GREEN ROOFS – HYGROTHERMAL SIMULATION OF MOISTURE AND ENERGY PERFORMANCE

Daniel Zirkelbach[1]

[1] Fraunhofer Institute for Building Physics (IBP) Holzkirchen, Department Hygrothermics, Fraunhoferstr. 10, 83626 Valley, Germany, email: daniel.zirkelbach@ibp.fraunhofer.de

SUMMARY: Based on laboratory and field tests at the Fraunhofer IBP field test site a hygrothermal green roof model was developed, which allows to model the performance of extensive green roofs in hygrothermal simulation software. A comparison of the measured and simulated temperatures beneath the greenery shows, that the model well reproduces the real conditions. Also the moisture conditions in timber roof constructions as well as the heat flows through the roof assembly are compared once with the measured conditions from the field tests and once with the new simulation model. Main focus of the model is the evaluation of the moisture performance of roof assemblies which is of special importance in case of moisture sensitive timber roofs. But also a prediction of the energetic behaviour and the cooling effects of the roof as well as an evaluation of the comfort conditions in the room beneath the green roof becomes possible and is shown exemplarily for the warm Mediterranean climate of the South Croatian city Split in comparison to flat roof with a white and a black roof surface.

ZELENI KROVOVI – MODELIRANJE HIGROTERMALNOG PONAŠANJA

SAŽETAK: Na osnovi laboratorijskih i terenskih ispitivanja na terenskom ispitnom polju Instituta Fraunhofer razvijen je higrotoplinski model zelenoga krova koji omogućuje modeliranje svojstava velikih zelenih krovova u softveru za higrotoplinsku simulaciju. Usporedba mjerenja i simuliranih temperatura ispod zelenila pokazuje da model dobro reproducira stvarne uvjete. Uvjeti vlage u drvenim krovnim konstrukcijama i prolazak topline kroz sklop krova prvo su uspoređeni s mjerenim uvjetima pri terenskim ispitivanjima, a potom s novim modelom simulacije. Glavna pozornost u modelu vrednovanje je ponašanja krovnoga sklopa pri vlazi koja ima posebnu važnost kod drvenih krovova osjetljivih na vlagu. No moguće je i predviđanje energetskog ponašanja i učinaka hlađenja krova te vrednovanje uvjeta udobnosti u prostoriji ispod zelenoga krova što je kao primjer pokazano za toplu mediteransku klimu južnohrvatskog grada Splita u usporedbi s ravnim krovom s bijelom i crnom površinom.

1. INTRODUCTION

Many people regard greeneries as a rather winsome roof type. Apart from that they provide some benefits like a higher durability due to the protection of the sealing by the soil layer, energy savings and better comfort especially in summer time due to evaporation cooling, retention of precipitation water as well as reduction of heat island effects and improvement of air quality. Therefore more and more green roofs are built in many countries worldwide. However, in Central Europe there have been reported some problems and damage cases related to green roofs applied on moisture sensitive timber roofs. As the hygrothermal performance of a green roof can hardly be evaluated by means of dew point calculations like [1] or [2], a hygrothermal evaluation [6] of such assemblies is necessary. Within a project, funded by the German Federal Ministry of Transport, Building and Urban Affairs, a hygrothermal green roof model could be developed [4] which can be used together with the hygrothermal simulation software WUFI® [4]. The main focus of the model development was the evaluation of the roof construction's moisture performance. But comparison with measurements showed, that also the thermal behaviour and the energetic consequences can be well reproduced.

2. MODELING THE CONDITIONS IN THE GREEN ROOF LAYERS

The conditions beneath a green roof clearly differ from the ones on a normal roof top. This is due to the effects of the plants which cover and shade the roof from long and short wave radiation influences, the high thermal inertia of the soil layer, the stored water and its heat enthalpy including fusion and evaporation effects. Modelling these effects is rather difficult, especially under real weather conditions [7][8].

