Green Resilient City - A framework to integrate the Green and Open Space Factor and climate simulations into everyday planning to support a green and climate-sensitive landscape and urban development

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Abstract. Continued urban growth, densification and the constantly increasing number of days with excessive heat provide challenging conditions for urban green infrastructure (UGI) and intensify the Urban Heat Island effect (UHI). Therefore, new approaches are required to improve the urban ecological function of buildings and to provide high-quality (urban) open spaces that affect the meso- and microclimate in a positive way. Based on the research project “Green Resilient City”, this paper shows how climate simulations can support landscape and urban planning and development. A proof of concept for a multiscale tool set for the evaluation, regulation, and optimization of green and climate-sensitive urban planning projects is the overall aim. The tool-set combines a Green and Open Space Factor, as an urban planning index and controlling instrument, as well as three climate simulation models on different scales in order to harmonize them: the GREENPASS® as an optimization instrument on parcel and neighborhood level, MUKLIMO_3 on neighborhood and city level and Cosmo-CLM as evaluation tools on mesoclimatic and regional level. Several advantages arise from the unprecedented combination of these four instruments: It transfers the use of climate models to the planning process, enables the testing and optimization of different UGIs with a focus on how they can influence the climatic performance of the proposed design of an urban development or retrofit project and serves as a scientific basis for urban planning decisions on a political level.

1. Introduction
Half the world’s population lives in cities and migration to urban areas is ongoing globally [1,2]. The United Nations estimate urban population to reach 68 % by 2050 [3]. Urban growth and the increasing densification of urban areas with high-density housing and the increase of impervious surfaces threaten green and open spaces. In addition, to the loss of urban green spaces [1] and urban green infrastructure (UGI), there is a constantly increasing number of days of excessive heat due to the interaction of Urban Heat Island (UHI) effect and the climate change related higher temperatures [4]. The UHI effect describes the difference in temperature between the cooler surroundings and the hotter dense built-up urban areas. The main cause for the UHI are sealing of soils and building coverage, as they store energy
radiated by the sun. Cities are, therefore affected twofold: the increase of urban growth and the temperature increase due to climate change.

The reduction of the urban heat load is thus a central challenge for future urban development and a number of cities are therefore considering adaptation measures, including the City of Vienna. Additionally, in Vienna, the urban climate has changed noticeably, especially in the last decades [5]. The year 2018 was a record-breaking year with 42 tropical nights counted in Vienna Inner City and it was the fourth warmest summer in Vienna for more than 250 years [6].

Urban green infrastructure as a strategy for achieving resilience against weather extremes and a sustainable, functioning urban system is indispensable in urban planning. Even more so as social and economic demands can be met in addition to ecological ones since society benefits from the ecosystem services provided by UGI. Urban ecosystems are particularly important for the city residents in terms of their climatic (e.g. reduction of the UHI effect), ecological (e.g. increase in biodiversity) and social (e.g. benefits for health, well-being, recreation) function and they contribute significantly to the quality of life in cities [7–10].

Urban structures and green areas influence the urban climate on different spatial scales. For example, roof greening as individual measure of a single building has positive, but limited effect on microclimate. On the other hand, if several roofs within an urban quarter are greened, the range of influence is already greater and can positively affect large areas of the city. If there are several quarters within a city where UGI is sensibly combined, the effect reaches far beyond and can have a positive influence on the entire urban climate and surrounding area [11]. Thus, the sum of several small-scale changes can have a combined impact on the entire city. In order to have a positive influence on the urban climate, urban planning requires new, holistic approaches that take account of different levels of scale. As urban development is also a multi-level planning approach, steering and decision-making tools must be reconciled with the different planning levels.

To address these issues this paper answers following research questions:

- How should a tool set, consisting of several instruments (planning tool and climate simulation models), look like in order to be able to control and evaluate green spaces in the city?
- How can climatic performance be represented by the tool set?
- Which different planning levels can be addressed by the proposed tool set?

