Urban Densification and Urban Climate Change – Assessing Interaction through Densification Scenarios and Climate Simulations

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1 ABSTRACT

The paper discusses interrelations of urban densification and urban climate under global warming conditions by means of microclimate simulations as well as urban densification scenarios, referring to two research projects exploring test areas in Vienna and Linz, Austria. The impact of the extension of building heights on microclimate in densely urbanized areas is tested applying 3D city models describing building height distribution, surface properties and open space characteristics. In Vienna the densification impact on the local climate is explored for a larger study area by extruding the buildings' footprints towards the maximum height as allowed by the current zoning regulations. In Linz the urban densification impact on the local climate is tested by adding high-rise buildings which are planned to be developed in a selected neighbourhood.

Building height extension scenarios allow on the one side examining the densification potential to create new residential floorspace without requiring additional building land and on the other side to investigate the impact of densification on climate conditions by modelling the effects on heat storage during sunlight hours, nocturnal heat radiation from buildings and air flow. Microclimate simulations show significant differences in the diurnal variation pattern of the mean radiant temperature depending on increase or decrease of shading and heat storage effects due to densification.

Keywords: climate simulation, climate-urban fabric interaction, climate change, urban densification, climate adaptation

2 BACKGROUND AND OBJECTIVE

Urban Climate and climate change is an issue of growing importance with respect to urban neighbourhoods as well as entire cities. First attempts to explore urban climate issues and their interrelation with the "urban canopy" can be found in the early 19th century. Luke Howard (1818, 1833) carried out theoretical discussions on urban climate and related empirical studies for the City of London, based on monitoring data collected for 25 years (1806-1830). In the later 20th century the so-called "Urban Heat Island (UHI-)effect" was examined, characterised by a higher temperature in densely urbanised urban areas compared to their rural outskirts (e.g. Garstang et al., 1975; Oke 1982).

In the 21st century climate change was starting to raise world-wide interest, as climate projections show accelerated global warming with significant impact on urban thermal comfort in cities - even in mid-latitude cities (c.f. Jänicke et al., 2015; Kuttler, 2011; Loibl et al., 2011; Rosenzweig et al., 2015). As the urban population will still grow, anthropogenic heat flux will increase too, which will speed up urban heat island effects. Thus, climate dynamics must be considered in combination with urban dynamics, requiring adaption activities to better cope with urban dynamics under future climate change. Circumstances of urban growth and changing climate conditions require a clear call for action. An important step is to link climate modelling to on-going urban planning processes. This has been carried out to describe the current situation as well as for urban development projects in the cities' fringe areas (e.g. Rosenzweig et al., 2015; Tötzer et al. 2018). While urban growth has been in between frequently related to climate change urban densification has been less considered as issue affecting urban microclimate until now, specifically with respect to heat island effects, air flow and air quality.

This paper is thus dealing with the interaction of urban densification and urban microclimate and will explore the effect of adaptation measures to mitigate these negative effects. Here the impact of the extension of building heights on microclimate in densely urbanized areas is tested in Linz, Upper Austria, and in a district in Vienna, the Capital of Austria, In Vienna the densification impact on the local climate is explored for a larger study area – Vienna's 12th district Meidling. In Linz the microclimate conditions are examined for several areas – here we focus on the "Tabakfabrik" development area, a former cigarette factory site which is going to be transformed into a mixed-use building complex with some new low-rise buildings and a high-rise office tower as massive urban densification intervention.

The following two figures show the case study areas discussed in this paper: the densely urbanized part of the 12th district in Vienna, Meidling (figure 1) and the Tabakfabrik Linz - development project – with its current state (figure 2). The data sources respectively the data generation are described in the next chapter.

