Chapter 27
Optimization of Windows for Daylighting and Energy Consumption for South Facade in Office Building in Hot and Dry Climate of India

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Abstract The windows have a great influence on daylighting in the interior of the building and are considered as an important element for energy-efficient buildings. The size of the opening area, its orientation, and shading device affect the inside illumination. This study assesses the relation between heating, cooling, and daylighting and provides solutions for opening in an office building. The study focuses on the effect of changing Window Wall Ratio (WWR), sill level, window height, number of windows, glazing materials, and shading device on daylight in the built environment. The consequences of the two objectives, i.e., daylight and energy consumption are contradictory in terms of openings. Therefore, optimizing the window area is essential in low-energy buildings. Optimization has been done for the south facade by computer-generated models and simulations. This study covers the essential factors of daylight and energy, i.e., daylight autonomy, useful daylight illuminance, daylight uniformity, total load, and optimization of fenestration design.

27.1 Introduction

In the history of architecture, from the Roman vault to the crystal palace of the nineteenth century, the major structural changes in buildings reflected the goal of increasing the amount of daylight that was collected [1]. Daylighting is one of the effective ways to minimize energy consumption as well as satisfy biological and human needs. Humans are affected both psychologically and physiologically by the different spectrums of light. These effects are easily overlooked benefits of

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daylighting. Daylighting has been associated with improved mood, enhanced morale, lower fatigue, and reduced eyestrain [2]. In 2016, the commercial sector accounted for about 8.59% of the total units of electricity consumed in India (MOSPI 2017) [3]. Lighting and air conditioning account for over 80% of energy end use in a typical commercial buildings in India in which lighting accounts for 59% and air conditioning accounts 31% of energy use [4]. Lighting up spaces generate heat in and around the building, which again increases the cooling load. Daylighting is one of the effective approaches for improving the energy efficiency of buildings. Energy savings from artificial lighting during the daytime with the help of daylight design strategies can have a significant impact on the energy efficiency of office buildings. Windows characterize energy use and daylight level in buildings. Choosing their areas and proportions are early design stage decisions, which are hard to change later. Therefore, window design parameters must be a part of an integrated design process, considering multiple aspects at the same time so that we can get proper quantity and quality of daylighting as well as minimize the total energy consumption of the building [5].

27.2 Literature Review

The size of the window not only determines the total energy consumption of a building directly through the availability of direct solar radiation but also indirectly through the availability of daylight. The amount of electric lighting indirectly influences the total energy demand for heating, cooling, and lighting due to the heat production by the electric lighting fixture. Cooling load increases as WWR increases, on the other hand, the trend for artificial lighting energy is just the opposite that is it decreases with increasing WWR. Thus, the overall impact of WWR on total energy consumption gives a U-shape curve with a minimum value of energy consumption for a WWR. The minimum value of total energy consumption, which includes cooling load, heating load, and lighting load and optimized WWR varies with different types of building, the orientation of opening, and climate condition of the place [6]. The electric lighting demand is not only influenced by the size of the window. The window position and the window shape also influence the illuminances in a room. In this way, the window position and the window size also affect the electric lighting demand [7, 8].

27.3 Methodology

27.3.1 Location and Climate Description

The computer model was evaluated for the climate of Jaipur, Rajasthan, India (26.91°N, 75.78°E). It comes in Hot and Dry Climate zone of India. The summer in

Jaipur is very hot while winters are extremely cold. The maximum temperature in the summers ranges between 40 and 47 °C in May, June when in the winter minimum temperatures remain about 4–9 °C. Simulation has been done using the energy plus weather file (.epw format) of Jaipur.

27.3.2 Building Model Parameters

The study has been done on a hypothetical open plan office model. In this research, only one room is considered without any obstruction in the field of view and ground reflectance. Average floor height for an office building in a high rise is 3.9 m [9]. Office space was chosen as a base case for study with 3.9 m ceiling height. According to the ceiling height, all other parameter has been assigned (Table 27.1).