2. Methodological approach and introduction of instruments

In an interdisciplinary and transdisciplinary, collaborative approach the research team developed a novel tool set demonstrating its feasibility in a proof of concept. The various input parameters of the individual instruments (Green and Open Space Factor of Vienna, GREENPASS®, MUKLIMO_3 and CosmoCLM) were compared, adjusted and coordinated. The focus of the study lays on coordinating different scale models by analyzing data interfaces, harmonizing input parameters and setting the same reference time periods to examine the possibility of using a multi-scale tool set. The aim is to find out whether different, independently used and validated climate simulation instruments can be combined into a multi-scale tool set in order to support everyday planning in the future as an overall instrument. It will be evaluated if the combination of the individual simulation models with the Green and Open Space Factor of Vienna (GFF) can work as proposed in the tool set and deliver useful results to support green and climate-sensitive landscape and urban planning.

2.1. Green and Open Space Factor of Vienna (GFF – “Grün und Freiflächenfaktor”)

Following the example of other cities (e.g. Berlin, Helsinki, Seattle, Stockholm, London) [12–16] a green and open space factor (GFF – in German: “Grün und Freiflächenfaktor”) was developed for Vienna. Reacting to the fact that the fraction of green areas decreased especially in the last 15 to 20 years in Vienna, it is now aimed to maintain, and also to expand, existing UGI, because private and semi-public green and open spaces have positive effects for the entire city through ecosystem services.
At present, the floor-space-index (GFZ – in German: “Geschoßflächenzahl”), together with other measures (e.g. degree of sealing, building density, building height, etc.), is the determining factor for urban development. The GFF for Vienna is the counterpart to the floor-space-index. In addition, the GFF considers the ecological, climatic and socio-economic aspects of UGI by factoring in the different ecosystem services and selected elements of UGI. Each of the category contains individual UGI elements and is underlined with a specific factor determining the final GFF.

The calculation method of the GFF of Vienna gives a ratio of the UGI (in square meters) to the respective reference area on the ground floor, façade or roof (Figure 1). Due to the different reference areas, a differentiated consideration of the UGI elements (green and open space, façade greening, roof greening) is possible, as a function of the building size and height.

Figure 1. GFF and its respective reference areas (ground floor, façade and roof)

2.2. Climate simulation tools on different scale levels

The possibilities of the instruments for simulation and evaluation of urban climate are comprehensive and varied, but not yet tailored to the needs of landscape and urban planning. Three different simulation tools, developed and individually validated in previous research projects have been selected to cover the different climatic impact areas and planning scales: the GREENPASS® as an optimization instrument for the microclimatic effects of green infrastructure at parcel and neighborhood level, the MUKLIMO_3 urban climate model as an evaluation instrument for the local scale impact on city level and Cosmo-CLM as a regional climate simulation model to provide projections on large-scale climate developments. In the course of the research project "green.resilient.city", the individual climate simulation instruments are coordinated, cross-validated and harmonized in order to adjust the input and output parameters (Figure 2). On the basis of a first case study (situated in an urban development area: aspern Seestadt), GFF and GREENPASS® were adjusted and used jointly in an urban planning competition. The effects of integrating these two instruments by increasing the use of urban green infrastructure could be shown by the urban climate model MUKLIMO_3 on larger scale. In further
steps, harmonization with the regional climate model Cosmo-CLM and cross-validation of all instruments will be carried out.

Figure 2. GFF and climate simulation tools on different scale levels – downscaling of climate simulations to local scale (Source: Own representation based on ZAMG, 2019)

2.2.1. GREENPASS®
GREENPASS® defines standardized processes to assess and evaluate the climate resilience and cost-efficiency of architecture and urban planning. It combines the holistic high-resolution numerical simulation software ENVI-met with area analyses, evapotranspiration models, cost analyses and qualitative indicators [17]. ENVI-met was developed at the Chair of Environmental Meteorology Group at the Johannes Gutenberg University in Mainz [18–20]. In several European research projects (e.g. “Biotope City is Smart”, “Nature4Cities”), the prerequisite for the planning use of the microclimate simulation software was created and linked with other models. Urban and object planning projects up to a size of 40 ha (with an internal resolution of 2 m) can not only be simulated, but can also be analyzed and optimized with regard to thermal comfort, rainwater management, costs for construction and maintenance, CO₂ storage, cooling degree hours, water demand and ecological quality.

