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Generation of typical meteorological year for integrated Climate Based Daylight Modeling and building energy simulation

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Abstract

Daylight plays an indispensable role in promoting the energy efficiency of buildings and satisfying the health and productivity requirements of occupants. Dynamic daylight and thermal modeling approaches have been widely adopted to evaluate the energy performance of daylight-utilized design. At present there has been no typical meteorological year (TMY) files specifically developed for daylight-utilized building energy simulation. In this study, a feasible TMY generation method is developed specifically for integrated Climate Based Daylight Modeling and building energy simulation (CBDM-BES). Based on the Sandia method, the proposed TMY generation leverages building energy simulation and NSGA-II algorithm to directly link energy prediction and weighting scheme assignment during the generation process. Monthly and annual deviations of multiple energy consumption parameters from long-term average performance are applied as multi-objective functions. An application example of Hong Kong indicates that, with the generated TMY file, simulated results of multiple energy consumption parameters are simultaneously close to the long-term average on both the monthly and annual basis. The proposed TMY generation method is found effective in generating feasible TMY file for CBDM-BES. The workflow of the proposed TMY generation also facilitate it to be implanted as a module in future architectural parametric design.

Keywords: Typical Meteorological Year; Building energy simulation; Climate Based Daylight Modeling; Architectural parametric design

1. Introduction

IEA Annex 53 summarizes the six factors that can affect building energy consumption as climate, building envelopes, equipment, operation and maintenance, occupant behavior, and indoor environmental conditions [1]. As one of the unique and important factors, local climate can directly affect the performance of daylighting and energy saving measures in buildings, especially for air conditioning system, daylight-linked lighting system control, solar energy measures and other renewable power systems [2]. Currently, building energy simulation has become an indispensable research method for architectural design evaluation and decision making, and an essential tool in the process of architectural parametric design. However, the accuracy of building energy simulation is closely related to the reliability of input meteorological data. Selecting feasible meteorological input data is a prerequisite for producing valid simulation results [3].

Although the selection of a feasible meteorological data file is the premise of getting valid results from building energy simulation, at present there has been no typical meteorological year (TMY) files specifically developed for daylight-utilized building' energy simulation. In practice, indirect description of luminous environment is usually adopted in daylight-related study. Short-term luminous environment observation data are used to establish luminous efficacy models and sky luminance models. Various luminous efficacy models have been developed. Littlefair [4] proposed luminous efficacy models of direct and diffuse solar radiation in 1984-1985 for southern part of England. Olseth and Skartveit [5] developed a luminous efficacy model based on the Norwegian measurement. Lam and Li [6], and Chung [7] provided a luminous efficacy model based on Hong Kong measurement data, using solar elevation angle and cloud cover as inputs. Muneer and Kinghorn [8] described a luminous efficacy model based on British data and used sky clearness as input. Kong and Kim [9] present a luminous efficacy model for Korea. Perez et al. [10] also proposed a luminous efficacy model which used hourly irradiance data to obtain hourly illuminance data. Among various luminous efficacy models, Perez luminous efficacy model has been widely applied in simulation software such as Radiance, Daysim, and EnergyPlus. Radiance, Daysim and other daylighting software use Perez all-weather sky model to realize the climate based daylight modeling (CBDM). Available irradiance data are used to derive illuminance related parameters.

Studies about weather data files for outdoor luminous environment is quite limited. Markou et al. [11] used observation data of Athens and Bratislava's 5-8 years record to generated Daylight Reference Years (DRYs). Meteorological parameters include global horizontal illuminance, diffuse horizontal irradiance, diffuse horizontal illuminance, global horizontal irradiance, zenith luminance, linke's turbidity factor, relative sunshine duration, and luminous turbidity factor, have been applied as considered meteorological parameters during generation process. However, these luminous meteorological parameters are difficult to get under normal circumstances. Moreover conventional thermal meteorological parameters were not considered during generation process. The considered meteorological parameters lack the connection with building energy consumption. Unfortunately, the generated DRYs are still not feasible for energy simulation of daylight-utilized buildings. Wong et al. [12] used nine meteorological parameters (dry bulb temperature, maximum and average wind speed, daily minimum, maximum and average values of dew point temperature, and total solar radiation) to generate typical meteorological year and typical reference year files for Hong Kong. The result indicated the necessity of generating daylight-related parameters based on different standard skies of International Commission on Illumination (CIE) for daylighting analysis. Bellia et al [13] compared the results of simulation-based daylight metrics calculated with IWEC, TRY, and weather data files generated by Meteonorm and Satel-Light. The comparison between different weather data files showed that using TRY led to lower calculation value. The results predicted by the other three weather data files were closer to the long-term average performance. However, as the exterior window was only on north exterior wall in the building model, the analysis results were with some limitation.