Most previous models were developed to consider the thermal performance of the roofs and handled the influences of the plant canopy in great detail, often based on the research of Perrier [9] or Frankenstein and Koenig [10]. Models are for example available from del Barrio [11], Theodosiou [12], Kumar und Kaushik [13], Lazzarin et al. [14] Alexandri und Jones [15], Sailor [8], Ouldboukhitine [16], Olivieri et. al [16] and Tabares-Velasco et al.. The detailed calculation of the plants requires input parameters which are difficult to measure and hardly available in practice. In many cases they were even not known for the greenery, used for the models validation. On the other hand, the moisture processes in the soil, with drainage, liquid water transport due to capillary forces, local moisture level and its influence on the heat capacity and the thermal conductivity as well as on the evaporation rate at the soil surface, are modeled only in a simplified way or even neglected. Also, the effect of rain water absorption and redistribution due to capillary forces and heat of fusion is not considered in most of the available models. As the evaporation rate depends on the moisture content directly at the surface and not on the average content over the whole thickness of the soil, this seems to be a crucial point. Furthermore a whole year simulation under natural weathering, which is required to reliably predict the hygrothermal performance of a roof construction, is hardly possible without considering ice formation and fusion.

3. HYGROTHERMAL GREEN ROOF MODEL

An alternative approach based on the hygrothermal simulation model WUFI® [4] was developed, which considers the moisture balance of the soil more in detail, as this is a standard application of this software. However, some effects like drainage, shading by the plants, reduced surface transfer etc. were not directly available in the software. Therefore the multidimensional effects in drainage layer, soil and plant canopy were complemented in a way, that accounts for the greenery together with the normal building component.

3.1. GENERIC AND OPTIMIZED MODEL

A first version of the hygrothermal green roof model, based on field tests at four different Central European locations, was presented in [19]. This was limited to climate conditions similar to Central European, as no sky radiation influence was considered and only a combined model for drainage and plant soil can be handled, while today mainly separate drainage boards are used. Therefore the model was further optimized to become applicable for extensive green roofs in all climates [3] [20]. Figure 1 shows the four transfer phenomena which are used to implement the greenery to hygrothermal simulation software.

This comprises the handling of precipitation including drainage transport through the soil and storage in the drainage boards, effective surface transfer and insulating properties of the plant canopy, effective hygrothermal material properties of the different layers of the greenery as well as the effective solar and sky radiation exchange of the planted surface. Thus the model requires measured properties of the used soil and drainage layers and outdoor climate data including sky radiation and precipitation. Compared to the previous models the plant canopy is just considered by its effective heat transfer, additional insulation due to the rather stagnant air in-between the plants as well as the self-shading and thus reduced long- and shortwave radiation exchange.

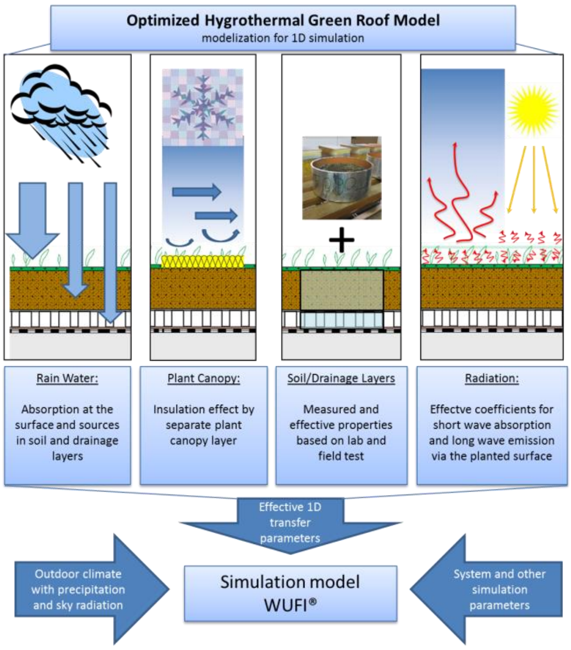

Figure 2: Input and transfer parameters of the optimized hygrothermal green roof model

3.2. VALIDATION

This approach seems rather simple – however, it leads to a good correlation with both, the measured temperatures beneath the greenery as well as the hygrothermal conditions in the roof assembly when simulating it once with the measured temperatures from the field test and once with the new model. Figure 2 shows exemplarily for roof 1 the comparison between the measured (two measurement axes in the test field) and the simulated temperature conditions.

