The role of green roofs on reducing heating and cooling loads: a database across Chinese climates

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Abstract*—This paper aims to use detailed modelling techniques and develop a database for assessing in a quick and easy way the energy performance of green roof designs across a range of Chinese climates. The focus is on heating and cooling loads by calculating indoor temperatures using the EnergyPlus simulation tool. The study covers 5328 configurations by varying model parameters such as location, climate, seasonal periods, glazing type, wall insulation levels, roof insulation, soil thickness and condition, and vegetation density characteristics. It was found from the results that green roofs can offer significant energy savings for heating and cooling loads if they are applied on roofs without insulation but only limited energy savings where heavy insulation on the roof is also applied. This database can prove to be a useful tool to the practitioners who want to perform rapid assessments of the potential energy savings that could be gained from a green roof installation in a Chinese location.

Keywords- green roofs; database; detailed simulation; heating/cooling loads; Chinese climate;

I. INTRODUCTION

Green roofs have been recognised as a great means of limiting the Urban Heat Island effect by removing heat from the air through evapotranspiration of the plants, which leads to a reduction of the temperatures of the roof surface and the surrounding air [1]. However, the application of green roofs is often limited due to the additional construction cost and the inability of the building practitioners to accurately demonstrate during the design stage the potential energy and comfort benefits on building occupants by quantifying, for example, the potential reduction of heating and cooling loads that green roofs may offer. Research in the past, (e.g. [2], [3]) has shown that green roofs can reduce the heating and cooling loads of buildings but a consensus has not been reached on the specific characteristics of green roofs (e.g. types of soil, plant, etc.) that best fit the specific building's climate. The issue becomes more important in China, where the climate and the construction standards are significantly diverge across the country and large dense cities experiencing the Urban Heat Island in summer drive energy demands up.

This paper is addressing this issue by using a whole building detailed simulation program to assess the effect of green roofs on reducing heating and cooling loads across major Chinese climate zones. The study aims to optimise the type of green roofs that best fits the Chinese climates for a number of construction types (e.g. glazing types, wall and roof insulation, etc.) and develop an easily accessible database that is based on detailed simulations. This database can be easily used at the same time for rapid comparisons of the building cases without the knowledge of the simulation program. The focus is on demonstrating the effect that different green roof configurations may have on heating and cooling loads. However, comparisons could also be made with this database against alternative energy saving building envelope upgrades, for example a practitioner could compare the difference on heating and cooling loads from a wall insulation upgrade against an installation of a specific type of green roof. The details of the building configurations in this database are described in the following section.

II. METHODOLOGY

The EnergyPlus whole building simulation software [4] was used for the simulations mainly because of its ability to model in detail the performance of green roofs for whole building studies (i.e. multi-zone models that integrate all the energy related features of the building). The green roof component in EnergyPlus [5] is integrated with the rest of the building model and energy balance calculations are performed for the soil and foliage layers. It accounts for the solar radiation incident on the green roof and it balances the energy gains from this solar radiation with sensible (convection) and latent (evaporation and transpitation) heat flux from soil and plant surfaces combined with conduction of heat into the soil and long-wave thermal radiation to and from the soil and leaf surfaces. A detailed description of the mathematical model is given in the literature [5].

A typical building that fits the shape of a Chinese apartment was prepared in the software (Fig. 1).

A total of 5328 building configurations were modelled in order to cover all the configurations described in Table 1 and develop the green roof application database.

All cases were studied with and without the green roof. A drainage layer of 100 mm was also included below the soil of the green roof cases. The analysis was done at free float conditions, i.e. no heating or cooling system affected the internal conditions, and temperature results were extracted as metrics for the reduction of heating and cooling loads. In detail, the assessment for the performance of the cases in the green roof database was done with the following metrics:

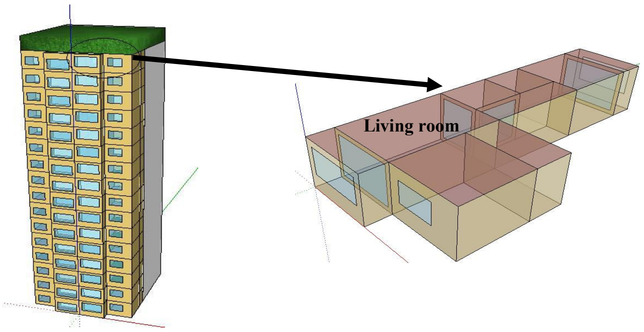

Figure 1: A typical building apartment was used for the modelling cases.

