Optimization of Daylighting and Energy Performance in Bangladesh Ready-Made Garment Factories: Use of Parametric Design, Simulation Modeling, and Genetic Algorithms

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Abstract

The ready-made garment (RMG) sector is an essential contributor to the economy of Bangladesh. Most RMG buildings in the country are often found to be inefficient in terms of natural light, energy consumption and the thermal comfort of the workers. Computational modeling, simulation and optimization analysis could be used during the building planning and design phases to effectively integrate these three issues and improve the working environment. This research first evaluates both daylighting and energy performance of a real-world existing air-conditioned RMG factory building in Dhaka. Next, an optimized design solution is proposed for the factory. Finally, we correlate the relationship between design variables and performance metrics. Nine independent variables (north, south, east and west window-to-wall ratios and shading; and skylights) are identified to evaluate performance. The variables are connected with parametric sliders (value expressed by a range of numbers despite a constant value), so that performance can be checked for different possible configurations. Rhinoceros, Grasshopper, ClimateStudio, Octopus, TT toolbox, and Energy plus™ software with plugins are used to conduct the optimization process. Genetic Algorithms are used to narrow down the optimization results and identify the best options that comply with the multi-objective goal. Predicted Percentage of Dissatisfaction (PPD) is also analyzed for the best options identified from the optimization process. The result shows the balanced option (best for both daylighting and energy) with changed materials satisfies the thermal comfort of users.

1. Introduction

Ready-made garment (RMG) factories in Bangladesh have been heavily criticized for their working conditions. More than 80 % of the export earnings of Bangladesh come from the RMG sector (Islam, 2021) and about four million people are involved in this industry. In the factories, workers are engaged in sewing, ironing, packing, tailoring, operating machines and other labor-intensive works. Due to the nature of their work and the heat generated from machinery, the indoor environment of the factories is often uncomfortable and workers suffer a range of health problems that affect the individual as well as the overall productivity of the factory. In RMG factories, along with other physical conditions, the quality of the luminous environment is affected by poor natural lighting systems and high internal heat gain from artificial lighting (Hossain & Ahmed, 2013). This creates an intolerably hot and uncomfortable working environment for the workers that is non-compliant with national and international standards. Since lighting directly affects visibility, light is critical to the productivity, safety and healthy working conditions of workers (Zohir & Majumder, 2008). Industrial workers spend more than 90 % of their lives in artificial luminous environments and in such conditions, natural light could work as medicine (Gligor, 2004). Different studies have shown that lighting is one of the biggest consumers of power in the RMG sector, accounting for around 21-35 % of the total

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energy consumption (EAC, 2009). Much work has been done to reduce the power consumption of machinery in RMG factories; however, developments in the areas of lighting, heating and ventilation are limited (Godiawala et al., 2014).

Appropriate use of daylight and removing generated heat by effective natural and/or artificial ventilation systems can be an effective means to reduce energy consumption and excessive cooling load. With the appropriate use of technology, it is anticipated that the energy consumption in the building sector can be reduced to about 30 % to 80 % (Gupta, 2017). Due to current environmental concerns, energy saving has become the leading driving force in modern research (Bojic et al., 2013). Appropriate architectural design can reduce the energy consumption of heating or air conditioning systems significantly (Kalmár & Csiha, 2006). The EU energy policy in the buildings sector, including technical solutions and legal procedures, aims to improve the energy performance of buildings and guarantee human comfort (Tronchin & Tarabusi, 2013).

In recent times, to ensure workers' comfort and productivity, the construction of fully air-conditioned factory buildings with excessive artificial lighting has been gaining in popularity among owners and management of RMG factories in Bangladesh. Electricity-based carbon-intensive air conditioning and lighting systems can result in a significant amount of energy consumption. On the other hand, the use of daylight with passive or hybrid ventilation systems requires less energy to operate, while at the same time having less impact on the environment, carbon emissions and climate change. Using a case study approach based on a real RMG factory in Dhaka, this research presents a system for improving indoor lighting conditions and comfort by integrating passive strategies for the existing garment factories of Bangladesh. The research addresses the growing threat to worker health and productivity from the visual and heat stress that may be caused by climate change and seeks to identify sustainable passive strategies that will not add to the burden of greenhouse gas emissions.