Shading Device Design. The hours of the day during which temperatures are above adaptive comfort range, and the average direct normal irradiation values are greater than 630.9 Wh/sqm are marked as the overheated period for design shading device.

Table 27.1 List of variable design parameters studied in the research

Variable data		
Room height	3.9 m	CTBUH
Room depth	9 m	2.5 × (window height + sill height) SP41
Room width	18 m	
WWR	0.2, 0.3, 0.4, 0.5, 0.6	min to max (feasible)
Sill level	0.8, 1.0, 1.2 m	min to max (feasible)
Window height	1, 1.5, 2, 2.5 m	min to max (feasible)
No. of windows	1, 3, 5, 7 (uniformly distributed)	
Glazing material	(0.27, 0.15), (0.45, 0.40), (0.70, 0.79), (0.39, 0.60)	(SHGC, VLT) IESNA handbook
Shading device	With shade, without shade	VSA = 50°, 0.3 m depth

CTBUH Council on Tall Buildings and Urban Habitat; *SHGC* Solar Heat Gain Coefficient; *VLT* Visible Light Transmission; *IESNA* Illuminating Engineering Society of North America

27.3.3 Evaluation Criteria for Optimization

Daylight Autonomy (DA) and Useful Daylight Illuminance (UDI) are considered for visual and energy performance assessments in this study. UDI is the percentage of occupied hours of the year when illuminance lies within one of the three illumination ranges: 0–300 lx, 300–2000 lx, and over 2000 lx. It also provides information on excessive levels that could be the cause of glare. For glazing material, LSR (light to solar ratio) (VLT/SHGC) value is considered. The threshold for indoor lighting level is considered 300 lx on a horizontal plane at the height of 80 cm above the floor. Yearly average value of uniformity ratio (minimum illuminance/average illuminance) of daylight has been analyzed for evaluation. Energy consumption evaluation benchmarks included minimal heating, cooling, and artificial lighting load.

27.3.4 Simulation Process

Due to the number and complexity of the parameters and objectives under study, different simulation engines are combined under the same platform. This way, a single simulation run was possible to provide result data regarding multiple objectives, including heating, cooling, and lighting. For this study Radiance and Open Studio as daylight and thermal engines are selected which are embedded in Ladybug and Honeybee tool. These tools are plugins for Grasshopper tool which is a graphical algorithm editor integrated with Rhino software. To conduct the energy analysis, a simplified BIM model is created in Grasshopper according to predefined building model data (Table 27.1). The room has been simulated as a single unit of a larger office building located in Jaipur, and only one facade was exposed to the outside climate. Ceiling, floor, and internal walls were assumed to face the same thermal environment as the room investigated. The study has been done to analyze the optimized values for south orientation. After parametric modeling, inputs for energy simulation has been assigned which described in Table 27.2. The schedule used for energy modeling is shown in Table 27.3.

27.4 Results and Discussion

At first screening, the experiment has been done with a complex system of many design variables to determine most important ones to reduce the number of experimental data for study by stepwise multiple regression for each dependent variable, i.e., total energy consumption, DA, $\mathrm{UDI}_{300\text{–}2000\ \mathrm{lx}}$, and uniformity ratio. Then, the subsequent refined analysis is performed to set the functional relations of