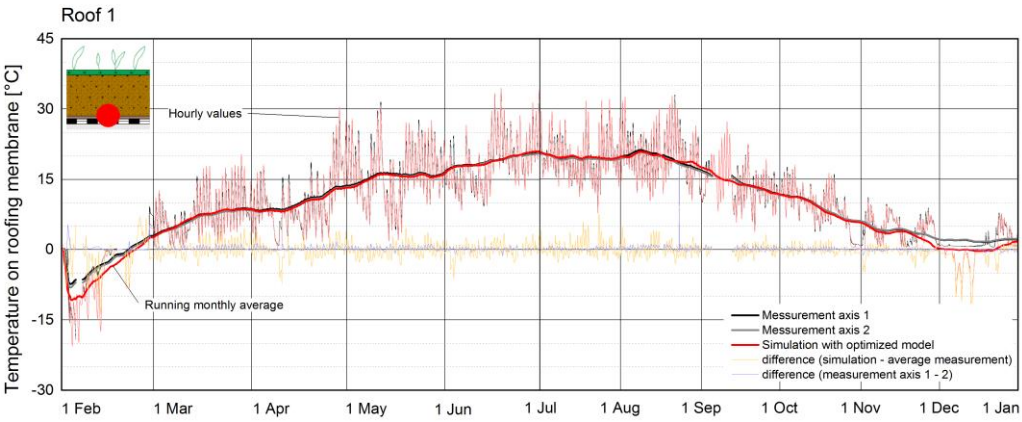

Figure 3: Comparison of the measured and simulated temperatures beneath green roof 1

The agreement is very good from spring to autumn while certain deviations can occur in winter during periods with snow cover, which cannot be accounted for in the simulation. The average annual temperature difference is -0,4 K which means, that the model remains colder and thus slightly on the save side. As the snow reduces the short wave radiation influence due to the white surface as well as the long wave radiation influence, the temperature beneath the snow remains mostly around 0 °C. As, during winter, long wave losses dominate over short wave gains neglecting the snow in the simulation leads to colder conditions than the measured ones. Thus the model remains on the safe side. More details concerning the thermal and hygrothermal evaluation can be found in [5] and [20].

To check the applicability for energy and comfort simulations, a single test room was simulated, using the hygrothermal whole building simulation tool WUFI® Plus [21]. The test room represents one room at the top floor (beneath the green roof) of a bigger residential building and is shown in Figure 4. The size is 5 m by 5 m and 2.8 m height. The side and back walls as well as the bottom ceiling are assumed to be adiabatic, as the neighbour rooms feature the same operation. The influence of the thermal mass is minimized by using timber constructions. The U-value of the external wall is very low with 0,15 W/(m²K) again to minimize that side influence. The roof construction has the same U-value like the test roof from the field test – this is necessary to be able to compare the results of a simulation with the green roof model and with the measured temperatures beneath the green roof. For comparison also a simulation with a conventional black roofing membrane is performed. The room has two North oriented windows with an U_w-value of 0,8 W/(m²K), a SGHC value of 0,5 and an area of 3,6 m² (without shading devices). The internal heat load is assumed to be rather low (20 W for 24 h), the air change rate is 0,3 h^{-1}. The acceptable temperatures in the room range from 20 to 23 °C. As outdoor climate the measured data at the IBP field test at Holzkirchen (South Germany) are use.