2. Case Study

The case building is an 864-square-meter factory building with a pitched roof (Fig. 1). The building is north facing (Fig. 2: top) towards the access road. The roof is made of a metal sheet adjacent to a truss frame structure (Fig. 2: bottom). The north façade of the factory has two large gates (6 meters x 2.5 meters) made of steel. During working hours, these two gates remain closed for security purposes. So, for simulation modeling, the north façade of the base case was provided with no opening.

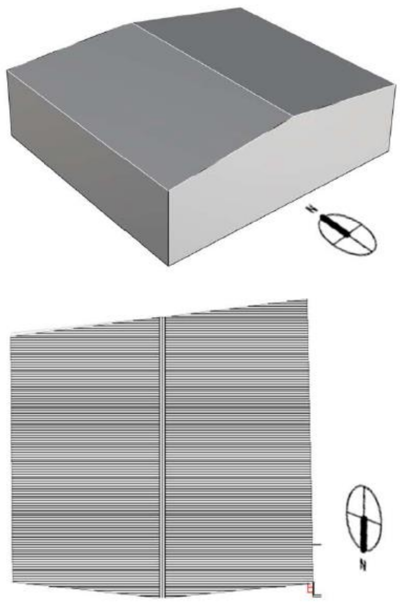


Fig. 1 – Rhinoceros model for case RMG factory (top) and top view of the roof (bottom)

A Kestrel 5400 pro instrument was installed inside the factory to measure air temperature, relative humidity (RH), wind speed, and black and wet bulb globe temperatures (Table 1). Three wireless tag loggers made by OnSolution were also placed at different locations inside the factory to measure temperature and RH. The collected data were cross-checked with the base case simulation modeling for validation.

3. Method

This study seeks to test and verify the effectiveness of optimization processes in the tropical climatic context, in this case, Bangladesh. Based on the

RMG factory described in Section 2, the internal conditions were optimized for the target parameters of daylighting and energy consumption. There are six main steps for the research, as explained below.

Fig. 2 – North side view of the case factory building (top), floor plan (middle), and inside view of the RMG factory (bottom) (pictures by Photographer Md M A R Joarder, 2020)

The first step is to select an RMG building for a case study. This research selected a single-storey RMG building constructed with steel and brick, located in northwest Dhaka (Fig. 2). The factory undertakes garment manufacture, from cutting through sewing and ironing to packing. A physical survey was conducted in the first step to measure the existing configuration and collect the climate data (Table 1) that is required for simulation analysis.

Table 1 – Indoor and outdoor mean maximum temperature (T_{max}) and mean minimum relative humidity (RH_{min}) between 08:00 and 18:00 on the days the factory was operating in 2021

	Indoor	Outdoor
January (*n*=308 hours over 28 days)		
T_{max} (°C)	28.6	24.5
RH_{min} (%)	44.2	50.3
March (*n*=264 hours over 24 days)		
T_{max} (°C)	29.6	33.3
RH_{min} (%)	59.9	38.8
September (*n*=286 hours over 26 days)		
T_{max} (°C)	30.1*	32.6
RH_{min} (%)	62.4*	64.3
All of 2021 (*n*=3234 hours over 294 days)		
T_{max} (°C)	30.9^	30.6
RH_{min} (%)	58.7^	55.9

*30 hours of missing data not included
^ 39 hours of missing data not included

The second step was to prepare the 3D model using the data collected during the physical survey. The simulation of the base case factory building was carried out at this step. Materials and other information for zones were transferred into simulation settings and Grasshopper scripts accordingly. In this script, the workflow could be divided into six parts. Part A was the components for developing the building geometry (floor, wall, roof, window, shading and skylight). The geometry was connected to components in Part B for energy and daylighting modeling. In this part, material selection for individual elements of the building, sensor grid settings for daylighting, zone settings, adiabatic and boundary condition settings were operated. The daylight model was connected to components in Part C for daylighting simulation. In this part, various simulation-related settings were identified (e.g., the number and name of the objectives and ClimateStudio Result [CSR] settings). Part D connected both the energy model from Part B and the daylighting simulation output from Part C for energy simulation. Part E was the components for optimization. Part F was the components for data output (Fang, 2017).