Table 27.2 Energy model input data

Input data		Standard code
Office working hours	9 a.m. to 6 p.m. (Mon–Sat)	
Construction for energy simulation		
Heat transfer coefficient of wall (U-value)	0.44 W/m^2 K	NBC 2016
Heat transfer coefficient of the roof (U-value)	Adiabatic	
Heat transfer coefficient of the floor (U-value)	Adiabatic	
Heat transfer coefficient of glazing (U-value)	2.74 W/m^2 K	NBC 2016
Materials for daylight simulation		
Wall, ceiling and floor reflectivity	0.6, 0.8, 0.3	SP41 (BIS)
Infiltration	0.000542 m^3/s.m^2	ASHRAE 2009
People	0.10 people/m^2	NBC 2016
Occupancy schedule	As shown in Table 27.3	ECBC 2016
Metabolic rate	120 W/person	ASHRAE 55
Equipment load	10.8 W/m^2	ASHRAE 2009
Equipment schedule	As shown in Table 27.3	ECBC 2016
Electrical lighting power density (LPD)	11.8 W/m^2	NBC 2016
Lighting schedule	From daylight analysis	
Mechanical ventilation		
Ventilation per area	0.0003 m^3/s.m^2	NBC 2016
Ventilation per person	0.0025 m^3/s	NBC 2016
Heating and cooling schedule	On from 9 a.m. to 6 p.m.	
Heating and cooling temperature setpoint	24–27 °C	IMAC model

NBC National Building Code; *BIS* Bureau of Indian standards; *ASHRAE* The American society of Heating, Refrigerating, and Air-conditioning Engineers; *ECBC* Energy Conservation Building Code; *IMAC* India Model for Adaptive (thermal) Comfort

Table 27.3 Occupancy schedule and equipment schedule

Schedule	0–7	7–8	8–9	9–13	13–14	14–18	18–19	19–22	22–24
Occupancy	0	0.1	0.2	1	0.5	1	0.3	0.1	0
Equipment	0	0	0	1	1	1	1	0	0

how the variables affect the objective functions. Finally, the optimization of design variables is performed to yield the optimum outputs from the derived functions.

27.4.1 Analysis of Screening Experiment Results

All data were analyzed using Statistical Package for the Social Sciences (SPSS) tool.

Table 27.4 Model summary for total load

Model summary[a]

Model	*R*	*R* square	Adjusted *R* square	Std. error of the estimate	Durbin–Watson
1	0.526[b]	0.277	0.276	19.66943	
2	0.715[c]	0.511	0.510	16.18155	
3	**0.731**[d]	**0.535**	**0.533**	**15.79169**	**0.841**

[a] Dependent variable: normalized total load
[b] Predictors: (constant), LSR
[c] Predictors: (constant), LSR, shading device
[d] Predictors: (constant), **LSR**, **shading device**, **WWR**

Table 27.5 Stepwise regression result for total load

Coefficients[a]

Model		Unstandardized coefficients		Standardized coefficients	*t*	Sig.	Correlations		
		B	Std. error	Beta			Zero-order	Partial	Part
3	(Constant)	158.644	1.914		82.866	0.000			
	LSR	−33.945	1.299	**−0.526**	−26.134	**0.000**	−0.526	**−0.611**	**−0.526**
	Shading device	−74.552	3.102	**−0.484**	−24.035	**0.000**	−0.484	**−0.579**	**−0.484**
	WWR	26.939	3.524	**0.154**	7.644	**0.000**	0.154	**0.220**	**0.154**

[a] Dependent variable: normalized total load

Total Energy Consumption. Tables 27.4 and 27.5 present the result of stepwise regression using SPSS. There are three steps that are used to select the controlled variables. For the total energy consumption, the value of *S* (Std. Error of the Estimate) decreases from step 1 to step 3, R-Sq and R-Sq (adj) in step 3 is higher than step 1 and step 2. Hence, these statistics indicate step 3, which contains independent variables LSR, Shading device, and WWR that better fit to the data. The value of R-Sq is 0.535 (Model 3) which shows that there are 53.5%

Table 27.6 Model summary daylight autonomy

Model summary[a]

Model	*R*	*R* square	Adjusted *R* square	Std. error of the estimate	Durbin–Watson
1	0.734[b]	0.539	0.539	20.47887	
2	0.807[c]	0.651	0.650	17.83925	
3	0.819[d]	0.670	0.669	17.33918	
4	**0.819**[e]	**0.671**	**0.670**	**17.31731**	**0.385**

[a] Dependent variable: DA
[b] Predictors: (constant), LSR
[c] Predictors: (constant), LSR, WWR
[d] Predictors: (constant), LSR, WWR, shading device
[e] Predictors: (constant), LSR, WWR, shading device, No. of windows