- *Peak indoor air temperature* for the cooling cases and *minimum indoor temperature* for the heating cases. The results of the model cases can be compared with each other. A reduction for the peak indoor temperature during the cooling season and an increase of the minimum indoor temperature during the heating season will mean a reduction on peak space cooling and heating loads respectively.
- *Peak inside face roof surface temperature* for the cooling cases and *minimum inside face roof surface temperature* for the heating cases. This metric is useful for assessing the roof structure itself and can indicate the effect of the green roof on reducing heat transfer through the roof. This will demonstrate how the roof construction affects the heating and cooling loads (i.e. by comparing against the indoor air temperature results) and conclusions could be drawn on the importance of the roof area for peak heating and cooling load reductions.
- *Average indoor air temperature* and *average inside face roof surface temperature* for the 3 days of the simulation period. The average temperatures could prove that a specific roof construction can be beneficial during a period of time and not only during extreme peak periods.
- For the cooling cases *the sum of difference between the indoor air temperature results and the design temperature of 24 ^oC* while for the heating cases *the sum of difference between the design temperature of 20 ^oC and the indoor air temperature* results. i.e. for cooling: "SUM(Tair - 24)" and for heating: "SUM(20 - Tair)". This will allow comparing the cases for the improvements they may offer across the whole simulation period.

III. RESULTS AND DISCUSSION

A large amount of results were extracted from the simulations and were placed in the database. The most important outputs that lead to conclusions will be described below. The results shown here (Tables 2 & 3) are for the living room of this study's apartment and they are just a sample of the large output that it is available in the database. The details of each case were given in Table 1.

The following can be noticed from the overall results in the database:

- The trend of the results for the effectiveness of the green roof application is similar across the six Chinese locations. The heating load is insignificant for the locations of Shanghai, Guangzhou and Sanya while the cooling load is an issue for all six locations.

TABLE 1. DETAILS OF THE CASES INCLUDED IN THE DATABASE

No. of configurations	Parameter	Description
6	Location/climate	Dense and important Chinese cities from the wide range of Chinese climates are covered: *Beijing, Shanghai, Guangzhou, Xian, Harbin, Sanya.*
2	Seasons	Three (3) typical cold and hot days were used from each climate to assess the performance of the green roofs during the *heating* and *cooling* seasons respectively
2	External glazing types	Typical glazing was used, i.e. *-a single clear 3mm,* *-a double glazing for which two clear 3mm layers are separated by an air filled 13mm gap.*
3	External wall insulation levels	*-Uninsulated concrete call (thermal transmittance U-value of 2.83 W/m^{2}K),* *-externally medium-insulated concrete wall (25mm of insulation and U-value of 0.83 W/m^{2}K),* *-externally heavily-insulated concrete wall (75mm of insulation and U-value of 0.35 W/m^{2}K).*
2	Roof insulation levels (excluding green roof layers)	*-Uninsulated concrete roof (thermal transmittance U-value of 4.09 W/m2K),* *-heavily insulated concrete roof (100mm of insulation and U-value of 0.28 W/m^{2}K).*
1+1 = 2	Green roof application	*Yes, No*
3	Soil thickness (green roof)	*10 cm, 35 cm* and *70 cm*
4	Soil conditions (green roof)	*-Dry soil (thermal conductivity 0.5 W/mK, Density 500 kg/m^3, Specific heat 1460 J/kgK),* *-Wet soil (thermal conductivity 1.5 W/mK, Density 900 kg/m^3, Specific heat 2040 J/kgK),* *-Dry soil (as above) where constant high levels of irrigation (0.1m per minute) are applied from 07.00 to 17.00 o'clock daily.* *-Wet soil (as above) where constant high levels of irrigation (0.1m per minute) are applied from 07.00 to 17.00 o'clock daily.*
3	Vegetation density (green roof plant layer)	*Leaf Area Index (LAI) of 0.1, 1* and *5*
Number of model cases without the application of green roof: 6*2*2*3*2*1 = 144 Number of model cases with the application of green roof: 6*2*2*3*2*1*3*4*3 = 5184 **Total number of model cases: 144 + 5184 = 5328**		

