A coupled modelling approach to quantify the microclimatic effects of green infrastructure on residential buildings

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1. Abstract

Rising temperatures and the further intensification of the urban heat island (UHI) effect are major challenges for cities. They lead to an increase in energy demand for cooling which counteracts climate change mitigation efforts. Adaptation via urban green infrastructure (UGI) can significantly reduce the UHI effect. Our study aims at quantifying UGI measures at scale of an urban block with benefits for outdoor as well as indoor thermal comfort and buildings' energy demand by coupling microclimate modelling with thermal building simulation.

The microclimate modelling software ENVI-met simulates the surface-plant-air interaction in an urban quarter. We use ENVI-met to analyse outdoor thermal comfort conditions in different urban greening scenarios. In order to evaluate the effect of these scenarios on indoor thermal comfort and buildings' energy demand, we employ IDA Indoor Climate and Energy, a building performance simulation tool. As ENVI-met operates at a temporal resolution of single extreme weather days while analyses of energy demand and thus CO_2 emissions are based on yearly records, an approach to coupling the simulation approaches needs to be developed. In our approach yearly weather files are clustered into typical-day categories. For each of the typical-days an ENVI-met simulation is run for the different UGI scenarios. The results of these calculations are the input for the building simulation. The input of yearly weather files are both measured data of actual conditions and climate change scenarios. The methodological approach is tested for an urban block in Munich, Germany, representing a typical inner urban fabric with a high degree of compactness and surface sealing.

Coupling microclimate modelling with thermal building simulation allows a detailed analysis of how UGI measures at the building (e.g. green roofs and facades) as well as UGI measures in public space (e.g. street trees) are reducing the potential for indoor overheating for the typical-days of a year. Furthermore the impact of UGI on cooling measures at building level (e.g. cross ventilation, mechanic cooling) will be shown. The results are expected to serve as decision support for urban planners and city administrations when implementing UGI measures.

2. Introduction

Climate change is happening. Scientists agree on the fact that adaptation as well as mitigation are needed to limit the impacts of projected climatic changes on society and to reduce the magnitude of further changes (IPCC, 2014). In European temperate climate temperature is expected to rise. Moreover, extreme events such as heat waves are likely to happen more frequently and with a higher intensity in the near future. The impacts of climate change are intensified within cities due to the dense building structures and sealed surfaces, in conjunction with a reduced ventilation and transpiration potential, leading to the so-called urban heat island (UHI) effect (EEA, 2012). Rising temperatures and the intensified UHI effect are expected to create an increase in energy demand for cooling which counteracts global efforts for climate change mitigation and may compromise local efforts for more sustainable urban development (Akbari, 2002, Fahmy and Sharples, 2011).

Adaptation via urban green infrastructure (UGI) has a significant reduction potential on the UHI effect as UGI provides climate regulating services like evapotranspiration and shading (Whitford et al., 2001, Akbari, 2002). There are several studies that have shown the positive effects of UGI on air temperature and outdoor thermal comfort in cities (Skelhorn et al., 2014b, Middel et al., 2015, Jänicke et al., 2014, Perini and Magliocco, 2014, Gill et al., 2007). The reductions of indoor temperatures and of energy loads for cooling on hot summer days via UGI were established in some studies, too (Wang et al., 2014, Yang et al., 2012, Skelhorn et al., 2014a, Fahmy and Sharples, 2011).. However, none of them focus on the implications of UGI on buildings over the course of a whole year, i.e. the effects of UGI during the different seasons of the year. Therefore, there is a lack of knowledge on the overall performance of UGI to reduce building energy demands.

Against this background, our interdisciplinary study aims at quantifying the effects of UGI measures at urban micro-scale with benefits for outdoor as well as indoor thermal comfort and buildings' energy demand for a whole year. By coupling microclimate modelling with thermal building simulation together with a cluster method for yearly weather files the following research questions shall be answered using the example of an urban block in Munich, Germany:

1. How does urban green infrastructure affect outdoor thermal comfort during the course of a year?
2. How does urban green infrastructure affect indoor thermal comfort as well as building's energy demand during the course of a year?
3. Which type of green infrastructure measures provides combined benefits for outdoor and indoor thermal comfort?

3. Methodology

3.1 Case study

The methodological approach proposed in this study is tested for an urban block in Munich, Germany, representing a typical urban fabric with a high degree of compactness and surface sealing. It is a closed perimeter block in downtown Munich. The Maxvorstadt neighbourhood was planned in the neo-classical style and is characterized by a rectangular street system and a high building and population density (Landeshauptstadt München, 2008, Landeshauptstadt München, 2015). The selected block of 9655 m2 is very densely built (69% of total surface area) and the total cover of impervious surfaces is 91%. It is a typical block structure of the 19th century, but most houses are post-WWII (constructed between 1949 and 1960). Most of the buildings are residential, but there is also commercial use in particular in the buildings of the backyard and on the ground floor of the main buildings. The current green cover is only 6%, mainly consisting of street trees and trees and shrubs in the inner backyards.