The third step was to run the optimization process for Option 1 (the best option for daylighting). Grasshopper script was prepared for modeling the case space with parametric design variables. Phenotype toggle in Octopus is connected with daylight performance batteries (LEED: Leadership in Energy and Environmental Design credit; sDA: Spatial Daylight Autonomy; ASE: Annual Sunlight Exposure; and Mean Illuminance) and energy performance batteries were skipped, as the best daylighting option was the target. As windows have a large-scale impact on daylighting and thermal comfort considering their size, orientation and shading configurations, as well as on the energy consumption of the building, it was thus necessary to optimize window design for maximum benefit (Aman, 2017).

The fourth step was to run the optimization process for Option 2 (the best option for energy). The overall procedure was similar to daylighting optimization. The difference was only in the optimization objective, which is Energy Use Intensity (EUI), and CO_2 emissions. Daylighting performance batteries were skipped here, as the best energy option is the target. Therefore, the Phenotype toggle in Octopus was connected with EUI and CO_2 only.

The fifth step was to run the optimization process for option 3 (the balanced option for daylight and energy both). In this step, three performance objectives (e.g., sDA, ASE and EUI) were identified to run the simulation. Octopus by default found the minimum value of each objective, so the objective to be maximized (sDA) should be multiplied by -1. Pareto Frontiers with the trade-off between each performance metric were found after the optimization process.

In the final (6^{th}) step, Percentage of Mean Vote (PMV) and Predicted Percentage of Dissatisfaction (PPD), analyses were carried out to check thermal comfort inside the factory space. ClimateStudio and Grasshopper were used to run this analysis as well. Five simulations were run in this step (for Base case, Op1- Daylighting, Op2- Energy, Op3- Balanced, and Op4- Balanced and changed materials). Comparing the results of these five simulations, the best one complying with both the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) standard and the Bangladeshi standard (BNBC, 2020) and which could provide thermal comfort inside the factory, was identified.

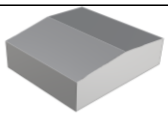
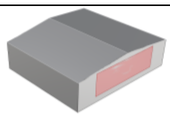
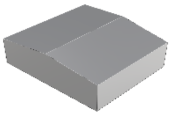
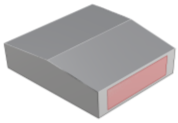
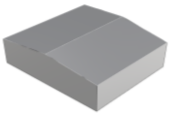
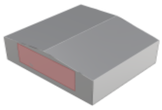
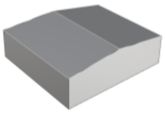
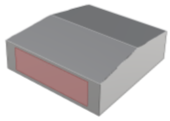
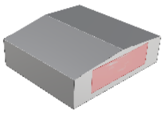
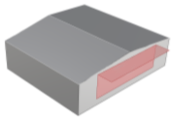
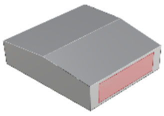
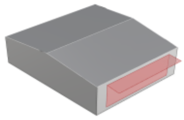
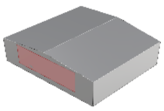
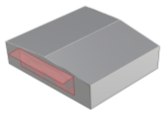
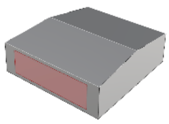
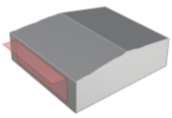
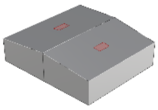
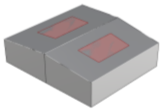
4. Simulation and Results

In this research, the percentage of windows and skylights, and depth of shading was explored for optimal daylighting and energy performance. There were no windows and shading on any of the façades of the factory building, and no skylight on the roof. For the modeling of the optimization process focusing on daylighting and energy, the placement of the doors and the interior partitions was not considered. The model was developed with Rhinoceros 7.1 (Fig. 1) and Grasshopper scripting. ClimateStudio 1.1 plugins were used for simulation. Existing data collected through factory visits were used for zone settings while simulations were conducted. There were 26 daylighting sensors evenly spaced at a height of 0.75 meters above the floor. Some building parameters were fixed throughout the optimization process: the height of the building from the ground to the edge of the pitched roof was 5 meters; windows were considered from 0 to 100% of the façade; areas of skylight were considered from 0 to 20% of the roof surface.