For project quick assessment and mesoclimatic urban climate simulations, so called urban standard typologies were developed which assign specific land use data to an urban structure [21].

2.2.2. MUKLIMO_3
Urban climate model MUKLIMO_3 and the cuboid method developed by the German Meteorological Service (DWD - “Deutscher Wetterdienst”) allows the investigation of urban heat load with spatial resolution of about 20 m to 200 m and on a time scale, which is suitable for the daily development as well as for the climatological analysis of UHIs. Based on topography and land use data, the urban climate model MUKLIMO_3 [22–25] simulates the radiation balance, wind, humidity and temperature distribution in the city, taking into account potential atmospheric conditions during periods of heat. Using the cuboid method [26] that combines high-resolution urban climate model output with long-term climate information from monitoring stations or regional climate projections it is possible to calculate climatological indices such as mean annual number of summer days, heat days or tropical nights for the 30-year climatic periods. Furthermore, the model can be used to assess the effects of different climate
change adaptation measures, including the implementation of green infrastructure or unsealing of sealed surfaces.

2.2.3. COSMO-CLM
The German regional climate model Cosmo-CLM with special urban extensions (CLM-URB)[27–29] which integrate anthropogenic heat emissions [30,31] and a high-resolution sealing layer [32], is used to provide high-resolution climate scenarios. That allows simulations with a resolution of 1x1 km for the greater Vienna area (100x100 km). The simulations are calculated in four nesting steps at 50 km, 10 km, 4 km, and 1 km horizontal resolution. The first three runs are performed with the standard Regional Climate Model Cosmo-CLM. The urban extensions are applied in the 1 km run, with two additional input fields: the urban fraction (URBAN) and annual-averaged anthropogenic heat (AHF). By applying the urban extensions, the UHI effect can for the first time be mapped relatively fine-scaled with regional climate models in the context of large-scale climate developments. For the simulation of the past and the model evaluation ERA40/ERAInterim forcing data are used. AIT performs high resolution model runs for the greater Vienna area for various time slices until 2100. Model output is stored as hourly, daily, monthly, seasonal and yearly values and can be transferred to ArcGIS maps on future climate scenarios for Vienna.

3. Results - Requirements for a tool-set for a climate-sensitive urban development and its elaboration

3.1. Interface definition and data transfer to harmonize the instruments
The GREENPASS® urban standard typologies (USTs) represent an essential link between microclimate and mesoclimate simulations. These USTs have been developed in several research projects (e.g. “Green4cities”) and allow the abstraction of global urban structures. International case study cities (Hongkong, London, Santiago de Chile and Vienna) were analyzed using GIS data and aerial photos [33]. In a first step a set of USTs for each city was elaborated and finally merged to one set of global applicable USTs. Existing sets of USTs have been respected, as the Local Climate Zones published by Oke [34] which are limited to Northern American urban structures. In addition, the GREENPASS® USTs are more detailed in regard to the differentiation of areas, surfaces, materials and green infrastructure, which supports the calculation of the GFF. Furthermore, each GREENPASS® UST is available in four varieties: a worst case, status quo, moderate greening and maximum greening scenario. The scenarios describe the level of integration of urban green infrastructure, ranging from no green for the worst-case scenario to dense green at the maximum scenario. The mesoclimatic simulation models require land use data, such as the degree of sealing, canopy area, etc. The USTs provide this information as a basis for mesoclimatic simulations, not only in one but in four different greening scenarios. This unique approach allows to quickly exchange the scenario for a selected urban area and to increase or decrease the level of integrated urban green infrastructure without changing the building structure.