Table 27.7 Stepwise regression result daylight autonomy

Coefficients[a]

Model		Unstandardized coefficients		Standardized coefficients	*t*	Sig.	Correlations		
		B	Std. error	Beta			Zero-order	Partial	Part
4	(Constant)	**−10.780**	2.289		−4.709	0.000			
	LSR	**61.780**	1.424	**0.734**	43.374	**0.000**	0.734	**0.788**	**0.734**
	WWR	**76.214**	3.865	**0.334**	19.721	**0.000**	0.334	**0.503**	**0.334**
	Shading device	**−28.132**	3.401	**−0.140**	−8.271	**0.000**	−0.140	**−0.237**	**−0.140**
	No. of Windows	**0.451**	0.228	**0.033**	1.975	**0.048**	0.033	**0.058**	**0.033**

[a] Dependent variable: DA room

(R = 0.731) changes are occurred in dependent variable because of changes in the combination of three predictor variables.

Daylight Autonomy. Tables 27.6 and 27.7 present the result of stepwise regression using SPSS.

There are four steps that used to select the controlled variables. For the DA, the value of S (Std. Error of the Estimate) decreases from step 1 to step 4, R-Sq and R-Sq (adj) in step 4 is higher than step 1, 2 and 3. Hence, these statistics indicate step 4, which containing independent variables LSR, shading device, and WWR is provided better fits to the data. The value of R-Sq is 0.671 (Model 4) which shows that there are 67% (R = 0.819) changes occurred in dependent variable because of changes in the combination of selected four variables.

Uniformity. Tables 27.8 and 27.9 present the result of stepwise regression using SPSS.

The value of S (Std. Error of the Estimate) decreases from step 1 to step 5, R-Sq and R-Sq (adj) in step 5 is higher than step 1, 2, 3, and 4. Hence, these statistics

Table 27.8 Model summary daylight uniformity

Model summary[a]

Model	*R*	*R* square	Adjusted *R* square	Std. error of the estimate	Durbin–Watson
1	0.516[b]	0.266	0.266	0.05841	
2	0.723[c]	0.523	0.522	0.04713	
3	0.863[d]	0.745	0.744	0.03448	
4	0.866[e]	0.750	0.749	0.03413	
5	**0.867**[f]	**0.752**	**0.751**	**0.03404**	**0.927**

[a] Dependent variable: mean daylight uniformity

[b] Predictors: (constant), shading device

[c] Predictors: (constant), shading device, No. of windows

[d] Predictors: (constant), shading device, No. of windows, WWR

[e] Predictors: (constant), shading device, No. of windows, WWR, Window height

[f] Predictors: (constant), **shading device**, **No. of windows**, **WWR**, **window height**, **sill level**

Table 27.9 Stepwise regression result daylight uniformity

Coefficients[a]										
Model		Unstandardized coefficients		Standardized coefficients	*t*	Sig.	Correlations		
		B	Std. error	Beta			Zero-order	Partial	Part
5	(Constant)	0.035	0.008		4.502	0.000			
	Shading device	0.234	0.007	0.516	35.057	**0.000**	0.516	**0.719**	**0.516**
	No. of Windows	0.015	0.000	0.506	34.396	**0.000**	0.506	**0.713**	**0.506**
	WWR	0.265	0.009	0.514	30.201	**0.000**	0.471	**0.666**	**0.445**
	Window height	−0.012	0.002	−0.085	−5.007	**0.000**	0.173	**−0.146**	**−0.074**
	Sill level	0.016	0.006	0.039	2.619	**0.009**	0.039	**0.077**	**0.039**