It should be pointed out that illuminance parameters were not included in early meteorological data files. However, in recent years, to facilitate research of daylight-utilized simulation, illuminance parameters have also been provided in some versions of TMY files. For example, TMY2 file format includes global horizontal illuminance, direct normal illuminance, diffuse horizontal illuminance, and zenith luminance. The values of these illuminance parameters are not obtained from observations, but are calculated from irradiance parameters. The illuminance parameters in the above-mentioned TMY files are provided mainly to reduce the cumbersome conversion workload of users. Luminous environment are still not taken account during the TMY generation.

In this paper, existing TMY generation methods and weighting schemes applied within Typical Meteorological Month selection are first reviewed. The required features of Typical Meteorological Year for integrated Climate Based Daylight Modeling and building energy simulation (TMY for CBDM-BES) are summarized. Then the generation workflow of the feasible TMY file is proposed. Finally a case study is implemented to demonstrate the application of the new proposed typical meteorological year generation method.

2. Review of TMY generation

Meteorological data have certain randomness and uncertainty. Observations of the same meteorological parameter tend to vary significantly between years. However, meteorological data is not completely random. Daily, monthly and annual profiles of observation values often show certain periodicity and regularity. Meteorological data applied to energy simulation should fully represent the above-mentioned characteristics of local climate so as to better assess long-term average performance of design schemes.

The typical meteorological year (TMY) file contains 8760 datasets of hourly meteorological parameters, which represent the characteristics of on-site outdoor environment. TMY can bring better balance between simulation accuracy and speed, and has been widely used in dynamic energy simulation in recent years [14].

2.1 TMY generation methods

TMY consists of 12 Typical Meteorological Months (TMMs). The generation of TMY transforms the selection of annual data into the selection of monthly data. From multi-year records, the monthly data that best represents the feature of certain calendar month is selected as the TMM. The selected 12 TMMs are then connected to form an artificial year.

Typical weather data files generated with Typical Meteorological Year concept include the TMYs series (TMY[1] [15], TMY2 [16], TMY3 [17]) for the United States; the IWECs series (IWEC [18], IWEC2 [19]) for the United States, Canada, and other international regions; and the WYECs series documents (WYEC [20], WYEC2 [21]) for cities and regions in the United States and Canada. The WYECs series further replace some hourly or daily data in the selected TMMs with data from other candidate months, making the final result closer to the long-term data.

So far there has been no general agreement on the generation method of TMY. Various methods have been developed, including Sandia method [15], Festa-Ratto method [22], Danish method [23], Miguel-Bilbao method [24], Crow method [20], and Gazelae-Mathioulakis method [25]. Detailed comparison between these methods could be found in reviews done by [26, 27]. Among the existing generation methods, Sandia method, Danish method and Festa-Ratto method are commonly used. The Sandia method has the advantages of clear process, strong operability and easy customization. Lam et al. [28] used the Sandia method together with non-parametric statistical method Kolmogrov–Smirnov (KS) parameters to measure the maximum deviation of the month from long-term average. Rather than focus on the statistical processing of meteorological parameters, Chan [29] developed a novel generation method based on the Sandia method. By embedding the energy simulation software and Genetic Algorithm (single

[1] TMY here specifically indicates the first generation of TMYs series which are generated for the United States.

objective function) into the TMM selection, Chan's modified methodology has boosted the representativeness of TMY at reflecting the characteristics of region, architectural element design and specific energy-consuming systems.

Although there are many different details in various TMY generation methods, the generation process of TMY could be generally summarized into three steps: raw data collection, TMM selection and TMMs connection. Among all the meteorological parameters contained in TMY file, only a small amount of these parameters (N) have been taken into consideration and are not equally weighted during the TMM selection. The considered meteorological parameters x and their assigned weighting factor (WF_x) is often referred as weighting scheme, following Equation 1.

$$\sum_{x=1}^{N} WF_x = 1 \tag{1}$$

The weighting scheme of TMM selection is critical in the whole generation process. As different energy systems focus on different aspects of climatic environment, the considered meteorological parameters and their weighting factors need to be adjusted according to the type and feature of studied energy system [30]. Petersen and Svendsen [31] further found that for renewable energy systems, the weighting factors used in TMM generation is critical.