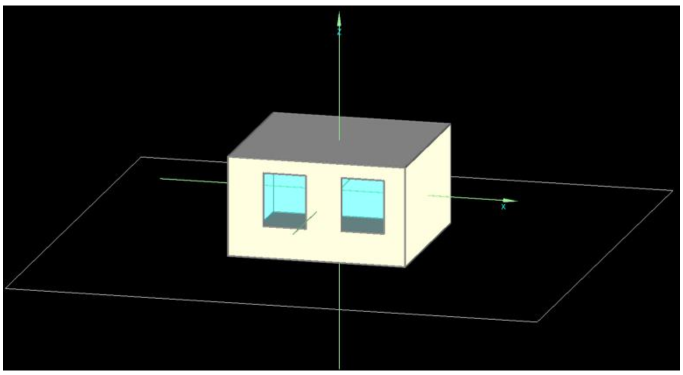

Figure 4: Test room for validation of energy performance of the green roof model
with hygrothermal whole building simulation

The results of the simulation are shown in Figure 5 as heat fluxes through the roof during winter and summer time. The overall agreement between the green roof heat fluxes with measured temperature and the new green roof model are quite good – especially in the summer months. In winter again some deviations can be observed when snow is on the roof from second half of January until last week of February. However, evaluating the hourly curves (figures on the right), the small differences between model and measured values compared to the big differences to the heat fluxes of the black roofing membrane become obvious. Looking on the energy demand for heating and cooling of the test room with measured and modelled green roof, also these values are very close to each other. The heating energy demand differs only by 0,4 % (1334 kWh with measured temperatures compared to 1329 kWh with the model). Also the black roof case needs only 1.5 % more heating energy with 1349 kWh. In summer time the cooling demand with the model with 126,3 kWh again is only 0,4 % higher than with the measured data (125,9 kWh). But now, with 255 kWh, the cooling energy demand of the room with the black roofing membrane exceeds the ones of the green roofs by 50 %.

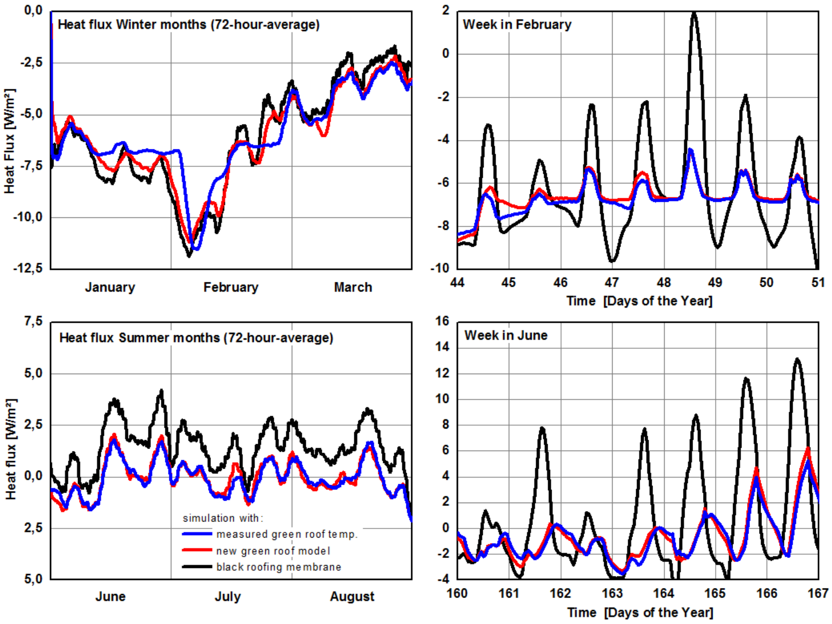

Figure 5: Heat fluxes through the roof in summer and winter simulated based on the measured temperatures beneath the green roof (blue) and the new green roof model (red) compared to the heat fluxes of a black membrane roof (black).