3.2. Combination of the instruments to form a multi-scale tool set
To incorporate city-specific information on urban structures provided by the USTs into the MUKLIMO_3 model, physical parameters like the degree of soil sealing, percentage of built-up area, percentage of vegetation (trees, low vegetation, green roofs) that are available for each UST category are translated into characteristic land use information that can be handled by the urban climate model. Model simulations at 100 m spatial resolution are performed to investigate urban heat load distribution in Vienna, based on the land use information gathered from the USTs. Subsequently, by implementing variations of the USTs that mainly consider different types of greening measures, their cooling effect can be assessed through an analysis of modification in urban temperature distribution on a daily basis or a modification of climate indices considering 30-year climatological periods. In order to harmonize the different climate models, MUKLIMO_3 model output (temperature, relative humidity, radiation) can be used as input for the microclimate simulations carried out with ENVImet. Similarly, model output
obtained by the regional climate model Cosmo-CLM may serve as background climate information for the derivation of long-term climate indices with MUKLIMO_3. Integrating micro-scale urban fabric related information into the regional climate model Cosmo-CLM is challenging. The first step for identifying interfaces between micro- and macro-scale was to incorporate the sealing values of the USTs as input parameters into Cosmo-CLM. Test simulation runs have shown a high sensitivity of the model to changes in the degree of sealing. In further steps, plant cover, Leaf Area Index (LAI) and average building heights will be additionally integrated.

The GFF and GREENPASS® differ in the level of detail. The two instruments were coordinated by means of a tabular comparison. Due to the harmonization, the GFF contains all relevant UGI types used in GREENPASS® with only some exceptions. The GFF is partly more detailed, as social criteria are also included and evaluated. The higher level of detail is the logical conclusion due to the smaller area of use (parcel level). The combination allows the GFF to be calculated for each UST using GREENPASS® greening scenarios. The results show how much greening is possible for each typology. Based on this, target values can be derived which can be used to control the amount of greenery at parcel level.

3.3. Coordination of the tool set with the urban planning levels

In order to develop a tool set suitable for everyday use in urban planning, the steering and evaluation instruments must be harmonized with the multi-level planning approach of urban development. Therefore, all relevant planning levels and areas of the city must be covered. In summary, these are: (1) metropolitan area (2) city (3) urban district and larger urban development areas (4) urban quarter, smaller development areas (neighborhoods), and the parcel level. These planning levels influence each other, therefore all instruments used must be coordinated within the planning tool (Table 1).

| Planning levels and planning instruments | Climatic levels and spatial resolution | Climate simulations |
|-----------------------------------------|--------------------------------------|---------------------|
| Beyond city limit/metropolitan area/regional Regional development concepts and strategies | Regional-/meso-climate (1-10 km) | COSMO-CLM |
| | | | |
| City | Meso-/local-climate (100 m – 1 km) | COSMO-CLM/ MUKLIMO_3/ GREENPASS® |
| Urban development concept | | |
| District | Local-/micro-climate (20-100 m) | MUKLIMO_3/ GREENPASS®/ (GFF) |
| Land-use- and development-plan; Urban development competitions and guidelines | | |
| Urban quarter/parcel | Micro-climate (0,5-20 m) | GFF/ GREENPASS® |
| Developer completion; Urban development contract; Building permission | | |

In contrast to their local impact, the instruments described also show differences in their climatic impact. As explained in the introduction, the sum of measures at microclimatic level can achieve a large-scale effect. In order to improve the climate effectively, control instruments are needed at every scale level. By merging them, the planning levels and climatic scales are linked with each other. This leads to
a proposal for a multiscale toolset (Figure 3) for meso- and microclimate regulation, optimization and evaluation in relation to the different levels of urban planning.

**Figure 3.** Proposal for a multi-scale tool set for climate-sensitive landscape and urban development

3.4. **Application on the basis of a case study in an urban development competition in aspern Seestadt**

Case studies are used to test the implementation and applicability of the proof of concept. One of these is located in aspern Seestadt, one of the largest urban development areas in Vienna. In aspern Seestadt a two-stage urban development competition "Quartier Seeterrassen" was accompanied by the research project and the joint use of the instruments was successfully tested. The GFF and the GREENPASS® were combined and applied in several phases of the competition process (Figure 4).

In the tender documents for the first competition phase, the special focus on the microclimate was already announced in the form of general dos and don'ts for a climate sensitive urban development. The existing master plan for the entire aspern Seestadt was simulated in order to show the climatic performance of the current state of planning. Based on this, qualitative recommendations regarding the urban structure were given. In addition, as a part of the preparation phase for the second stage of the competition, quantitative specifications were defined with the GFF. A target value was set in order to achieve a sufficient degree of greening.

In the course of the preliminary assessment of the contributions to the competition, the GREENPASS® was used to simulate, compare and analyze the effectiveness of the use of green infrastructure and the effects of the development structure of the various competition entries and compliance with the GFF target value was checked. These results were prepared and served the competition jury as a basis for decision-making.