2.2 Weighting schemes in TMM selection

Tables 1 and 2 summarizes the weighting schemes used in previous studies. These weighting schemes have the following characteristics:

- Most weighting scheme is subjectively determined by researchers' domain knowledge [26, 32]. Quantitative studies of the relative influence of different meteorological parameters are rare;
- For the same meteorological parameter, the weighting factor of its mean value is greater than that of its maximum or minimum value;
- Priority is given to measured value. The weighting factor of measured parameter is greater than that of the calculated parameter.
- The considered meteorological parameters are mainly focused on thermal factors, such as dry bulb temperature, dew point temperature, relative humidity, wind and solar radiation. Among them, weighting factors of solar radiation parameters are usually the highest. Parameter of daily total or average horizontal solar radiation is often weighted between 40%-50%.Meanwhile distinction of direct and diffuse solar is not considered.

Meteorological parameter	[23,33]	[18]	[34]	[16,17]	[35]	[36]	[37]	[38,39,40]	[41]
Dry-bulb temperature (maximum)	1/24	5/100	1/24	1/20	1/10	1/32	1/24	1/24	1/22
Dry-bulb temperature (minimum)	1/24	5/100	1/24	1/20	1/10	1/32	1/24	1/24	1/22
Dry-bulb temperature (mean)	2/24	30/100	1/24	2/20	2/10	2/32	3/24	2/24	1/22
Dry-bulb temperature (range)			1/24		1/10	1/32			1/22
Dew point temperature (maximum)	1/24	2.5/100	1/24	1/20	1/10	1/32			
Dew point temperature (minimum)	1/24	2.5/100	1/24	1/20	1/10	1/32			
Dew point temperature (mean)	2/24	5/100	1/24	2/20	2/10	2/32			
Dew point temperature (range)			1/24		1/10	1/32			
Relative humidity (maximum)								1/24	1/22
Relative humidity (minimum)							1/24	1/24	1/22
Relative humidity (mean)							2/24	2/24	1/22
Relative humidity (range)									1/22
Wind speed (maximum)	2/24	5/100	1/24	1/20		1/32	2/24	2/24	1/22
Wind speed (minimum)			1/24			1/32			
Wind speed (mean)	2/24	5/100	1/24	1/20		2/32	2/24	2/24	1/22
Wind speed (range)			1/24			1/32			1/22
Wind direction (mean)						1/32			
Global horizontal irradiance	12/24	40/100	12/24	5/20		8/32	12/24		11/22
Horizontal beam irradiance				5/20		8/32		12/24	

Table 1 Weighting schemes applied in previous studies (a)

Meteorological parameter	[42]	[43]	[44]	[45,46]	[47]	[48]	[49]	[50]	[51]
Dry-bulb temperature (maximum)	1/20	1/24	1/20	1/24	1/100	1/24	2/16	1/32	5/100
Dry-bulb temperature (minimum)	1/20		1/20	1/24	2/100	1/24	1/16	1/32	5/100
Dry-bulb temperature (mean)	3/20		6/20	2/24	1/100	3/24	1/16	2/32	30/100
Dry-bulb temperature (range)								1/32	
Dew point temperature (maximum)					2/100				
Dew point temperature (minimum)									
Dew point temperature (mean)				4/24	1/100				
Dew point temperature (range)									
Relative humidity (maximum)		1/24	1/40					1/32	
Relative humidity (minimum)	1/20		1/40			1/24		1/32	
Relative humidity (mean)	2/20		1/20			2/24		2/32	10/100
Relative humidity (range)								1/32	
Wind speed (maximum)	1/20	11/24	1/20	2/24	4/100	2/24		1/32	5/100
Wind speed (minimum)								1/32	
Wind speed (mean)	1/20		1/20	2/24	2/100	2/24	1/16	2/32	5/100
Wind speed (range)								1/32	
Wind direction (mean)					1/100			1/32	
Global horizontal irradiance	5/20	11/24	8/20	12/24		12/24	8/16	8/32	40/100
Horizontal beam irradiance	5/20				85/100			8/32	
Other					1/100		3/16		

Table 2 Weighting schemes applied in previous studies (b)

Solar radiation parameters are often given priority in weighting factor assignment because that most typical years are originally designed for solar energy system, which largely depends on the daily total amount of solar radiation. Moreover, solar radiation has significant impact on other outdoor meteorological parameters, such as temperature. The fluctuation of solar radiation will affect outdoor thermal environment, the performance of indoor passive or active heating systems and indoor air-conditioning loads either directly (through solar radiation) or indirectly (through temperature).