[a]Dependent variable: mean daylight uniformity

Table 27.10 Shared and unique contribution of independent variable

	Contribution	Glazing material (%)	Shading device (%)	WWR (%)	No of windows (%)	Window height (%)	Sill level (%)
Total load	Shared	37.33	33.52	4.80	–	–	–
	Unique	27.66	23.42	2.37	–	–	–
Daylight autonomy	Shared	62.09	5.62	25.30	0.34	–	–
	Unique	53.87	2	11.16	0.10	–	–
Daylight uniformity	Shared	–	51.70	22.18	50.84	3	0.59
	Unique	–	26.62	19.80	25.60	0.54	0.15

indicate step 5, which contain independent variables depth of shade, no. of windows, WWR, window height, and sill level provide better fits to the data. The value of R-Sq is 0.752 (Model 5) shows that there is 75.2% ($R = 0.867$) changes are occurred in dependent variable (mean daylight uniformity) because of changes in the combination of five selected variables.

Table 27.10 shows the shared and unique contribution of the independent variable to the dependent variable.

27.4.2 Analysis of Most Effective Parameters

Table 27.11 shows the standard deviation results for the summed energy load, DA and $\mathrm{UDI}_{300\text{–}2000\ \mathrm{lx}}$ by a combination of shading device—LSR of glazing material and shading device—WWR. According to the data, window material which has

Table 27.11 Standard deviation for dependent variables by a combination of parameters

		Total load		Daylight autonomy		$UDI_{300–2000\ lx}$	
		Without shade	With shade	Without shade	With shade	Without shade	With shade
LSR	0.56	5.48	8.19	**19.46**	15.9	16.96	15.29
	0.89	9.06	**9.47**	14.14	**20.44**	9.17	**18.37**
	1.13	**25.87**	8.09	1.84	4.51	**17.56**	12.75
	1.54	10.19	4.53	5.24	10.16	12.01	8.3
WWR	0.2	269.16	**404.64**	**31.08**	32.93	**26.44**	**30.97**
	0.3	276.13	403.34	27.22	**33.76**	20.22	30.13
	0.4	370.27	313.82	21.19	30.41	14.2	25.35
	0.5	565.83	212.85	15.85	25.06	12.68	19.49
	0.6	**846.89**	158.27	11.08	19.24	15.86	16.11

1.13 LSR shows the highest deviation in total load and $UDI_{300–2000\ lx}$ both when there is no shading device, but after applying shading device, LSR 0.89 shows the maximum deviation in total load, DA, and $UDI_{300–2000\ lx}$. It shows that these glazing materials are most affected by WWR, and careful consideration is needed when a window system is intended to be installed with LSR 0.89 (with shade), LSR 1.13 (without shade).

Table 27.12 shows the standard deviation and median results for the daylight uniformity, by a combination of shading device—no. of windows, shading device—WWR and shading device—window height. Data shows that as no. of windows increases standard deviation decreases but the median value of uniformity increases which indicates that more no. of windows give a better distribution of daylight. WWR 20, 30, and 40% have the highest deviation which indicates that these options are most affected by no. of windows, shading device, and window height and careful consideration is needed to choose the parameters. On the other hand, 60% WWR has the least standard deviation which indicates that this option is least affected by other parameters. Window heights 2 and 2.5 m have the highest deviation which indicates that these options are most affected by other parameters. Shading device increases the daylight uniformity.

Without shading device, 60% WWR shows the highest deviation in total load and 20% WWR shows in DA and $UDI_{300–2000\ lx}$. With shading device, 20–30% WWR shows the highest deviation in total load, DA and $UDI_{300–2000\ lx}$, which means these options are most affected by glazing material, and careful consideration is needed to choose the window glazing material when WWR is 60% (without shade) and 20–30% (with shade).

In Fig. 27.1, scatterplot graph with a cubic fit line of the total load, DA, $UDI_{300–2000\ lx}$, and uniformity with different WWRs, window material and shading device show the following.

