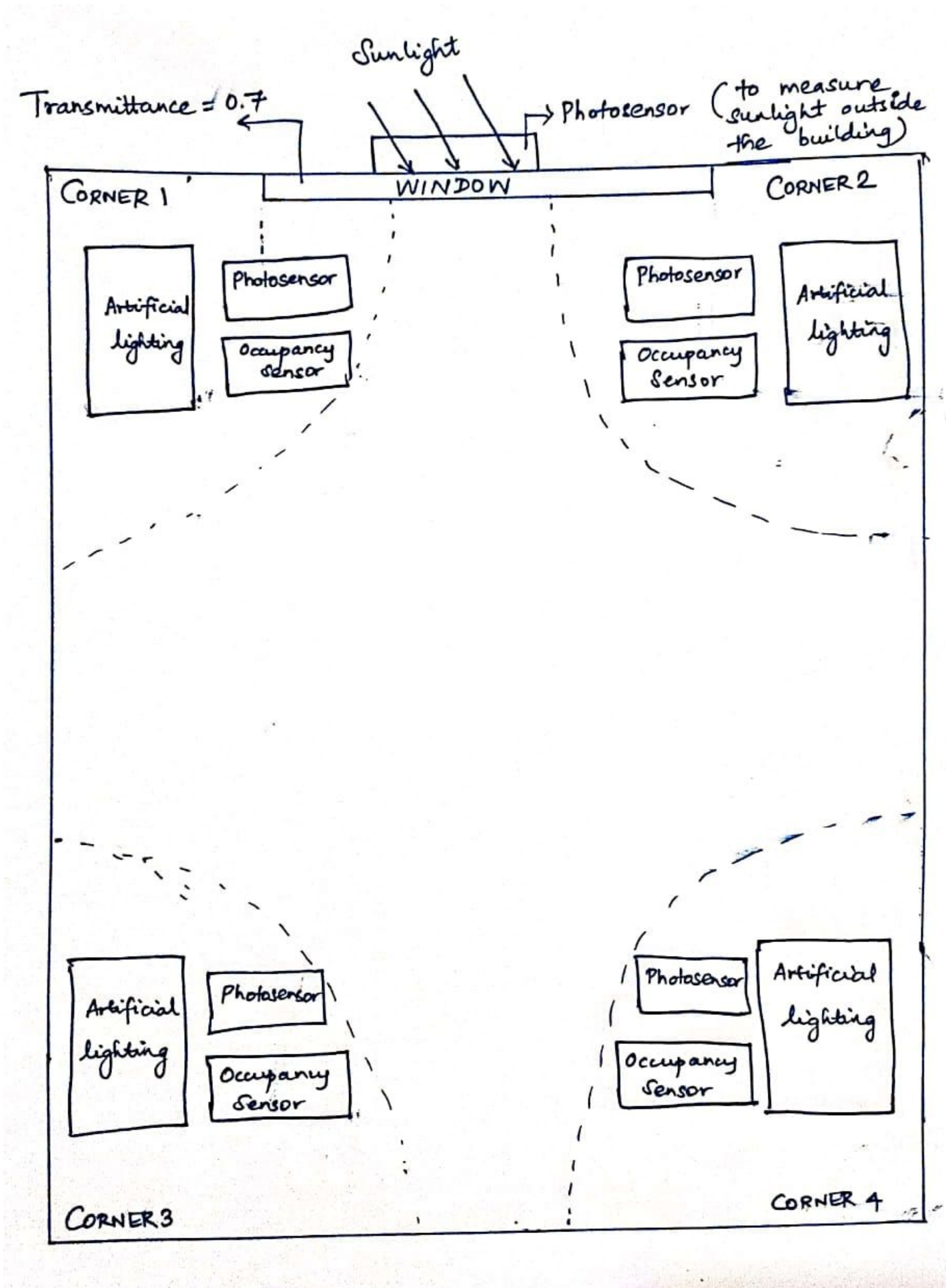
1. Percentage of blind that should be put up (%)

```
00:00:01:000 0
00:00:20:000 0
00:00:30:000 0
00:00:40:000 29.8709
00:00:50:000 74.3613
00:00:55:000 100
00:01:30:000 100
00:01:40:000 100
00:02:01:000 100
00:02:20:000 100
00:02:30:000 100
00:02:40:000 90.8519
00:03:01:000 33.0021
00:03:20:000 0
00:03:30:000 0
```