Figure 1: Case area in Munich Maxvorstadt, © Microsoft Cooperation

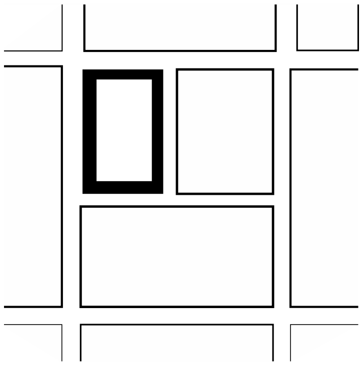

Figure 2: Schematic overview of case area

3.2 Typical-day categories

The microclimate modelling approach operates at a temporal resolution of single extreme weather days as the computing time for only single days in these complex model set ups already reaches up to five and more days. In contrast, analyses of energy demand and thus carbon emissions are based on yearly records. Hence, an approach is needed to overcome the temporal difference between the two modelling methods and to produce weather input files for every day of the year for the building simulation In our approach coupling between the ENVI-met microclimatic model and the energy simulation model IDA-ICE is achieved by clustering weather files into typical-day categories. Available yearly weather files are clustered into typical-day categories (VDI, 2012). The input of yearly weather files can be measured data as well as climate change scenarios to study the effects in a projected future climate. In the present study we have chosen the application of test reference years that were defined by the German weather service (Bundesamt für Bauwesen und Raumordnung (BBR) et al., 2014). To evaluate the potential of the typical-day approach and to provide reliable results the following five steps were taken:

1. Selecting a test reference year for the region of Munich (Bundesamt für Bauwesen und Raumordnung (BBR) et al., 2014)
2. Clustering the weather data based on the variables ambient temperature and solar radiation with a hierarchical approach by applying the Ward's method (R Core Team, 2015)
3. Preprocessing the weather data for the building simulation
4. Validating the approach by simulating the energy demand for the typical-days by using building simulation software
5. Summing up the results of the typical-day simulations and comparing it with a whole year simulation of the energy demand in the thermal building simulation software

3.3 Simulation approach

The microclimate modelling software ENVI-met simulates the surface-plant-air interaction in an urban quarter and hence, allows small-scale analyses of climate conditions and urban planning strategies (Bruse and Fleer, 1998, Bruse and Environmental Modelling Group, 2014). In this study we use ENVI-met to analyse outdoor thermal comfort conditions and to produce adjusted weather files in different urban greening scenarios.

In the scenarios the parameter of green volume is adapted by applying three different green infrastructure measures to the current greening situation of the case study area as shown in figure 3: a) greening of roofs, b) greening of facades and c) tree plantings in streets and inner courtyards.

Current greening situation | *a) Additional roof greening* | *b) Additional façade greening* | *c) Additional tree plantings*

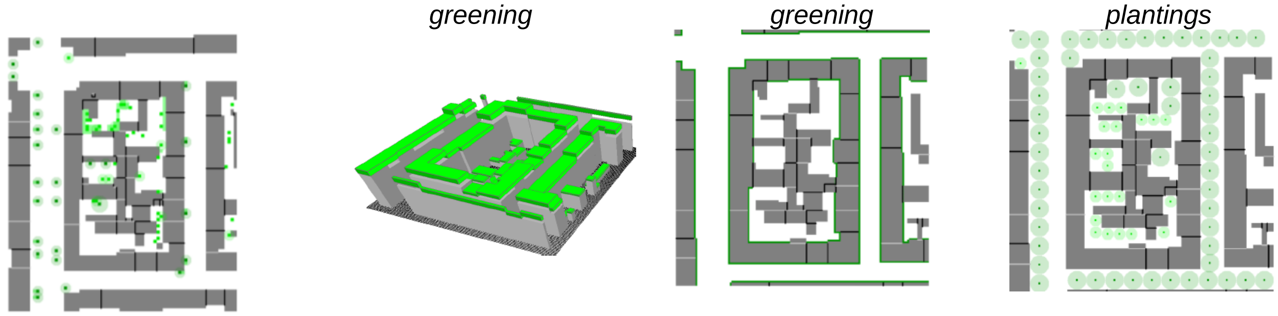

Figure 3: Urban greening scenarios displayed in ENVI-met

In order to evaluate the effect of these greening scenarios on indoor thermal comfort, the buildings' energy demand and thus CO_2 emissions, we employ IDA ICE, a building performance simulation tool. It has been developed to assess energy and indoor climate performance as well as moisture conditions (EQUA Simulation AB, 2014, Sahlin et al., 2004).