TABLE 2. COOLING – BEIJING (CHOICES IN DATABASE): SAMPLE OF IMPORTANT RESULTS

ID	External Glazing	Ext. wall insulation	Roof insulation	Green roof details	Peak air Temp. (°C)	Peak inside face roof surface Temp. (°C)	Average air Temp. (°C)	Average inside face roof surface Temp. (°C)	SUM (Tair -24)
1	Single	None	None	No green roof	36.74	43.54	31.59	34.04	570.35
13	Double	None	None	No green roof	36.68	43.48	31.58	34.02	569.73
5185	Single	None	None	Soil: 70cm thick, wet & irrigated, LAI: 5	29.62	28.20	28.33	27.48	335.71
5197	Double	None	None	Soil: 70cm thick, wet & irrigated, LAI: 5	29.52	28.11	28.28	27.42	332.31
4957	Double	Heavy	None	Soil: 10cm thick, wet & irrigated, LAI: 5	28.95	27.77	28.13	27.34	321.47
4669	Double	Heavy	None	Soil: 35cm thick, dry & irrigated, LAI: 5	29.10	27.62	27.76	27.09	295.05
2077	Double	Heavy	None	Soil: 35cm thick, dry & no irrigation, LAI: 5	29.18	27.79	27.84	27.24	300.63
133	Double	Heavy	Heavy	No green roof	29.53	29.10	28.54	28.13	350.90
2149	Double	Heavy	Heavy	Soil: 35cm thick, dry & no irrigation, LAI: 5	29.16	28.31	28.28	27.66	332.23
565	Double	Heavy	Heavy	Soil: 70cm thick, dry & no irrigation, LAI: 0.1	29.28	28.52	28.37	27.82	338.69
3157	Double	Heavy	Heavy	Soil: 70cm thick, dry & irrigated, LAI: 0.1	29.22	28.38	28.35	27.79	337.35

TABLE 3. HEATING – BEIJING (CHOICES IN DATABASE): SAMPLE OF IMPORTANT RESULTS

ID	External Glazing	Ext. wall insulation	Roof insulation	Green roof details	Minimum air Temp. (°C)	Minimum inside face roof surface Temp. (°C)	Average air Temp. (°C)	Average inside face roof surface Temp. (°C)	SUM (20-Tair)
7	Single	None	None	No green roof	9.17	1.96	11.61	5.18	623.91
19	Double	None	None	No green roof	9.23	1.96	11.58	5.11	626.16
5191	Single	None	None	Soil: 70cm thick, wet & irrigated, LAI: 5	16.86	15.54	18.14	16.27	154.12
5203	Double	None	None	Soil: 70cm thick, wet & irrigated, LAI: 5	17.02	15.60	18.19	16.24	150.30
4963	Double	Heavy	None	Soil: 10cm thick, wet & irrigated, LAI: 5	17.49	15.11	18.39	15.83	135.66
4675	Double	Heavy	None	Soil: 35cm thick, dry & irrigated, LAI: 5	18.72	17.11	19.58	17.70	50.09
2083	Double	Heavy	None	Soil: 35cm thick, dry & no irrigation, LAI: 5	18.72	17.11	19.58	17.70	50.09
139	Double	Heavy	Heavy	No green roof	19.73	18.76	20.66	19.45	-27.86
2155	Double	Heavy	Heavy	Soil: 35cm thick, dry & no irrigation, LAI: 5	20.15	19.55	21.07	20.14	-57.05
571	Double	Heavy	Heavy	Soil: 70cm thick, dry & no irrigation, LAI: 0.1	20.28	19.81	21.21	20.39	-67.29
3163	Double	Heavy	Heavy	Soil: 70cm thick, dry & irrigated, LAI: 0.1	20.28	19.80	21.21	20.38	-67.13

- Green roofs could significantly reduce heating and cooling loads for buildings that are not heavily insulated. For example, a reduction of the peak indoor air temperature by about 7°C can be noticed during the cooling season in Beijing when comparing case 1 against case 5185 (Table 2). The same applies for the double glazing cases of the cooling season (Table 2: case 13 against case 5197). The energy benefits from the green roof application are slightly less during the heating season (Table 3) when compared with those for the cooling season. However, an improvement by about 6°C on minimum indoor air temperature can be still noticed during the heating season.
- For heavily insulated buildings green roofs can offer small benefits in terms of heating and cooling loads reductions. For example, see Table 2 for the results of the cooling season where the outputs of case 133 are close to the outputs of cases 2149, 565 and 3157. The same applies for the heating season (Table 3: compare case 139 against case 2155, 571 and 3163). It should be noted here that such heavily insulated buildings as those for cases 133 and 139 are not common practice in China. The associated cost of upgrading to that degree of insulation shall be considered against the cost of adding a green roof on top of the building. In general, the roof insulation seems to be the most critical factor for reducing

heating and cooling loads and from the results obtained it can be seen that specific types of green roofs can have the same effect as the classic roof insulation layer.