4. APPLICATION EXAMPLE

As application example, a residential building under the climatic conditions of Split in the South of Croatia is simulated. The climate file with hourly data including precipitation and long wave radiation data was created by the help of METEONORM. Focus is on the energy demand of the top floor when using a green roof in comparison to a white and black roofing membrane. The exemplary building, plotted in Figure 6, has an unheated basement and two heated and air-conditioned floors. The building is 9 m by 11 m and 6 m height plus 2.5 m for the basement. Walls, ceilings and flat roof are made of masonry or concrete. The 24 cm thick clay brick walls feature an U-value of 0,5 W/(m²K) and the flat roof with 15 cm concrete and 8 cm EPS insulation has an U-value of 0,44 W/(m²K). The total area of the seven windows in the second floor is 15,4 m² with an U_w-value of 2,7 W/(m²K) and a SGHC of 0,7. The windows are temporarily shaded by 75 % to limit the solar radiation gains during summer and avoid overheating. The indoor loads represent a typical operation as residential building with living room and kitchen in the first and sleeping rooms in the second floor. In the simulation different zones are used for each floor – thus the second floor with the green roof influence can be evaluated separately. The design conditions require heating, when indoor air temperature falls below 20 °C and cooling when temperatures exceed 25 °C.

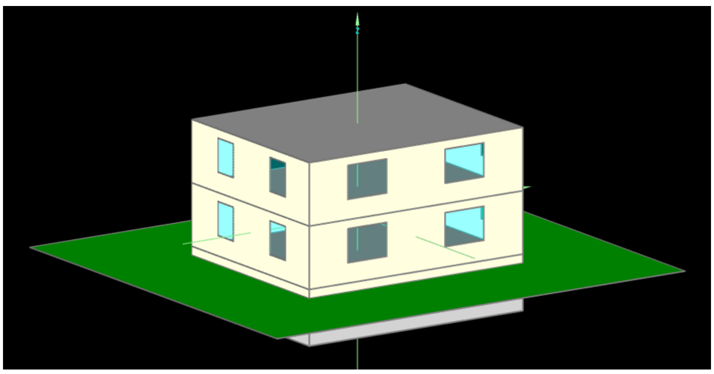

Figure 6: Exemplary residential building with two floors and basement with green roof, compared to a black or white roofing membrane.

As result, the total heat gains or losses during the summer and winter months are plotted in Figure 7. In summer the differences are obvious: the black roof shows the worst performance with gains of 1550 kWh, compared to only 590 when using a white roofing membrane instead. The green roof shows similar values as the white roof. Without irrigation the gains are a bit higher with 660 kWh. However, to ensure a good growth of the plants also during the summer months, some additional irrigation will be required anyway.

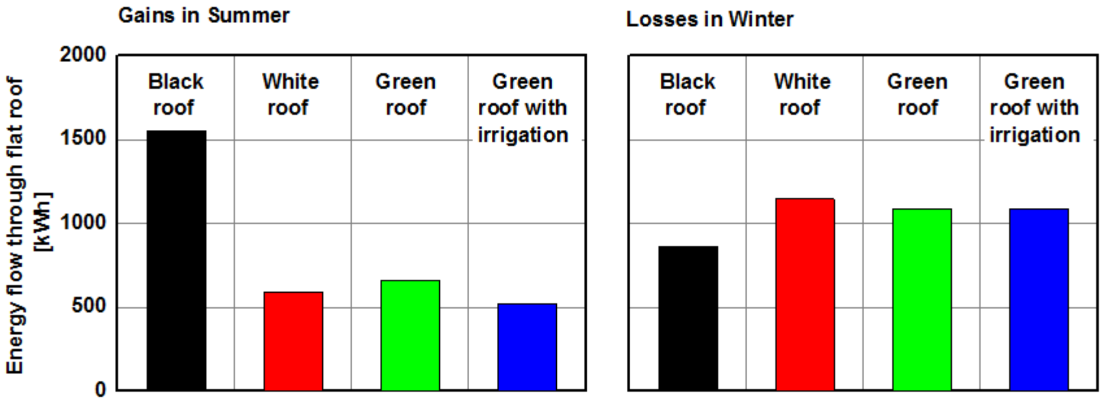

Figure 7: Energy gains and losses through the flat roof with black or white roofing membrane or greenery.