2. Illuminance at the required distance (lx)

```
00:00:01:000 22.7875
00:00:20:000 62.583
00:00:30:000 104.525
00:00:40:000 220.29
00:00:50:000 108.126
00:00:55:000 0
00:01:30:000 0
00:01:40:000 0
00:02:01:000 0
00:02:20:000 0
00:02:30:000 0
00:02:40:000 42.2289
00:03:01:000 215.528
00:03:20:000 227.211
00:03:30:000 136.145
```

4. Designed model of the system for sustainable lighting system



a. Assumptions

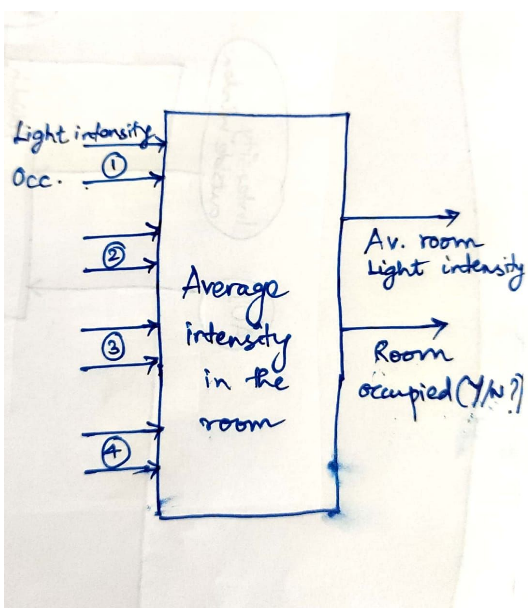
The room is assumed to be consisting of a window with a motorised controllable roller blind, 4 dimmable lights in the 4 corners of the room, 1 occupancy sensor in each corner (4 in total), 1 photosensor with each light and one outside the building (5 in total).

The optimal illumination level in the room (for a workspace) is taken as 350 lux. Previously we had verified the daylight intensity propagation through the room to be in inverse square relation with the distance from the window.

b. Model Description

i. Atomics

1. Average:
   This atomic performs the calculation of the average light intensity in the room with the data received from the 4 photosensors placed in the 4 corners. Also, this checks if any corner(s) is(are) occupied from the data received from the occupancy sensors and tells if the room is occupied or not.



2. Occupancy (Corner_illum):
   This atomic helps in checking if that particular corner is occupied, if yes, it sends the light intensity at that location and the distance of this corner from the centre of the window to ‘Average’.

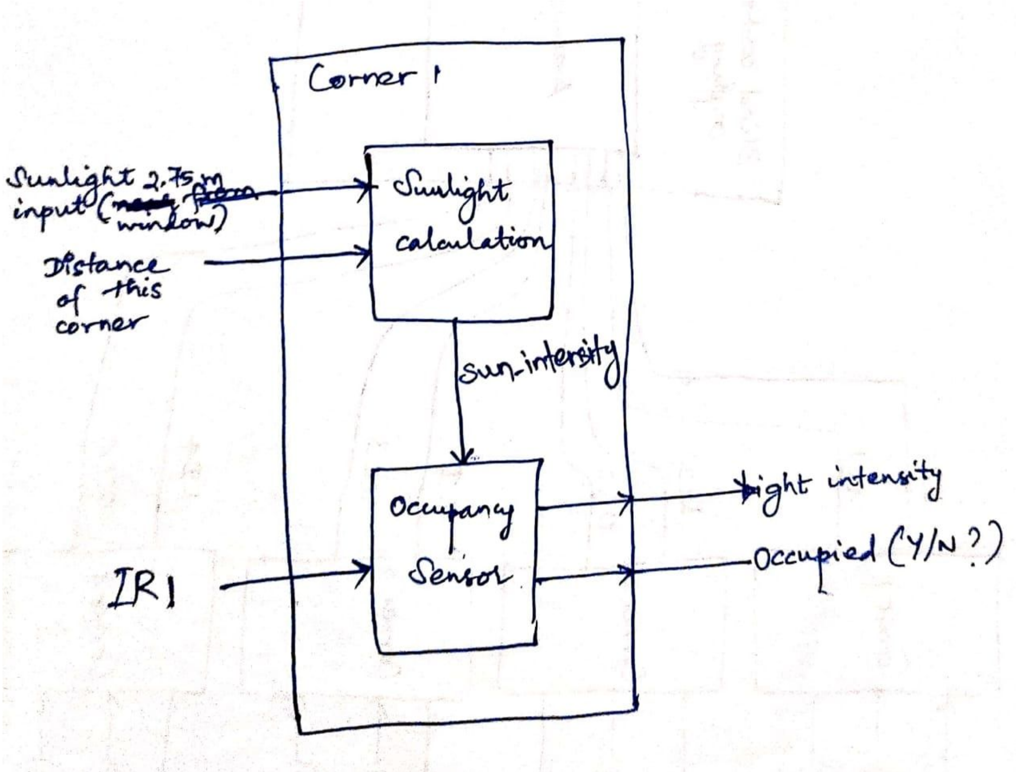
3. Sunlight calculation:
   This atomic takes in the distance from the window of that particular corner, predicts the sunlight intensity at this location and sends it back to the respective ‘Occupancy’ atomic.