- For the location of Beijing, the configuration that resulted to the highest reduction of the cooling load was case 4669 (see Table 2). In this case, double glazing and heavily insulated walls were applied. However, the roof of this case (i.e. 4669) was uninsulated and a green roof was applied with characteristics that can be seen in Table 2. The highest reduction of the heating load and for the same location was noticed for case 571 (see Table 3) in which all of the building upgrades of this study were applied (e.g. double glazing, roof insulation, etc.).
- Irrigation plays an insignificant role on reducing heating and cooling loads for most of the green roof configurations that are included in the database. It was found that only during the cooling season irrigation could be used in a way that peak indoor air temperatures could be reduced by about 1 ^{o}C and this was only confirmed for a limited number of green roof configurations. These configurations for which irrigation could be slightly beneficial were the uninsulated roof cases that had a green roof with soil of 10cm and Leaf Area Index of 0.1.
- Insignificant differences were noticed during the cooling season when green roofs with dry and wet soils were compared with each other. The thermal properties of the soil did not affect the cooling loads. However, the results for dry soil cases during the heating season have shown that minimum indoor air temperatures can be higher by about 1 to 1.5 ^{o}C than the results of wet soil cases when the roof is not well insulated (i.e. this improvement that dry soils offer applies only for the uninsulated roof cases).
- The thickness of the soil is an important parameter only for the uninsulated roof cases. In such cases, soils of greater depths (i.e. 70cm) improved the peak indoor air temperatures during the cooling season by about 1^{o}C when comparing with the same building configurations that use thin soil layers (i.e. 10cm). This trend was confirmed also for the heating season during which soils of greater depths gave higher reductions of the heating loads than thin soil layers. The corresponding improvement of the minimum indoor air temperature during the heating season was about 1 to 1.8^{o}C when thick medium layers were used instead of the thin ones.
- The density of the vegetation called Leaf Area Index (LAI) can determine the potential reductions of cooling loads for uninsulated roof cases. It is found that peak indoor air temperatures can be reduced by about 0.5 to 1.0^{o}C during the cooling season if high LAI plants are used (i.e. LAI = 5) instead of the plants with a LAI of e.g. 0.1. The LAI is not an important factor for the cases of the heating season, i.e. improvements of the minimum indoor air temperature were about 0.3^{o}C when plants with low LAI (i.e. LAI = 0.1) are used instead of the plants with high LAI (i.e. LAI = 5). To maximise the potential benefits from this parameter practitioners are advised to install green roofs with plants that have variable leaf area index over the year, i.e. high LAI during the cooling season and low LAI during the heating season.

IV. CONCLUSIONS

A database was developed from detailed modelling calculations in order to provide practitioners with a quick way of determining potential benefits on heating and cooling loads after applying different types of green roofs across a range of Chinese climates.

It was found that green roofs can offer maximum energy savings in China if the roof of the building is uninsulated. It can be concluded from the results obtained that green roof layers in these cases can offer the same or better thermal load reductions as those noticed in cases where a thick insulation layer was applied on the roof (i.e. without a green roof). On the other hand, green roofs offer only a small reduction of heating and cooling loads if they are installed on top of an already heavily insulated roof.

In general, the parameters that did affect the green roof's performance on reducing heating loads were the thickness and the conditions of the soil (dry and thick soils are the preferred option). The thickness was also an important parameter for reducing cooling loads which were also affected by the density of the vegetation layer (thick soils and high LAI plant layers are the preferred option).

It is expected that this study will be better integrated into Chinese context by matching the plant layer characteristics with plants and vegetables available locally at Chinese climates. Future work will aim to make these results easily available to practitioners. For example, the whole results database could be embedded in a web-based GIS tool for disseminating this output in an easy and interactive way.

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