As can be seen from Tables 1 and 2, luminous environment has not been taken into consideration for weighting schemes. This is a consequence of the lack of long-term observations of luminous meteorological parameters at present. Raw luminous data that can be used to generate TMY for daylight-utilized energy simulation are often unavailable. Unfortunately, luminous meteorological parameters are not part of the routine observation parameters for ground weather stations. The International Commission on Illumination (CIE) has launched the International Daylight Measurement Programme [52] in different climate regions around the world since 1991, aiming to provide basic research data for calculation of daylight-utilization and verification of sky luminance distribution models. However, as the observation of meteorological parameters usually requires a long span to complete data accumulation, daylight-related research will still confront the lack of long-term measured luminous environment data for quite a long time. In practice, illuminance parameters are calculated with available irradiance data and luminous efficacy model. The definition of the characteristics of illuminance parameters' daily profile cannot only count on daily total or average solar radiation.

3. TMY for integrated Climate Based Daylight Modeling and building energy simulation (CBDM-BES)

3.1 Required features of CBDM-BES

Based on the previous analysis, it can be found that the TMY generation method for CBDM-BES should have the following characteristics:

- Limited by the lack of long-term observations of illuminance parameters, description of luminous environment in simulation is indirectly realized by means of irradiance parameters. The calculation of hourly illuminance parameters counts on hourly values of multiple irradiance parameters. In TMM selection process, only the total amount of horizontal radiation is used as conventional solar irradiation parameter participating selection process. The characteristics of illuminance parameters daily profile cannot be fully reflected.

If the available data are sufficient, solar radiation parameters, such as daily average and maximum values of outdoor horizontal global irradiance, direct normal solar irradiance, and diffuse horizontal solar irradiance should be taken into consideration as many as possible. They could work together with daily mean and the maximum/minimum values of other considered meteorological parameters, such as dry bulb temperature, wet bulb temperature, to participate in TMM selection;

- In terms of monthly building energy consumption, large fluctuations can be found between years. As TMY generation is significantly affected by the adopted weighting schemes, simulation-based energy performance prediction would also be influenced. In order to avoid the bias caused by researchers' subjective experience, weighting scheme within TMY generation method is preferred to be determined under an objective workflow;

- The assignment of the weighting factors should directly reflect the emphasis of daylight-related energy performance on considered meteorological parameters. As daylight-utilized measures can simultaneously affect lighting and air-conditioning systems within buildings, weighting factor should be able to represent the relative importance of both thermal and luminous meteorological parameters in the studied case;

- Seasonal variation can be found in the interaction mode of daylight utilization and building energy consumption. In cooling season, the solar heat accompanying the introduced daylight will increase indoor cooling load and impact negatively on building energy performance. However, in heating season, the solar heat accompanying the introduced daylight will reduce the heating demand and have a positive effect on building energy performance. Therefore, the assessment of monthly energy performance is as important as annual assessment for daylight-utilized design. In general, TMY for daylight-utilized energy simulation should aim at accurately predicting the long-term average energy performance on monthly basis, as well as on annual basis.

3.2 Workflow of the proposed TMY generation method

According to the above characteristics and inspired by Chan's research [29], the generation process of TMY for CBDM-BES can be transformed into a multi-objective optimization problem. In this section, the multi-objective genetic optimization algorithm NSGA-II is introduced to optimize the assignment of weighting factors in TMM selection. Monthly and annual deviations of multiple energy consumption parameters (lighting, air conditioning, and their overall energy performance) from long-term average performance are set as multi-objective functions. Based on the Sandia method, the TMY generation method for CBDM-BES is proposed and includes the following steps:

Step 1 Select the considered meteorological parameters for TMM selection. The considered meteorological parameters should include the daily maximum, minimum, and average values of dry bulb temperature and dew point temperature. Based on the availability of meteorological data, irradiance parameters are selected as many as possible, such as daily maximum and average of horizontal globe solar radiation, normal beam solar radiation, horizontal diffuse solar radiation, etc. As the effectiveness of daylight-utilized measure does not depend on outdoor wind environment, wind parameters are excluded from the considered meteorological parameters that participate TMM selection.

Step 2 For each calendar month, calculate the short-term and long-term cumulative distribution function (CDF) of each considered meteorological parameter. The closeness of the short-term and long-term CDF for each considered meteorological parameter is calculate with Equation 2:

$$FS_x(y,m) = \frac{1}{N}\sum_{i=1}^{N}\left|CDF_m(x_i) - CDF_{y,m}(x_i)\right| \qquad (2)$$

where N is the number of bins, $FS_x(y,m)$ is the $FS(y,m)$ statistic of the meteorological parameter x for the year y and the month m, $CDF_m(x_i)$ is the long-term CDF value, which is calculated with the daily values of meteorological parameter x for month m over the whole available period of years; $CDF_{y,m}(x_i)$ is the short-term CDF value, which is calculated with the daily values of meteorological parameter x for month m over the specific year y in the available period.