Building material details found during the physical survey were used in the model. To avoid excessive heat gain or heat loss from the skylight, an insulated translucent material was used as its glazing material. The material had a U-value of 0.45 W/(m^2 K). The reflectance of the ceiling, floor, interior, exterior walls, and shading were 0.8, 0.2, 0.5, 0.5, and 0.8 respectively. The windows had a transparent material with visible transmittance of 0.65. Skylights had a translucent material with a transmittance of 0.24. Nine independent design variables for the building geometry were analyzed: north, south, east and west windows to wall ratios [WWR] and shade; and Skylights. Table 2 shows the minimum (0 % for WWR, 0.0m for shade and 2 % for skylight) and maximum (100 % for WWR, 2.0 m for shade and 20 % for skylight) values of the variables and the ranges used during simulation analysis. The daylighting simulation output included sDA and ASE.

The energy simulation output Included annual heating, cooling, equipment and lighting energy loads. Since the equipment load stays the same for studied design options, it was not considered. The energy optimization objective was to ensure the minimum total energy load. The total energy load was the sum of heating, cooling, and lighting loads. EUI was also calculated by dividing the total energy load by the occupied floor area of the factory building.

Table 2 – Design variables and ranges for simulation analysis

	Variable	Minimum	Maximum
1	WWR-North	 No windows	 Full-wall windows
2	WWR-East	 No windows	 Full-wall windows
3	WWR-South	 No windows	 Full-wall windows
4	WWR-West	 No windows	 Full-wall windows
5	Shade Depth-North	 No shade	 2.0m shade
6	Shade Depth-East	 No shade	 2.0m shade
7	Shade Depth-South	 No shade	 2.0m shade
8	Shade Depth-West	 No shade	 2.0m shade
9	Skylight	 2 %	 20 %

4.1 Base Case Modeling and Analysis

The first simulation was conducted for the base case, to understand the existing status of the building in terms of daylighting and energy performance. The model was prepared considering the exact dimensions of the building collected during the physical survey. The weather data file for Dhaka was used during the simulation process. The building was counted as air-conditioned and values of independent variables (windows, shading and skylight) were set to 0 (zero) representing the existing building. Simulation results for LEED credit, sDA, ASE, mean illuminance values, EUI and CO_2 emissions were 0, 0 %, 0 %, 0 lx, 223 kWh/(m² yr) and 198 kg_{CO2e}/(m² yr), respectively.

4.2 Optimization of Daylighting

The second simulation was conducted for the best daylighting results (Option 1). In this simulation, the population size was set to 20 and maximum generations were set to 10. In total, 200 iteration process were carried out to identify the best daylighting results. Pareto Front algorithm identified the best configurations among these combinations. Four daylighting performance objectives (LEED credits, sDA, ASE and mean illuminance) were set to run this optimization process. Table 3 shows the results of the simulation. LEED credit, sDA, ASE and mean illuminance values for the best daylighting case results are 3, 1 (100 %), 0.134 (13 %) and 1003 lx, respectively. In Fig. 3 (top), Pareto Front 3-dimensional graph shows the optimized results along with the Pareto Frontier (marked with a red circle).

4.3 Optimization of Energy

The third simulation was conducted to find the best energy consumption (Option 2). The process is similar to the prior simulation. The only difference is that two energy performance objectives (EUI and CO_2 emissions) were set to run this optimization. In Table 3, the third column presents the values of the independent variables that resulted from the optimization process and which were identified through the Pareto Front algorithm. The EUI and CO_2 emissions for the best energy case are

56 kWh/(m² yr) and 46 kg_{CO2e}/(m² yr), respectively. In Fig. 3 (middle), the Pareto Front 3-dimensional graph shows the studied iterations with the optimized one highlighted.