The monitoring and optimization did not end with the awarding of the prize to the winning project. Based on the results of the previous simulation, adaptations for the winning project were formulated and
optimizations made by various specific measures. As there are many different requirements regarding urban development and usability within the framework of an urban development competition, the winning project had to be optimized from a microclimatic point of view. In a workshop with the planning team (architects and landscape architects) adaptations were worked out. Building structures were slightly modified, breakthroughs in the perimeter block were defined for optimal air circulation, groups of trees were moved and façade greening was added to mitigate heat islands and optimize PET (physiological equivalent temperature). The winning design was revised and simulated again to make the optimization measures visible. It was gratifying to see that after the adaptations it became the best design both from an urban planning and a microclimatic point of view. The planning area was additionally simulated with MUKLIMO_3 in order to demonstrate the climatic effects on the entire quarter.

In the urban development guideline, which has to be taken into account when designing the individual building sites, both qualitative recommendations from the GREENPASS® simulations and quantitative specifications with the GFF were included in order to achieve a climate-sensitive urban development. With the GFF, a target value for UGI was anchored in the urban planning model for further planning and implementation processes. It has been shown that the monitoring and optimization of an urban development project by the tool set is feasible and shows positive results. In another case study, the applicability of the whole tool set in existing urban structures will be examined.

**Figure 4.** Workflow for the implementation of GFF and GREENPASS in an urban planning competition

4. **Discussion**

The GFF enables a (microclimatic) assessment of buildings, open spaces and UGI at parcel level. On the one hand, it enables accompanying urban planning procedures in order to compare and evaluate submitted development proposals. On the other hand, the need for optimization can be identified for existing built structures. The GREENPASS® can represent the climatic performance of individual building sites or urban quarters. For planning this means the following: By linking and coordinating these two instruments (GFF and GREENPASS®), the microclimatic impact of changes to individual UGI elements at site level can be simulated for an entire urban quarter. Since the urban climate model MUKLIMO_3 and the regional climate model Cosmo-CLM were also linked in the tool set and coordinated with the USTs, the output parameters of the GREENPASS® can be used in these instruments as an input. The advantages of implementing the USTs in the climate simulation models are the intersection with urban structural information and building types. The evaluation with regard to individual UST types makes it possible to generate general statements. Furthermore, greening scenarios can be integrated into the simulations. Thus, it can be shown which building type in combination with which greening type is climatically particularly effective.
The tool set can also be used in reverse order, from large scale to parcel level. The use of Cosmo-CLM and MUKLIMO_3 as climate simulation models on city level and its surroundings, allows the representation of UHI effect and intra-urban hot-spots under current and future climate scenarios. This results in target areas where improvements must be achieved in order to maintain a high quality of life for the residents. These findings can be embedded as initial conditions for the GREENPASS®. Through different greening scenarios, the GREENPASS® can demonstrate how much more UGI is needed within a city quarter. By considering wind direction and wind speed, the GREENPASS® indicates on which parcels specific measures have to be taken. The GFF can then control the use of UGIs on exactly these parcels by specifying target values. The sum of several microclimatic improvements leads to a positive influence on the urban climate.

The tool set supports political decisions with a scientific basis. It serves the city to foresee climatic developments and effects of urban development changes and to demand and achieve targeted measures. As there is not one holistic instrument for analyzing the urban climate at different planning levels and no steering instrument for UGI at parcel level in Vienna yet, the combination of different climate simulation models with the GFF can make a significant contribution to green, resilient urban planning.

5. Conclusion
In summary, it can be stated that the proposed tool set is applicable for the entire city and differentiates between the individual scale levels. Currently, the tool set consists of several components (GFF, GREENPASS®, MUKLIMO_3, Cosmo-CLM) that have to be operated individually. The combination into a single, coherent instrument requires further research. The possibility of controlling, evaluating and optimizing makes it suitable for both urban development processes and for conversions of existing urban structures. Building on this, links can be established to the relevant urban planning instruments in order to develop a regular urban planning instrument to consequently implement a steering tool for green infrastructure in (planning) administration.

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