4. Illuminance (for blind control):
   This atomic takes inputs like the angle of incidence(AOI), intensity at a point outside the window and predicts the intensity due to sunlight for further distances in the room. It also tells if the blind control needs to be working based on whether the room is occupied or not. (ie, blind is controlled only when the room is occupied).

ii. Coupled Models:

1. Corner1:
   This model consists of the instances of the two atomics - ‘Occupancy’ & ‘Sunlight calculation’. It takes 3 inputs {sun_out, Dist_1, IR_1} and 2 outputs {light_out_1, occupy_1}. It calculates the required illuminance that the particular light in that corner has to provide in order to maintain the optimal value of illuminance. For simulation purposes the intensity value that the photosensor in that corner has to send is considered to be the required ‘light intensity value’ (light_out) generated by the model. But in real-time the actual photosensor value is taken and given to ‘Average’ and the calculated ‘light intensity value’ is sent to the dimmable light. Also, the value from the occupancy sensor is read and sent to ‘Average’ through ‘occupy_1’.

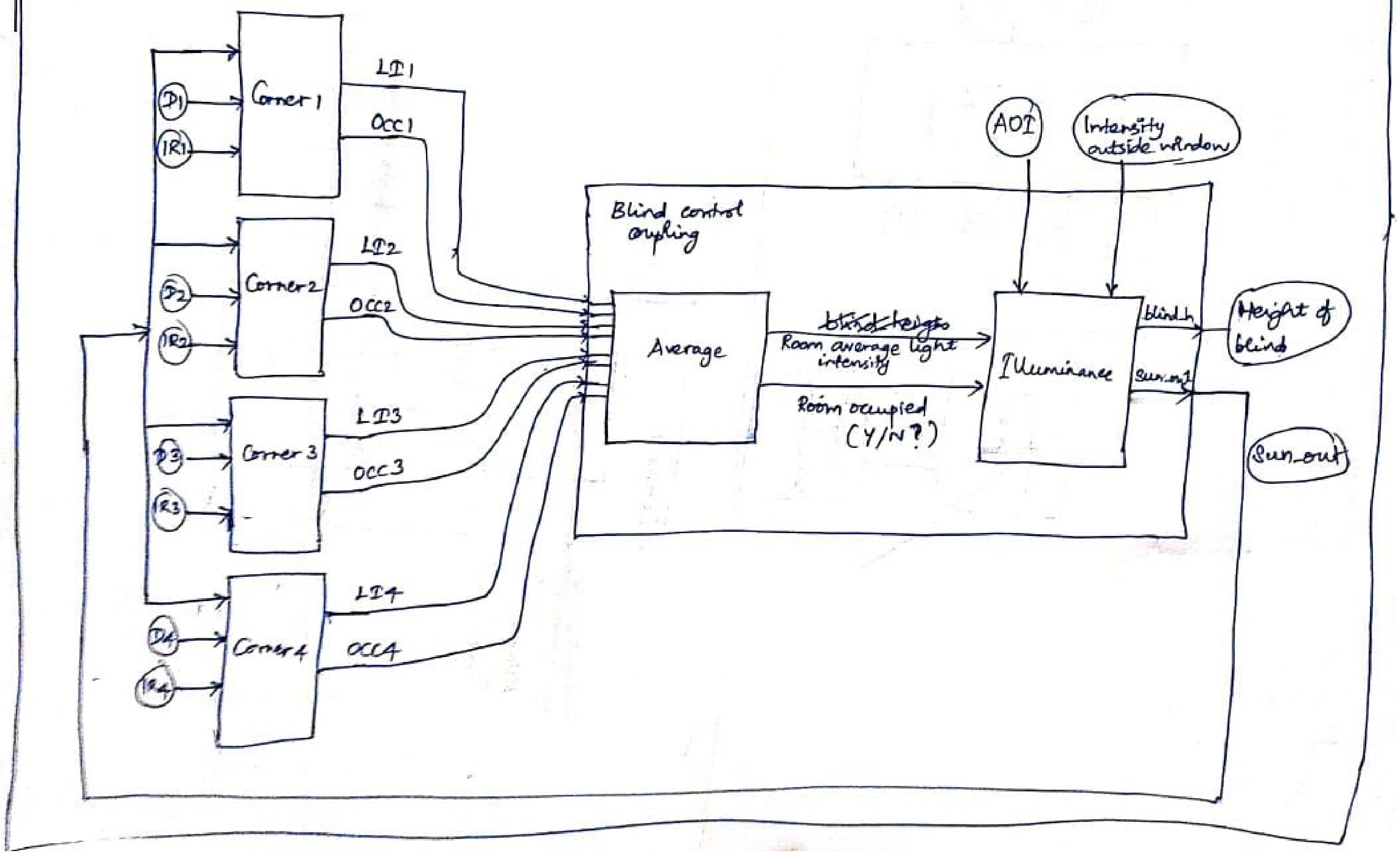
   The same happens with the other 3 corners {Corner2, Corner3, Corner4}.