Step 3 Energy simulations over the long-term period are conducted for the studied energy system using hourly historical weather files. The long-term mean monthly and annual outputs of lighting, air conditioning and their overall energy consumptions are calculated

Step 4 K sets of different weighting factors are generated as the new population. Each set of the generated weighting factors follow the two constraints in Table 3. For each candidate month, the jth different FS statistics calculated from the jth meteorological parameter will multiply their corresponding weighting factors $WF_{p,j}$. The weighted sum of FS statistics, WS_p (y,m), is then calculated with Equation 3. For each calendar month, the candidate month with the smallest WS is selected as the TMM. The twelve TMMs are connected to formulate a TMY. K different TMY files will be generated for each iteration.

$$WS_P(y,m) = \sum_{j=1}^{N} FS_j(y,m) \cdot WF_{p,j} \tag{3}$$

Step 5 Multi-year energy simulations will be ran for the studied system with the K different TMY files. Root mean square error (RMSE) and KS are used to measure the deviation of the monthly/annual simulation output between an individual TMY and long-term average.

$$RMSE_{p,lighting} = \sqrt{\frac{\sum_{m=1}^{12}\left(y_{p,m,lighting} - \overline{y_{m.lighting}}\right)^2}{12}} \tag{4}$$

$$RMSE_{p,AC} = \sqrt{\frac{\sum_{m=1}^{12}\left(y_{p,m,AC} - \overline{y_{m,AC}}\right)^2}{12}} \tag{5}$$

$$RMSE_{p,lighting+AC} = \sqrt{\frac{\sum_{m=1}^{12}\left(y_{p,m,lighting+AC} - \overline{y_{m,lighting+AC}}\right)^2}{12}} \tag{6}$$

$$KS_{p,lighting} = \max\left(\left|\frac{y_{p,m,lighting} - \overline{y_{m,lighting}}}{\overline{y_{m,lighting}}}\right|\right) \tag{7}$$

$$KS_{p,AC} = \max\left(\left|\frac{y_{p,m,AC} - \overline{y_{m,AC}}}{\overline{y_{m,AC}}}\right|\right) \tag{8}$$

$$KS_{p,lighting+AC} = \max\left(\left|\frac{y_{p,m,lighting+AC} - \overline{y_{m,lighting+AC}}}{\overline{y_{m,lighting+AC}}}\right|\right) \qquad (9)$$

where $y_{p,m}$ is the monthly value of the simulated output using the TMY file p, $p = 1, \cdots, K$, m is the month, $\overline{y_m}$ is the annual long-term monthly average of the month.

Step 6 Minimizing the RMSE and KS of multiple energy consumption parameters is set as the objective functions. NSGA-II algorithm is used to optimize and generate the new generation of weighting factors. Step 4 will be repeated until reaching the max-generation. The Pareto solutions are then extracted to get optimal and sub-optimal assignment of weighting factors, along with the corresponding 12 TMMs and the TMY file.

Objective Function
$\min f_{p,1} = RMSE_{p,lighting}$ $\min f_{p,2} = RMSE_{p,AC}$ $\min f_{p,3} = RMSE_{p,lighting+AC}$ $\min f_{p,4} = max\left(KS_{p,lighting} \bigcup KS_{p,AC} \bigcup KS_{p,lighting+AC}\right)$
Constraints I $0 \leq WF_{p,j} \leq 1$
Constraints II $\sum_{j=1}^{N} WF_{p,j} = 1$

Table 3 Objective functions and constraint

Users can select the preferred weight factor scheme, and its corresponding 12 TMMs along with TMY from Pareto solution based on different practical situations, such as the different emphasis of lighting and air conditioning energy consumption.

4. Case study: TMY of Hong Kong for CBDM-BES

With historical meteorological data of Hong Kong from 1979 to 2007, a medium office building floor implemented sided window daylighting is used to apply the proposed TMY generation method.

4.1 Configuration of CBDM-BES

The embedded CBDM-BES task within generation workflow is conducted by Openstudio. OpenStudio is used to realize the connection of EnergyPlus and Radiance, which are respectively used as energy simulation engine and daylight simulation engine. Radiance performs gridded daylighting simulation based on actual meteorological conditions. The resulted daylighting degree at each daylight reference point is then passed to EnergyPlus. With the received result, EnergyPlus calculates the dimming degree of lighting system and applies it in the subsequent energy consumption simulation calculation.

The layout and configuration of the building mode can be found in Fig.1 and Table 4. The outputs of lighting energy consumption and indoor cooling load of each perimeter zone are extracted. An overall COP of 3 is used to convert cooling load into air conditioning energy consumption. The overall energy consumption is calculated by summing up the lighting and air conditioning energy consumption.