The cooling energy demand to condition the whole 2nd floor is 2073 kWh per year for the irrigated green roof compared to 3100 kWh for the black and 2156 kWh for the white roof. As expected, the heating energy behaves contrary: here the black roof requires 3318 kWh compared to 3542 for the green and 3665 kWh for the white roof. That means, green and white roofs have advantages in summer and black roofs in winter time which compensate each other to a certain extent. However, the total energy demand throughout the year is lowest for the green roof with 5615 kWh, followed by the white roof with 5820 kWh (+3,7 %) and highest for the black roof with 6418 kWh (+14,3 %).

5. CONCLUSIONS

The validations show, that the new green roof model can be used with good accuracy for both, the hygrothermal building component as well as the whole building energy simulation featuring a good agreement between measured and simulated data all year round. The simulation of the whole year is essential especially for the moisture performance of building assemblies, as both, humidification in winter and drying in summer influence the hygrothermal behaviour. Compared to other green roof models, the more detailed simulation of the moisture balance in the soil, allows consideration of the influence of the natural weather conditions with precipitation in summer and winter. The more simplified handling of the plant canopy doesn’t seem to have relevant negative effects.

The evaluation of the example case results in Split shows, like the measurements in Germany, clear advantages concerning the summer overheating protection of the green roof with a reduction of the cooling energy demand by about 25 % compared to a black roofing membrane. However, a white roofing membrane behaves rather similar - only with irrigation a slight improvement by about 4 % can be reached with a green roof. In winter the black roof provides additional solar heat gains, while the white roof still features the highest losses. While under German conditions black and green roof show a similar performance in winter, the higher solar radiation gains of the black roof and the additional evaporation cooling effects of the green roof in Split led to certain advantages of the black roof in winter time. Clear advantages of the greenery concerning energy savings during the winter month, like mentioned in different other publications, cannot be confirmed. Over the whole year period a green roof solution still provides the best energy performance – in combination with the advantages mentioned in the introduction, a high durability of the roof, but also higher costs for building and irrigation.

ACKNOWLEDGMENTS

The research results presented in this paper were funded by the German Federal Ministry of Transport, Building and Urban Affairs within the research initiative “Zukunft Bau” under the project number F 2863. For application of the model a guideline with detailed settings and input parameters as well as the required material properties are available on the IBP homepage [23].

REFERENCES

[1] EN ISO 13788 Hygrothermal performance of building components and building elements -- Internal surface temperature to avoid critical surface humidity and interstitial condensation -- Calculation methods. (2012).

[2] DIN 4108-3: Wärmeschutz und Energie-Einsparung in Gebäuden. Klimabedingter Feuchteschutz. Anforderungen, Berechnungsverfahren und Hinweise für Planung und Ausführung. Juli 2001.

[3] Schafaczek, B. und Zirkelbach D.: Ermittlung von Materialeigenschaften und effektiven Übergangsparametern von Dachbegrünungen zur zuverlässigen Simulation der hygrothermischen Verhältnisse in und unter Gründächern bei beliebigen Nutzungen und unterschiedlichen Standorten. Forschungsinitiative Zukunft Bau, Band F 2863, Fraunhofer IRB Verlag 2013.

[4] Künzel, H. M.: Verfahren zur ein- und zweidimensionalen Berechnung des gekoppelten Wärme- und Feuchtetransports in Bauteilen mit einfachen Kennwerten. Dissertation Universität Stuttgart (1994).