2. Blind control coupling:

This model consists of the instances of the two atomics - ‘Average’ & ‘Illuminance’. It takes 10 inputs {angle_incidence, sun_intensity, occu_1, light_corner_1, occu_2, light_corner_2, occu_3, light_corner_3, occu_4, light_corner_4} and 2 outputs {blind_h, sun_out}. ‘Average’ calculates and sends the average light intensity in the room to ‘Illuminance’ and also sends if the room is occupied or not through ‘occupy’. ‘Illuminance’ checks if the room is occupied and takes in the intensity outside the window, angle of incidence, average light intensity and controls the height of the blind according to the availability of daylight and average intensity in the room. With the help of the intensity value outside the window it predicts the intensity values due to the sunlight in various points in the room with the inverse square relation verified previously.

TOP MODEL :

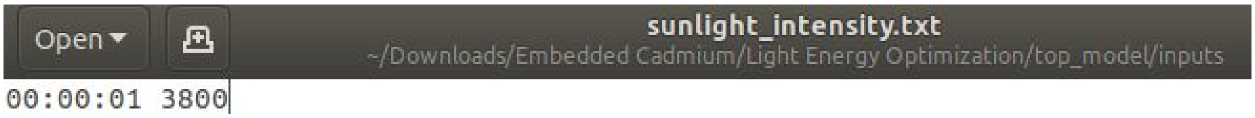


Corner 1
Corner 2
Corner 3
Corner 4
D1
IR1
D2
IR2
D3
IR3
D4
IR4
LI1
OCC1
LI2
OCC2
LI3
OCC3
LI4
OCC4
Blind control coupling
Average
~~blind height~~
Room average light intensity
Room occupied (Y/N?)
Illuminance
AOI
Intensity outside window
blind_h
sun_on
Height of blind
Sun_out

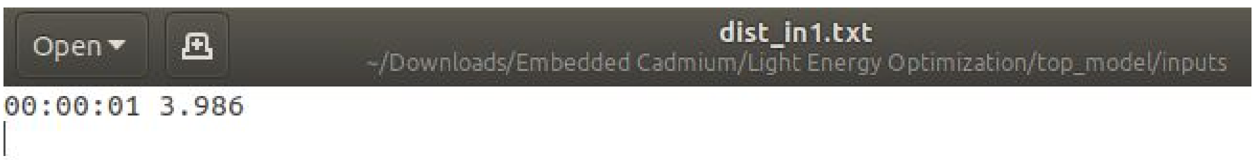
C. Results from simulation

Inputs:

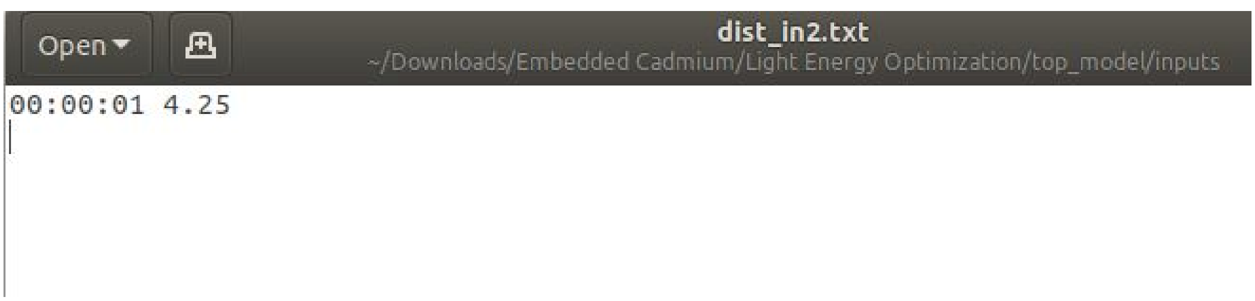
1. Sunlight Intensity outside the room (lx)



2. Distance of corner 1 from centre of window

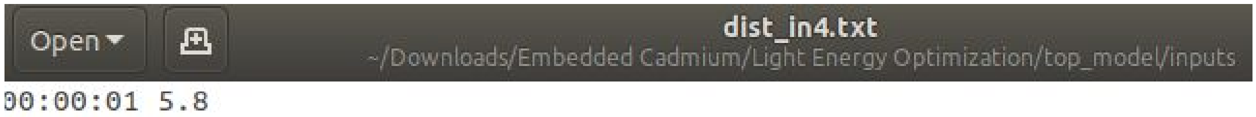


3. Distance of corner 2 from centre of window

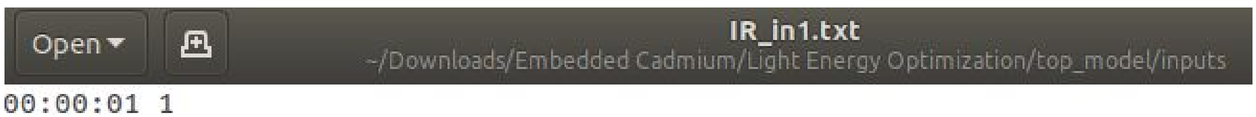


4. Distance of corner 3 from centre of window

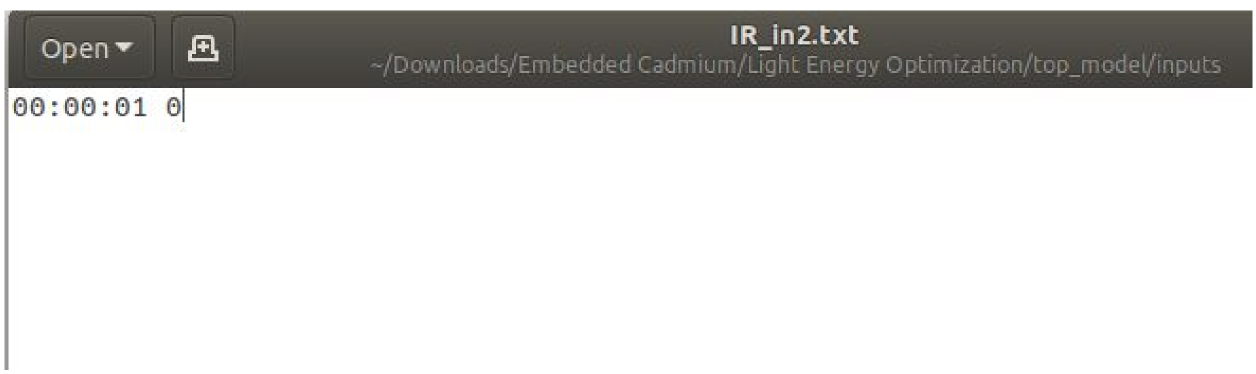
5. Distance of corner 4 from centre of window