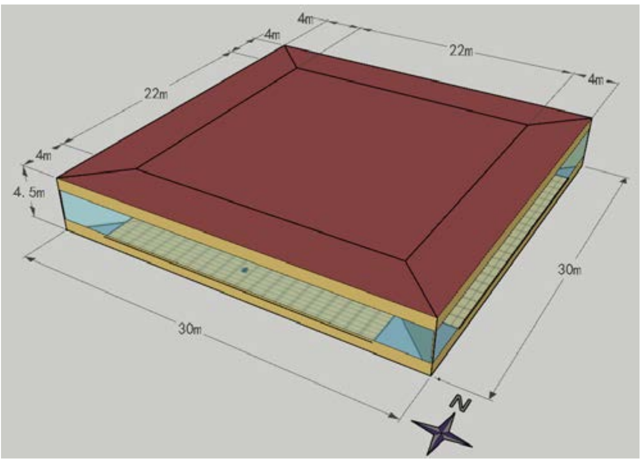

Fig.1 Layout of the building model {1-column} {coloured}

4.2 TMY weather file generator

According to the availability of historical meteorological data, a total of 12 meteorological parameters are selected to participate TMM selection. Considered meteorological parameters include the daily maximum, minimum, and average values of dry bulb temperature and dew point temperature, the daily maximum and average values of horizontal total solar irradiance, normal beam irradiance, and horizontal diffuse irradiance.

Properties of opaque envelope		Properties of exterior window	
U-value of exterior wall\(W/ m^2·K)	1.0	Glazing type	Double low-E
U-value of floor (W/ m^2·K)	0.5	U-value (W/ m^2·K)	1.4
U-value of roof (W/ m^2·K)	0.88	SHGC / VT	0.48 / 0.7
Indoor design parameter		Properties of shading	
Operation time	Weekday 8:00-18:00	Shading type	Interior blind
		Slat thickness (mm)	1
Lighting power density (W/ m^2)	20	Slat width (mm)	25
Illuminance target (lux)	500	Solar radiation reflectance (beam/diffuse)	0.5/0.5
Equipment power density (W/ m^2)	20		
Occupant density (m^2/person)	4		
Occupant heat dissipation (W/ person)	130	Visible reflectance (beam/diffuse)	0.5/0.5
Air change rate (m^3/ person·h)	30		
Cooling set temperature (˚C)	24		
Control Strategy When the incident radiation exceeds 100 W/m^2, the shading is activated, and the slat angle is adjusted to block the direct radiation. Otherwise, the shading is retracted.			

Table 4 Configuration of simulation

Objective Function
$\min f_{p,1} = RMSE_{p,lighting}$ $\min f_{p,2} = RMSE_{p,cooling}$ $\min f_{p,3} = RMSE_{p,lighting+cooling}$ $\min f_{p,4} = max\left(KS_{p,lighting} \bigcup KS_{p,cooling} \bigcup KS_{p,lighting+cooling}\right)$
Constraints I $\quad 0 \le WF_{p,j} \le 1$ Constraints II $\quad \sum_{j=1}^{12} WF_{p,j} = 1$

Table 5 Objective functions and constraints applied in the case study

The objective functions applied are refined as to minimize the RMSE (fp,1, fp,2, fp,3) and the largest monthly deviation (fp,4) of multiple energy consumption parameters. The objective functions and constraints in this case are shown in Table 5.