Table 3 – Optimization results for three different options

Design Variables	Op 1 (Daylighting)	Op 2 (Energy)	Op 3 (Balanced)
WWR- North (%)	82.5	40	100
WWR-East (%)	43	4	10
WWR-South (%)	7.5	24	22.5
WWR-West (%)	80	34	10
Shading-North (m)	1.17	1.86	1.58
Shading-East (m)	1.72	0.95	1.04
Shading-South (m)	1.52	0.09	1.84
Shading-West (m)	0.32	0.39	1.01
Skylight (%)	23	10	7

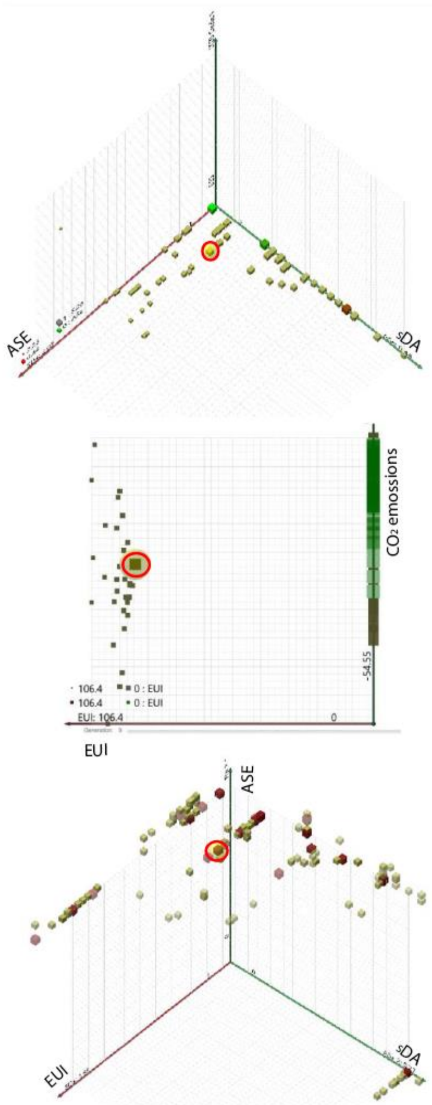


Fig. 3 – Pareto Front analysis for daylighting optimization (top), energy optimization (middle) and multi-objective optimization (bottom)

4.4 Optimization of Balanced Option

A Pareto optimization aims to find the trade-off front (ParetoFront) between multiple outcome objectives. The Octopus plugin handled the multi-objective optimization process using Pareto-Front algorithms (Aman et al., 2021). The fourth simulation was conducted for Option 3 (the balanced option for daylighting and energy combined). The simulation process was similar to the prior two simulations. Fig. 4 (top) shows the factory model while the optimization process of Op3 is running. Fig. 4 (bottom right) shows the ranges slider of nine variables in the Grasshopper script for this optimization. A large number of combinations are possible among these nine variables and within their ranges. Fig. 4 (bottom left) shows the values of six performance metrics (LEED credit, sDA, ASE, mean illuminance, EUI and CO_2 emissions) generated in this process. Later, three performance metrics (sDA, ASE and EUI) were considered for Pareto Front analysis to make the process simplified. The outcomes of the simulation studies are presented in Table 3 (fourth column, Op 3 Balanced; the values of design variables).

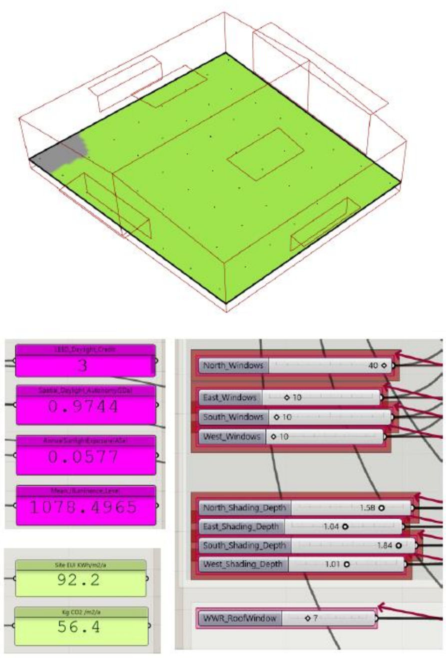


Fig. 4 – Rhinoceros model showing simulation process (top); results for six performance objectives appeared in Grasshopper script (bottom left); and Grasshopper slider for parametric design (bottom right)

In Fig. 3 (bottom), Pareto Front 3-dimensional graphs show different optimized results and locations (marked with a red circle) of the Pareto Frontier (the best one). sDA, ASE and EUI values for balanced option case are 0.90 (90 %), 0.09 (9 %) and 89 kWh/(m^2 yr), respectively.