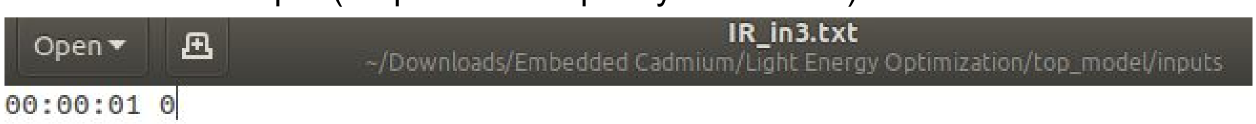
6. IR sensor 1 output (To predict occupancy in corner 1)



7. IR sensor 2 output (To predict occupancy in corner 2)



8. IR sensor 3 output (To predict occupancy in corner 3)



9. IR sensor 4 output (To predict occupancy in corner 4)

10. Angle of incidence of sunlight (radians)

Outputs:

1. Percentage of blind put up

```
Open ▾                          screen.txt
        ~/Downloads/Embedded Cadmium/Light Energy Optimization/top_model/outputs
00:00:02:000 100
00:00:04:000 0
00:00:05:000 0
00:00:06:000 0
00:00:08:000 0
00:00:09:000 0
00:00:10:000 0
00:00:12:000 0
00:00:13:000 0
00:00:14:000 0
```

2. Light intensity (lx) at corner 1

```
Open ▾                          light_intensity1.txt
        ~/Downloads/Embedded Cadmium/Light Energy Optimization/top_model/outputs
00:00:02:000 0
00:00:03:000 0
00:00:04:000 0
00:00:06:000 0
00:00:07:000 0
00:00:08:000 0
00:00:10:000 0
00:00:11:000 0
00:00:12:000 0
00:00:14:000 0
```

3. Light intensity (lx) at corner 2

```
Open ▾                          light_intensity2.txt
        ~/Downloads/Embedded Cadmium/Light Energy Optimization/top_model/outputs
00:00:02:000 600
00:00:03:000 600
00:00:04:000 600
00:00:06:000 523.842
00:00:07:000 523.842
00:00:08:000 523.842
00:00:10:000 523.842
00:00:11:000 523.842
00:00:12:000 523.842
00:00:14:000 523.842
```

4. Light intensity (lx) at corner 3

Open ▾

light_intensity3.txt
~/Downloads/Embedded Cadmium/Light Energy Optimization/top_model/outputs

```
00:00:02:000 600
00:00:03:000 600
00:00:04:000 600
00:00:06:000 315.783
00:00:07:000 315.783
00:00:08:000 315.783
00:00:10:000 315.783
00:00:11:000 315.783
00:00:12:000 315.783
00:00:14:000 315.783
```

5. Light intensity (lx) at corner 4

Open ▾

light_intensity4.txt
~/Downloads/Embedded Cadmium/Light Energy Optimization/top_model/outputs

```
00:00:02:000 0
00:00:03:000 0
00:00:04:000 0
00:00:06:000 0
00:00:07:000 0
00:00:08:000 0
00:00:10:000 0
00:00:11:000 0
00:00:12:000 0
00:00:14:000 0
```

6. Lux levels at Lux levels at 2.75 from centre of window due to sunlight alone

Open ▾

Illumination.txt
~/Downloads/Embedded Cadmium/Light Energy Optimization/top_model/outputs

```
00:00:02:000 0
00:00:04:000 181.899
00:00:05:000 181.899
00:00:06:000 181.899
00:00:08:000 181.899
00:00:09:000 181.899
00:00:10:000 181.899
00:00:12:000 181.899
00:00:13:000 181.899
00:00:14:000 181.899
```