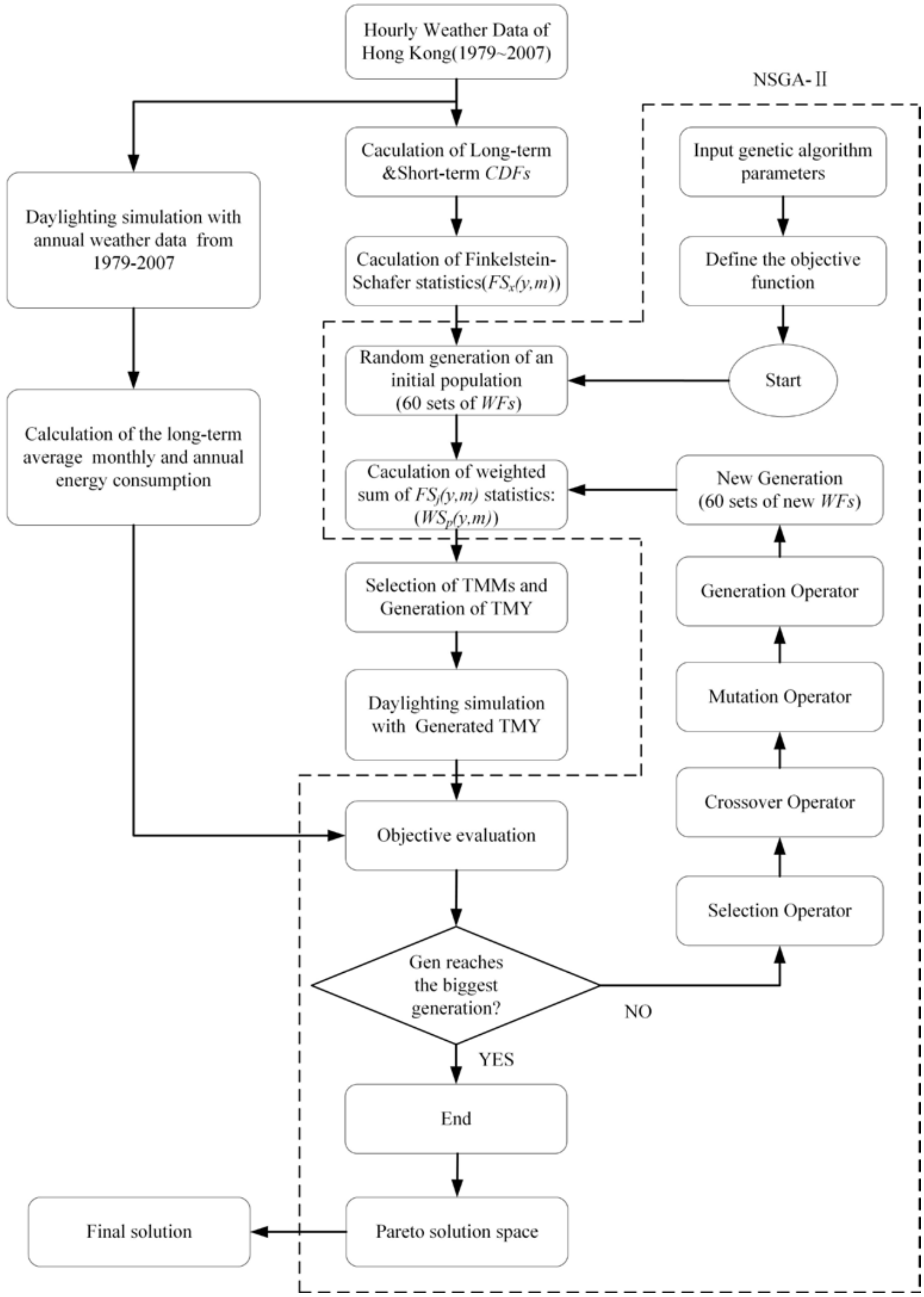

Fig.2 Refined workflow of the proposed TMY generation method for the case study

{2-column}

Parameter	value
Population size	60
Generations	500
Mutation probability	0.85
Crossover probability	0.1

Table 6 Parameter setup of the NSGA-II genetic algorithm

The workflow of TMY generation for daylight-utilized energy simulation is illustrated in Fig.2. The NSGA-II optimization process is implemented using the mco package function in the R language. The parameter setup of the NSGA-II genetic algorithm is listed in Table 6. The NSGA-II generates 60 sets of weight factors per generation, namely K is 60.

4.3 Result

All values of objective functions within Pareto solution space are listed in Table 7. The solution with the lowest f_4 is selected from Pareto solution space as the final solution.

Pareto solution NO.	f_1 (kWh)	f_2 (kWh)	f_3 (kWh)	f_4
1	7.25	260.65	83.86	11.27%
2	13.12	156.40	50.97	5.04%
3	7.54	173.19	54.69	4.27%
4	13.05	162.04	53.33	5.04%
5	7.48	208.22	66.15	9.44%
6	13.11	156.87	51.11	5.04%
7	7.40	221.67	71.49	11.27%
8	7.33	249.32	79.36	11.15%

f_1 RMSE of lighting energy consumption
f_2 RMSE of cooling load
f_3 RMSE of overall energy consumption
f_4 The largest monthly deviation of all the energy consumption parameters from the long-term average

Table 7 Values of the objective functions in the Pareto solution space (The highlighted line is the final solution) {coloured}

Table 8 shows the assignment scheme of weighting factors corresponding to the final solution. For annual and monthly energy performance, deviation of values obtained by the final solution's TMY from long-term average are listed in Tables 9 and 10. It should be noted that the IdealLoadsAirSystem module in EnergyPlus is set to operate HVAC system. Activation of cooling mode is determined through comparing actual temperature and set cooling temperature. For subtropical city like Hong Kong, only cooling mode is considered in the simulation. There is cooling load in twelve months throughout the whole year in the simulation. Considering that the main purpose of this section is to demonstrate the application of the new proposed typical meteorological year generation method through a case study, the calculated results of cooling load beyond common cooling season of Hong Kong is not eliminated.