Comparing the results of performance metrics for the base case (explained in Section 4.1) and the balanced option case reveals that the latter is performing effectively.

4.5 Thermal Comfort Analysis

By understanding the thermal behavior of the existing situation of factory buildings, owners can improve the indoor environment quality to increase their production (Sayem et al., 2011). The fifth simulation was conducted for analyzing the PPD. In this process, thermal comfort performance was checked for Base case, Op1 (daylighting), Op2 (energy), Op3 (balanced) and Op4 (balanced and changed materials). Design variables found in previous simulation results (presented in Table 3) were used in this study. In the base case, variables remain 0 (zero), as there were no windows, sunshades and skylights in reality. In Op4, variables were kept similar to Op3 (balanced), except for the changes of material for the roof and wall. 300 mm concrete, 80 mm insulation and 80 mm cement screed were used for the roof and walls. ClimateStudio's default script for spatial comfort analysis in the Grasshopper interface was used to run the PPD simulation. The building was considered non-AC during this simulation. Keeping the model static, the PPD analysis was performed by changing the values of design variables presented in Table 3.

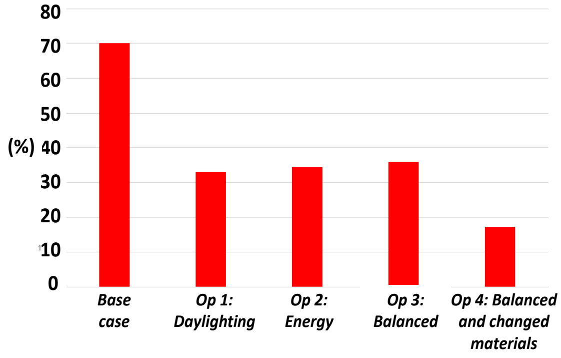


Fig. 5 – PPD results for the base case, daylighting, energy, balanced, and balanced and changed materials

In the case of Op4, in the Grasshopper script, roof and wall materials were changed from zone settings. Fig. 5 shows that the PPD value for the base case is 70 %, for Op1 32.9 %, for Op2 34.4 %, for Op3 35.9 % and for Op4 17.3 %. Although in ASHRAE standard below 10 % is recommended for thermal comfort, the value of 17.3 (below 20 %) for Op4 is also acceptable in the context of Bangladesh climate. The other 4 options do not comply with the ASHRAE standard and Bangladesh Standard (BNBC, 2020).

5. Conclusion

The global increase in demand for energy has generated pressure to save energy. Consequently, energy-efficient buildings are an important factor related to the energy issue (Jahangir et al., 2014). High-energy performance buildings can save primary energy and reduce CO_2 emissions. Optimization processes successfully present the ability to adapt to various design environments and provide design options with significant performance improvement. As a result, this method can be considered a valid approach (Fang, 2017). This research conducts three optimization processes and the results show that the configuration of the variables is changed in terms of Op1 (daylighting), Op2 (energy), and Op3 (balanced) (Table 3). The research recommends variables of Op3 (balanced) for RMG buildings in the context of Bangladesh, as it complies with both daylight and energy optimization. On the other hand, in the case of thermal comfort analysis, Op4 (balanced and changed materials) shows the best results among the options studied. In a nutshell, the features for RMG buildings in the climatic context of Bangladesh are: WWR-north 100 %, WWR-east 10 %, WWR-south 22.5 %, WWR-west 10 %, shade depth north- 1.35 m, shade dept east- 1.58 m, shade depth south- 1.63 m, shade depth west- 1.55 m, skylight- 10 %, roof and wall materials: 300 mm concrete, 80 mm insulation, and 80 mm cement screed performed the best among the options studied in terms of daylight penetration, energy consumption and providing thermal comfort. The features can be incorporated as strategies for sustainable RMG building design in Bangladesh.

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Nomenclature

AC	Air Conditioning
ASE	Annual Sunlight Exposure
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
CSR	ClimateStudio Results
EUI	Energy Use Intensity
LEED	Leadership in Energy and Environmental Design
PMV	Percentage of Mean Vote
PPD	Predicted Percentage of Dissatisfaction
RH	Relative Humidity
RMG	Ready-Made Garment
sDA	Spatial Daylight Autonomy

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