D. Mathematical working:

a) **Inputs:**

1. Sunlight Intensity (Sunlight from outside) = 3800 lx
2. Dist1 (Distance of corner 1 from centre of window) = 3.986 m
3. Dist2 (Distance of corner 2 from centre of window) = 4.25 m
4. Dist3 (Distance of corner 3 from centre of window) = 2.2 m
5. Dist4 (Distance of corner 4 from centre of window) = 5.8 m
6. IR1 output (Occupancy in corner 1) = 1
7. IR2 output (Occupancy in corner 2) = 0
8. IR3 output (Occupancy in corner 3) = 0
9. IR4 output (Occupancy in corner 4) = 1
10. Angle of incidence of input sunlight (AOI)= 1.0 radians

b) **Initial Output (Previous state):**

1. Percentage of blind put up = 100
2. Light intensity at corner 1 = 0 lx
3. Light intensity at corner 2 = 600 lx
4. Light intensity at corner 3 = 600 lx
5. Light intensity at corner 4 = 0 lx
6. Lux levels at Lux levels at 2.75 from | = 0
   centre of window due to sunlight alone |

The final output for each instant depends on the corresponding input and output from previous instant. This is because of the feedback loop involved in the model.

1. Sunlight entering the room = Transmittance of glass * Sunlight Intensity * cos(AOI) = 0.67 * 3800 * cos (57.3 degrees) = 1375.452 lx

2. Average sunlight inside the room = average of sunlight at 5 points
$= 0.2 * (1/ 2.25^2 + 1/ 2.5^2 + 1/ 2.75^2 + 1/ 3^2 + 1/ 3.25^2)$ * Sunlight entering the room
= 0.2 * 0.6956 * 1375.452 = 191.353 lx

3. Average light inside the room due to light = sum of (lux) lights from 4 corners/4
= (0 + 600 + 600 + 0) / 4
= 300 lx

4. Since average lux from lights is not greater than three times the average sunlight lux, we have -
Average light inside the room (sunlight + lighting) = (191.353 + 300)/2
= 245.676 lx

5. Since this light level is not greater than 300 lx (threshold for blinds to go up), the blinds are fully open. Hence, **percentage of blind that goes up = 0**

Illuminance at 2.75 m from centre of window only due to sunlight =
= Sunlight entering the room * (100 - Percentage of blind put up) / (100 * 2.75^2)
= 1375.452 * 100 / (100 * 2.75^2) = **181.878 lx**

6. If any corner is occupied, IR sensor sends a 0 output. If its empty, a 1 is sent from IR sensor.

Light at any corner (if occupied) =
= 600 - Illuminance at distance of corner (from centre of window) due to sunlight

Light at any corner (if not occupied) = 0

Light at corner 1 (NOT OCCUPIED) = **0 lx**
Light at corner 2 (OCCUPIED) = 600 - 181.878 * 2.75^2 / 4.25^2 = **523.85 lx**
Light at corner 3 (OCCUPIED) = 600 - 181.878 * 2.75^2 / 2.2^2 = **315.82 lx**
Light at corner 4 (NOT OCCUPIED) = **0 lx**

E. Comparisons

Final Output from simulation

1. Percentage of blind put up = 0
2. Light intensity at corner 1 = 0 lx
3. Light intensity at corner 2 = 523.842 lx
4. Light intensity at corner 3 = 315.783 lx
5. Light intensity at corner 4 = 0 lx
6. Lux levels at Lux levels at 2.75 from | = 181.899 lx
   centre of window due to sunlight alone |

Output from mathematical calculation

1. Percentage of blind put up = 0
2. Light intensity at corner 1 = 0 lx
3. Light intensity at corner 2 = 523.85 lx
4. Light intensity at corner 3 = 315.82 lx
5. Light intensity at corner 4 = 0 lx
6. Lux levels at Lux levels at 2.75 from | = 181.878 lx
   centre of window due to sunlight alone |

Hence, we can safely say that the model described correctly predicts and calculates sunlight and accordingly controls blinds and lighting system properly to reduce energy consumption.