Without shading device, LSR 0.56, WWR = 60% and for LSR 0.89, WWR = 30% gives the minimum total energy consumption. With shading device, LSR 0.56 with

Table 27.12 Standard deviation for uniformity by a combination of parameters

		No. of windows				WWR					Window height			
		1	3	5	7	0.2	0.3	0.4	0.5	0.6	1	1.5	2	2.5
Std. dev	Without shade	**0.05**	0.02	0.02	0.02	**0.04**	**0.04**	**0.04**	0.03	0.01	0.02	0.04	0.04	**0.05**
	With shade	**0.07**	0.05	0.04	0.04	0.05	**0.06**	**0.06**	0.05	0.02	0.04	0.06	**0.07**	**0.07**
Median	Without shade	**0.11**	0.19	0.2	0.2	0.17	0.19	0.2	0.21	0.22	0.16	0.18	0.19	0.2
	With shade	**0.14**	0.25	0.28	0.28	0.23	0.27	0.3	0.32	0.34	0.24	0.25	0.27	0.27

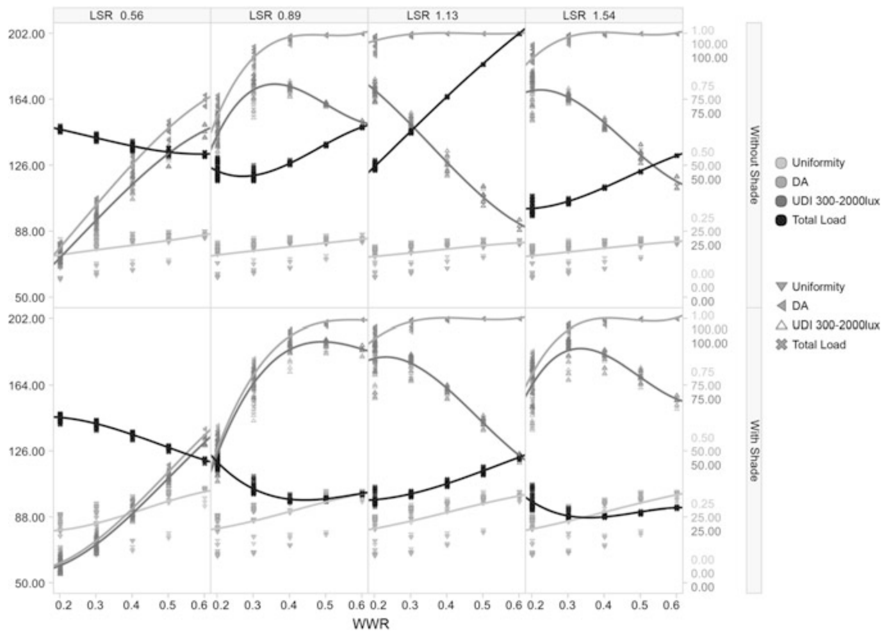

Fig. 27.1 Effect of WWR for each glazing material on energy consumption and daylight

60% WWR, LSR 0.89 with 40–50% WWR and LSR 1.54 with 30–40% WWR gives the minimum total energy consumption. Shading device reduces total energy consumption in all the cases because it reduces the amount of solar gain. Glazing material which has 1.54 LSR had the best performance in both the cases.

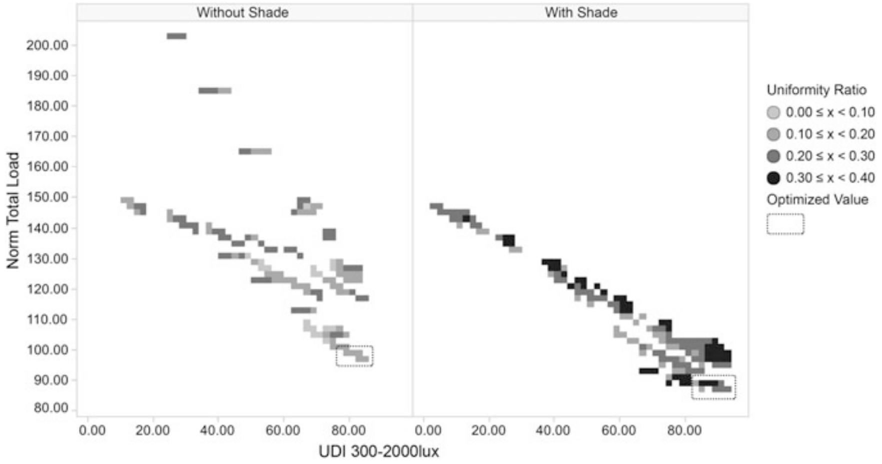

Fig. 27.2 Binned scatter plot between $\mathrm{UDI}_{300\text{–}2000\ \mathrm{lx}}$ and total load for optimization