[5] Zirkelbach, D.: Wärme- und Feuchteverhalten von begrünten Dachkonstruktionen. Dissertation Universität Stuttgart (2016).

[6] EN 15026:2007-07: Hygrothermal performance of building components and building elements. Assessment of moisture transfer by numerical simulation (2007).

[7] Liu, K. K. Y.: Sustainable building envelope - garden roof system performance, RCI building Envelope Symposium, New Orleans, USA (2004) S. 1-14.

[8] Sailor, D.J.: A green roof model for building energy simulation programs. Energy and Buildings 40 (2008), S. 1466-1478.

[9] Perrier A.: Étude et essai de modelisation des echanges de mass et d'energie au niveau des couverts vegetaux: profils microclimatiques, evapotranspiration et photosynthese Nette. Doctorat d'Etat, Universität Pierre et Marie Curie, Paris, Frankreich (1976).

[10] Frankenstein, S. und Koenig, G.: FASST Vegetation Models. U.S. Army Engineer Research and Development Center (ERDC), Cold Regions Research and Engineering Laboratory (CRREL), Technical Report TR-04-25 (2004).

[11] Barrio, E. P. del: Analysis of the green roofs cooling potential in buildings. Energy and Buildings 27 (1998), S. 179-193.

[12] Theodosiou, T. G.: Summer period analysis of the performance of a planted roof as a passive cooling technique. Energy and Buildings 35 (2003) H. 9, S. 909-917.

[13] Kumar, R. und Kaushik, S. C.: Performance evaluation of green roof and shading for thermal protection of buildings. Energy and Buildings 40 (2005), S. 1505-1511.

[14] Lazzarin, R., Castellotti, F. und Busato, F.: Experimental measurements and numerical modelling of a green roof. Energy and Buildings 37 (2005), S. 1260-1267.

[15] Alexandri, E. und Jones, P.: Developing a one-dimensional heat and mass transfer algorithm for describing the effect of green roofs on the built environment: Comparison with experimental results. Building and Environment 42 (2007), S. 2835–2849.

[16] Ouldboukhitine, S.-E., Belarbi, R., Jaffal, I. und Trabelsi, A.: Assessment of green roof thermal behavior - A coupled heat and mass transfer model. Building and Environment 46 (2011), S. 2624-2631.

[17] Tabares-Velasco, P. C. und Srebric, J.: A heat transfer model for assessment of plant based roofing systems in summer conditions. Building and Environment 49 (2012), S. 310-323.

[18] Olivieri, F., Di Perna, C., D'Orazio, M., Olivieri, L. und Neila, J.: Experimental measurements and numerical model for the summer performance assessment of extensive green roofs in a mediterranean coastal climate. Energy and Buildings 63 (2013), S. 1-14.

[19] Zirkelbach, D.; Schafaczek, B; Künzel, H.M.: Longterm hygrothermal performance of green roofs. In: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. ASHRAE. Buildings XI - Thermal Performance of the Exterior Envelopes of Whole Buildings: Proceedings, Paper 105. Atlanta, USA (2010).

[20] Zirkelbach, D.; Mehra, S.-R.; Sedlbauer, K.-P.; Künzel, H.-M.; Stöckl, B.: A Hygrothermal Green Roof Model to Simulate the Moisture Performance of Building Components. Energy and Buildings - Special Issue on The effect of indoor and outdoor vegetation on the building performance (2017).

[21] Antretter, F.; Sauer, F.; Schöpfer, T.; Holm, A: Validation of a hygrothermal whole building simulation software. Proceedings 12th Building Simulation 2011 (2011) p. 1694-1702.

[22] Meteonorm V. 6.1. Software from Meteotest. www.meteonorm.com

[23] Guideline for the calculation of extensive green roofs on WUFI®-Homepage:

[24] https://wufi.de/de/wp-content/uploads/sites/9/2014/09/Guideline_green_roof_150923.pdf