Another example -

a) **Inputs:**

1. Sunlight Intensity (Sunlight from outside) = 5000 lx
2. Dist1 (Distance of corner 1 from centre of window) = 3.986 m
3. Dist2 (Distance of corner 2 from centre of window) = 4.25 m
4. Dist3 (Distance of corner 3 from centre of window) = 2.2 m
5. Dist4 (Distance of corner 4 from centre of window) = 5.8 m
6. IR1 output (Occupancy in corner 1) = 0
7. IR2 output (Occupancy in corner 2) = 0
8. IR3 output (Occupancy in corner 3) = 1

9. IR4 output (Occupancy in corner 4) = 0
10. Angle of incidence of input sunlight (AOI)= 0.5 radians

b) **Initial Output (Previous state):**

1. Percentage of blind put up = 31 %
2. Light intensity at corner 1 = 476.8 lx
3. Light intensity at corner 2 = 494.6 lx
4. Light intensity at corner 3 = 445.1 lx
5. Light intensity at corner 4 = 543.2 lx
6. Lux levels at Lux levels at 2.75 from | = 0
   centre of window due to sunlight alone |

These are outputs generated in the previous time instant by a particular set of inputs when a sequence of inputs are given to the model.

1. Sunlight entering the room = Transmittance of glass * Sunlight Intensity * cos(AOI)

= 0.67 * 5000 * cos (28.65 degrees) = 2939.8424 lx

2. Average sunlight inside the room = average of sunlight at 5 points
= 0.2 * ($1/ 2.25^2$ + $1/ 2.5^2$ + $1/ 2.75^2$ + $1/ 3^2$ + $1/ 3.25^2$) * Sunlight entering the room
= 0.2 * 0.6956 * 2939.8424 = 408.991 lx

3. Average light inside the room due to light = sum of (lux) lights from 4 corners/4
= (473.8 + 494.6 + 445.1 + 543.2) / 4
= 489.175 lx

4. Since average lux from lights is not greater than three times the average sunlight lux, we have -
Average light inside the room (sunlight + lighting) = (408.991 + 489.175)/2
= 449.083 lx

5. Since this light level is greater than 350 lx (threshold for blinds to go up), the blinds are partially closed.

Percentage of blind that should be put up = Percentage increase of light inside the room

= (449.083 - 350)/350 * 100
= **28.31 %**

Illuminance at 2.75 m from centre of window only due to sunlight =
= Sunlight entering the room * (100 - Percentage of blind put up) / (100 * 2.75^2)
= 2939.8424 * 71.69 / (100 * 2.75^2) = **278.687 lx**

6. If any corner is occupied, IR sensor sends a 0 output. If its empty, a 1 is sent from IR sensor.

Light at any corner (if occupied) =
= 600 - Illuminance at distance of corner (from centre of window) due to sunlight

Light at any corner (if not occupied) = 0

Light at corner 1 (OCCUPIED) =600 - 278.687 * 2.75^2 / 3.986^2 = **467.35 lx**
Light at corner 2 (OCCUPIED) = 600 - 278.687 * 2.75^2 / 4.25^2 = **483.32 lx**
Light at corner 3 (NOT OCCUPIED) = **0 lx**
Light at corner 4 (OCCUPIED) = 600 - 278.687 * 2.75^2 / 5.8^2 = **537.35 lx**

Final Output from simulation

1. Percentage of blind put up = 28.8 %
2. Light intensity at corner 1 = 468.1 lx
3. Light intensity at corner 2 = 482.6 lx
4. Light intensity at corner 3 = 0 lx
5. Light intensity at corner 4 = 538.4 lx
6. Lux levels at Lux levels at 2.75 from | = 278.2
   centre of window due to sunlight alone |

Output from mathematical calculation

1. Percentage of blind put up = 28.31 %
2. Light intensity at corner 1 = 467.35 lx

3. Light intensity at corner 2 = 483.32 lx
4. Light intensity at corner 3 = 0 lx
5. Light intensity at corner 4 = 537.35 lx
6. Lux levels at Lux levels at 2.75 from | = 278.687 lx
   centre of window due to sunlight alone |

5. Future work

This model simulates the control technique proposed. This measures the sun intensity outside the building and helps analyse intensity in various parts of the room with minimum number of photosensors. The sensor values near the lights are taken as feedback. Only 4 corners and 4 lights have been considered. This method can be extended to any number of corners. As a next step, a hardware model with photosensors and dimmable lights can be created for this simulation model which would test its working and feasibility in actual conditions.

6. References

1. https://www.sciencedirect.com/science/article/pii/S0360132316303298
2. https://www.sciencedirect.com/science/article/pii/S0306261909002785