Table 27.13 Simulation results for the selected parameters for optimization

LSR	Window ht.	No. of win.	WS * 0.2 * 1	WS * 0.2 * 1.2	WS * 0.3 * 0.8	S * 0.3 * 1	S * 0.3 * 1.2	S * 0.4 * 0.8	S * 0.4 * 1
1.54	1.5	3				87.7|90|0.28	87.4|92|0.26		
		5				87.8|90|0.29	87.5|92|0.29		
		7				88.0|90|0.27	87.6|92|0.28		
	2	3		97.9|85|0.18	87.9|89|0.24	87.3|91|0.25	87.2|92|0.23		
		5		97.9|84|0.20	87.9|89|0.27	87.3|91|0.28	87.2|93|0.27		88.4|87|0.31
		7		97.7|84|0.19		87.6|91|0.28	87.4|92|0.27		88.7|87|0.32
	2.5	3	98.0|85|0.18	97.5|86|0.18	88.0|90|0.24	87.5|91|0.24	87.4|92|0.25		
		5	97.9|84|0.19	97.3|86|0.20	87.9|91|0.27	87.6|91|0.28	87.5|93|0.28	89.0|86|0.31	88.8|87|0.31
		7	97.9|84|0.19	97.4|85|0.19		87.7|91|0.27	87.7|93|0.28	89.3|86|0.3	89.0|86|0.31

Parameter: WS (without shade) or *S* (with shade) * WWR * sill level
Results: Total load\|$\mathrm{UDI}_{300\text{–}2000\ \mathrm{lx}}$\|uniformity

When LSR is 0.56, DA and $\text{UDI}_{300\text{–}2000\ \text{lx}}$ both increases as WWR increases. When LSR is 0.89, in both the cases with and without shade DA increases as WWR increases and after a certain point of time it reaches maximum but $\text{UDI}_{300\text{–}2000\ \text{lx}}$ start to decrease.

Without shading, LSR 1.13 and 1.54 at 20% WWR and LSR 0.89 at 30–40% shows maximum DA and with shading device LSR 1.54 at 30–40% WWR and LSR 0.89 at 40–50% WWR shows the maximum $\text{UDI}_{300\text{–}2000\ \text{lx}}$, Shading device increase the $\text{UDI}_{300\text{–}2000\ \text{lx}}$ in all cases.

27.4.3 Optimization

To identify optimum solution for the window parameter which can give the minimum total load with maximum $\text{UDI}_{300\text{–}2000\ \text{lx}}$ and uniformity ratio, binned scatter plot between total load and $\text{UDI}_{300\text{–}2000\ \text{lx}}$ has been created and is shown in Fig. 27.2.

In the binned scatter plot, binned boxes which fulfilled the optimization requirement has been selected. Selected window parameters which gave the optimized result are mentioned in Table 27.13. Values in cells have been written as Total Load $|\text{UDI}_{300\text{–}2000\ \text{lx}}|$ Uniformity.

27.5 Conclusion

The analysis of experimental office design provided a rank list of important window design parameters affecting total load as well as daylight in the office building. Glazing material was found to be the most significant design parameter together with WWR and shading device for total load and DA. The number of windows, shading device, and WWR were found to be most significant for daylight uniformity. From the study, it can be concluded that indoor daylight quality, quantity, and energy consumption is controlled by a combination of several parameters of building envelope. The optimized parameters will have different characteristics for a different location, building typology, room proportions, and when additional criteria for embodied energy, maintenance cost, surrounding condition, etc., are included.

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