Comparing the energy performance obtained by the TMY corresponding to the final solution with the long-term average, it can be found that the monthly deviation range is -2% to 1% for lighting energy consumption, -4% to 4% for indoor cooling load, and -3% to 3% for overall energy consumption. The annual deviation is 0.01% for lighting energy consumption, 0.45% for indoor cooling load, and 0.33% for overall energy consumption.

The simulation results of energy consumption parameters are close to the long-term average on both the monthly and annual basis. Monthly energy performance of the three energy consumption parameters, predicted with the obtained TMY, are simultaneously in good agreements with the long-term mean performance. This result suggests that the proposed TMY generation method can effectively generate the feasible TMY file of Hong Kong for CBDM-BES.

5. Conclusion

Considering the energy performance characteristics of daylight-utilized buildings, together with existing TMY generation methods and weighting schemes, a TMY generation method for CBDM-BES has been proposed. Based on the Sandia method, energy simulation and genetic algorithm are embedded into the process of proposed TMY generation method. NSGA-II is applied to meet the required feature. Monthly and annual deviations of multiple energy consumption parameters from long-term average performance are set as multi-objective functions.

Meteorological parameters	Dry bulb temperature			Dew point temperature			Globe solar radiation		Normal beam radiation		Horizontal diffuse radiation	
	Daily maximum	Daily minimum	Daily average	Daily maximum	Daily minimum	Daily average	Daily maximum	Daily average	Daily maximum	Daily average	Daily maximum	Daily average
Weighting factor	0.028	0.002	0.115	0.134	0.055	0.251	0.076	0.156	0.043	0.063	0.022	0.055

Table 8 Assignment scheme of weighting factor corresponding to the final solution

Parameters	Lighting energy consumption	Indoor cooling load	Overall energy consumption of lighting and air conditioning
Annual simulation results corresponding to TMY (kWh)	9020	68968	32010
Long-term average annual simulation results (kWh)	9019	68662	31904
The deviation	0.01%	0.45%	0.33%

Table 9 Annual deviation values of the energy consumption parameters

Parameters	Month	1	2	3	4	5	6	7	8	9	10	11	12
Simulation results corresponding to final TMY (kWh)	Year	1999	1988	2003	2005	1997	1991	1986	2002	1982	1984	1989	1985
	Lighting energy	799	688	795	705	773	704	654	751	708	799	843	801
	Cooling load	4341	3472	4051	4345	5952	6861	7105	7495	6584	7344	6231	5187
	Overall energy	2246	1846	2145	2154	2757	2991	3022	3249	2903	3247	2920	2530
Long-term average corresponding to historical data (kWh)	Lighting energy	794	702	803	698	770	701	641	743	713	797	848	809
	Cooling load	4284	3349	3967	4290	6204	6747	7422	7491	6740	7070	6113	4985
	Total energy	2222	1818	2125	2128	2838	2950	3115	3240	2959	3153	2886	2470
Monthly deviation	Lighting energy	1%	-2%	-1%	1%	0%	0%	2%	1%	-1%	0%	-1%	-1%
	Cooling load	1%	4%	2%	1%	-4%	2%	-4%	0%	-2%	4%	2%	4%
	Total energy	1%	2%	1%	1%	-3%	1%	-3%	0%	-2%	3%	1%	2%

Table 10 Monthly deviation values of the energy consumption parameters

An application example is conducted for Hong Kong. With the generated TMY file, simulated results of energy consumption parameters are close to the long-term average on both the monthly and annual basis. It can meet the concern of daylight-utilized energy analysis for lighting, air conditioning and their overall energy performance.

It is worth noting that, in the case study of Hong Kong, within the assignment scheme of weighting factor corresponding to the final solution, the sum of dry bulb temperature parameters is 0.145, which is less than the sum of dew point temperature parameters of 0.44.The result is quite different from existing assignment schemes of weighting factor. In existing assignment schemes, the total weighting of dry bulb temperature parameters is often equal to or slightly higher than dew point temperature parameters.

For daylight-utilized energy simulation, dew point temperature affects the calculation of energy calculation in two ways. First, dew point temperature participate in the energy calculation of air change rate. Second, dew point temperature also acts as a variable in the derivation of illuminance parameters in Perez's luminous efficacy model. Thus dew point temperature can simultaneously affect the calculation of lighting and air conditioning system, which is similar to solar radiation parameters. This also further demonstrates the particularity of TMY for CBDM-BES, and indicates that the proposed TMY generation method can reflect the focus of daylight-utilized measure on solar radiation and dew point temperature parameters.

Competing interests

The authors have declared that no competing interests exist.

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