The single steps of our coupled modelling approach are illustrated in figure 4. For each of the typical-days ENVI-met simulations of the different greening scenarios are run. The meteorological output files of these calculations serve then as input into IDA ICE. Again, simulations for each typical-day and each greening scenario are conducted. The results of the IDA ICE simulations are finally summed up to a whole year balance.

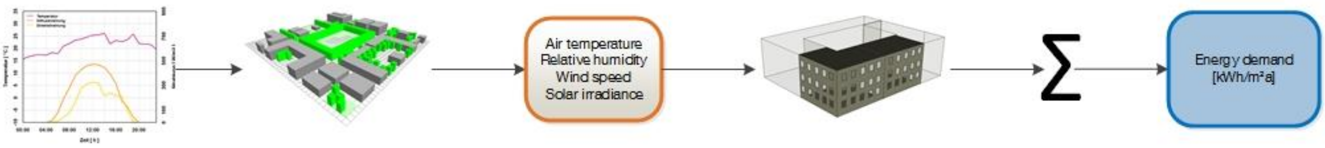

Figure 4: Methodological approach by coupling microclimate modelling with building simulation

4. Results

To conduct the clustering of a yearly weather file into typical-day categories a recent test reference year for the Munich city region was selected. An additional factor for the influence of the surrounding region was added to give credit to the UHI effect (Bundesamt für Bauwesen und Raumordnung (BBR) et al., 2014). Figure 5 shows the output dendrogram of the clustered test reference year. From the dendrogram five categories of different intervals were distinguished that cover one year (365 daily mean values). The red boxes in figure 5 represent the five clusters selected for the further analysis. Figure 6 shows the courses of the five typical-days for the parameters ambient temperature and diffuse and direct radiation.

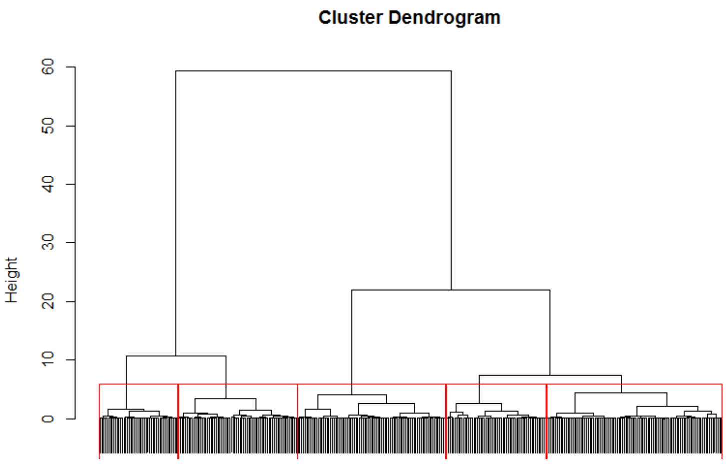

Figure 5: Dendrogram of the hierarchical cluster of the test reference year

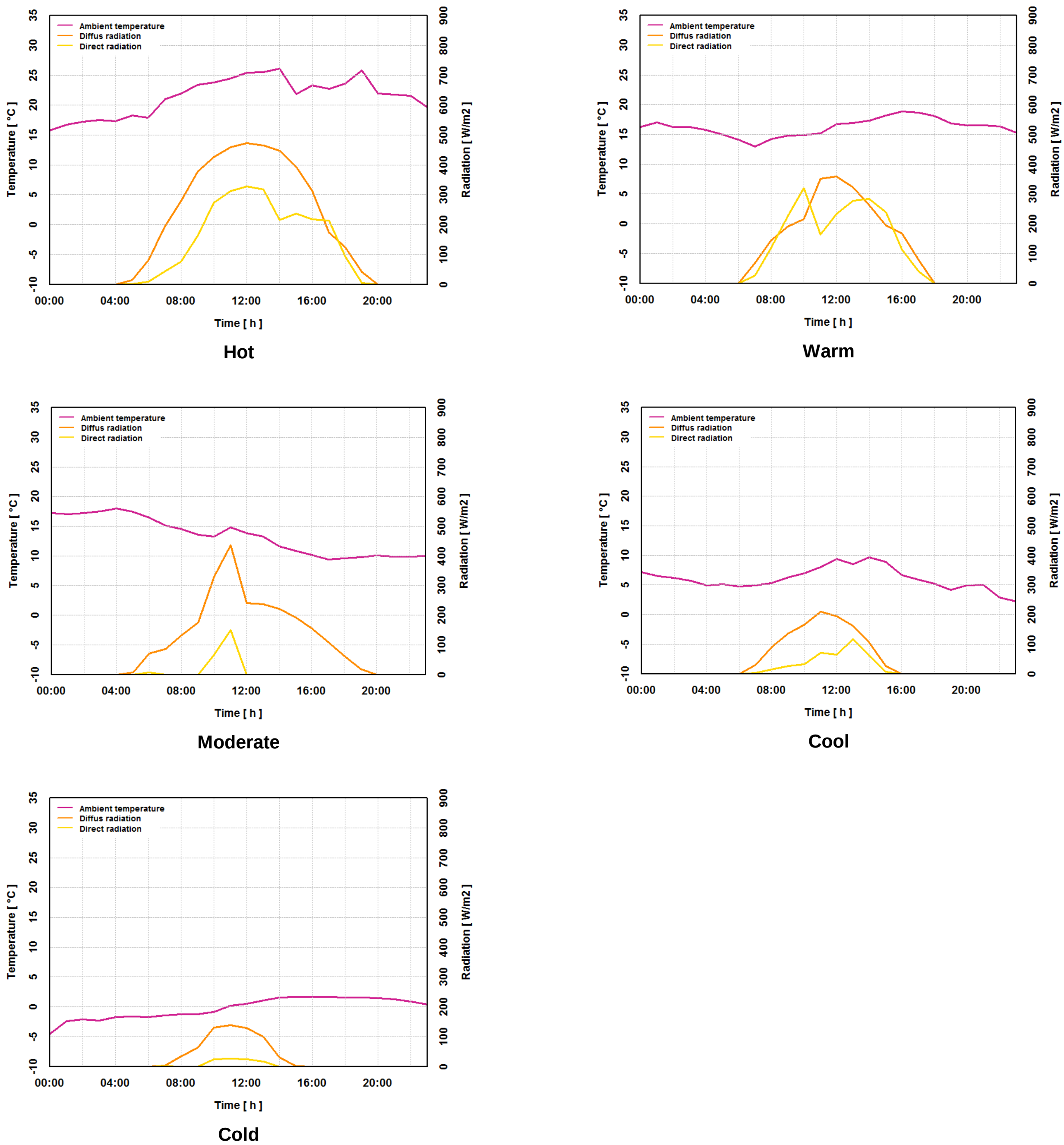

Figure 6: Typical-days for the test reference year

After a preprocessing for the building simulation five typical-day weather files were developed as input for IDA ICE. For validation, a single family home was then built in IDA ICE and simulations were undertaken first for the typical-day approach and secondly, on hourly basis over one year and compared with each other.

The results of the simulations are shown in table 1. The difference for the heating demand between the detailed simulation and the type days is about 3% which can be evaluated as a reliable output. For the cooling demand the typical-day approach comes to the same results as the hourly based building simulation, the relative difference is 0%.

Typical-day	Number of days	Type day heating [kWh]	Type day cooling [kWh]	Total heating [kWh]	Total cooling [kWh]
Cold	75	165	0	12375	0
Cool	89	100	0	8900	0
Moderate	75	35	0	2625	0
Warm	74	1	0	74	0
Hot	52	0	18	0	936
Typical-days				23974	936
IDA ICE				24687	936
Difference				713 (3%)	0 (0%)

Table 1: Simulation results of testing the typical-day approach for a single family home in IDA ICE

5. Discussion

This research tackles a major methodological challenge for an integrated assessment of climate change adaptation and mitigation at the scale of an urban quarter: the differing temporal scales between assessments of outdoor thermal comfort and indoor thermal comfort. The approach proposed in this paper is still under development and for its successful implementation further methodological challenges have to be overcome such as integrating the representation of vegetation dynamics over the year in ENVI-met.

In comparison to other studies, that have already coupled microclimate modelling with thermal building simulation (Fahmy and Sharples, 2011, Skelhorn et al., 2014a, Yang et al., 2012), the major innovation in our approach lies in the whole year assessment. This is highly demanded by decision makers as they have to take decisions, e.g. on investments into green infrastructure measures, not only based on the benefits during summerly heat periods, but based on whole year assessments. Still, the proposed method is a one-way approach and no feedback is given back to the ENVI-met model.

6. Conclusions and Outlook

The presented coupling of microclimate modelling with thermal building simulation allows a detailed analysis of how UGI measures at the building side as well as UGI measures in public space are reducing the potential for indoor overheating for the typical-days of a year. First results of our study clearly show that the approach of typical-days can be used to provide reliable results for a yearly based analysis. In the next work steps of our study ENVI-met simulations for all typical-day categories and greening scenarios as well as IDA ICE simulations with the produced output files will be conducted. Furthermore, we will assess the impact of combined UGI measures in greening scenarios and by linking them with technical cooling measures at building level. The results of this research are expected to serve as decision support for urban planners and city administrations when implementing UGI measures into practice.

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