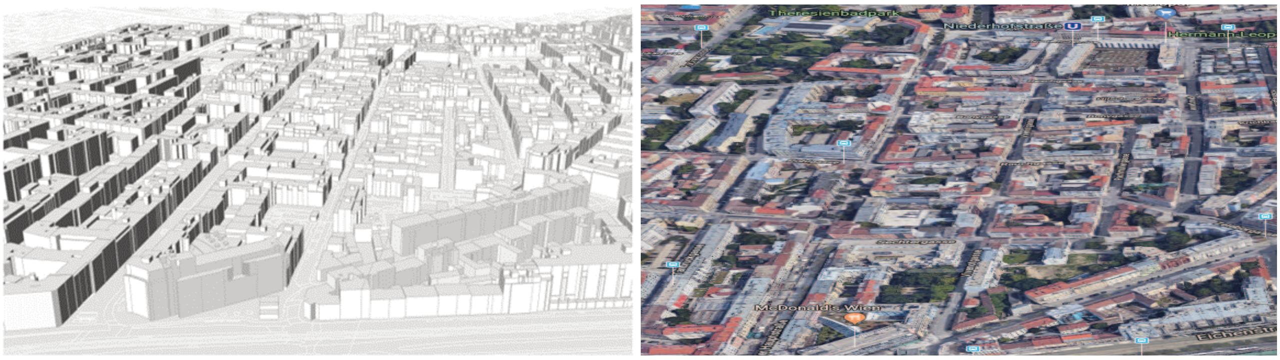

Figure 1: The densely urbanized centre of Vienna's 12th district Meidling: 3D-model with the current building height (left), bird's eye view (right) (Sources: building footprints: City of Vienna, 3D model processing: AIT(left); google maps - birds' eye view (right))

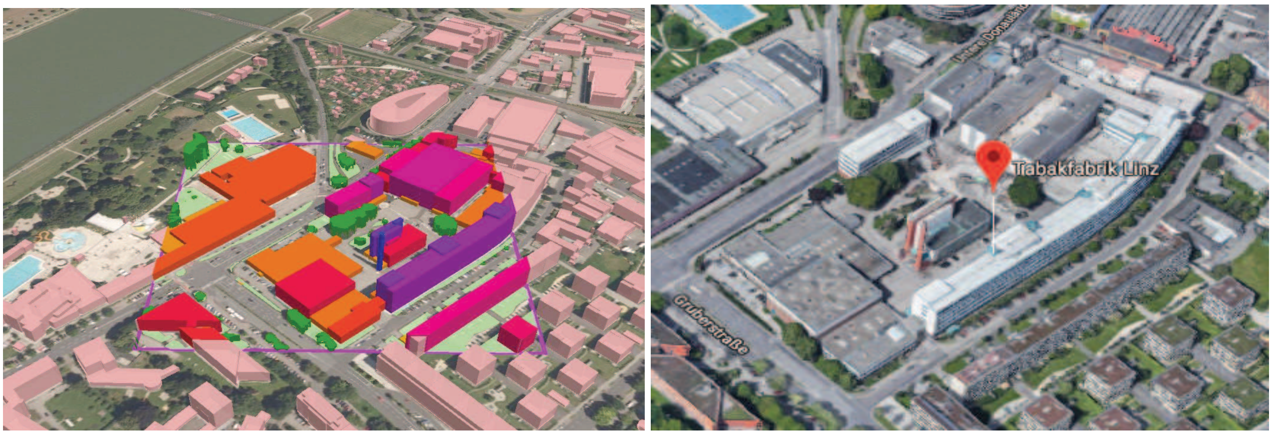

Figure 2: Tabakfabrik development area, Linz -: 3D model of current state (left), bird's eye view (right) (right) (Sources: building footprints, City of Linz, 3D model processing: AIT, google maps - birds' eye view (right))

3 DATA AND METHODS

Effects of urban densification on local climate is analysed for sample areas in Vienna and Linz, Austria. Hypothetical building height extensions allow to examine the densification potential leading to new residential and office floorspace without requiring additional building land. Plans for a property development in Linz allow modelling the urban densification potential based on future building layout and height.

The impact of densification on climate conditions is examined by modelling the effects of diurnal heat storage, nocturnal heat radiation and air flow. The microclimate simulations are carried out with different models. The results are compared, and uncertainty ranges are documented by testing the impact of urban fabric on current climate, future climate and considering climate adaptation options.

For Vienna's district Meidling the current building structure is generated as 3D model by taking the buildings' footprints and extruding those to 3D objects according to their building height information. An assumed average story height of 4 m for the old buildings let estimate the current gross floorspace in the study area. The district's floorspace extension potential through densification is estimated, based on the current building height limits derived from zoning plans. Therefore, the building height borderline- and annotation layers, obtained from Vienna's planning department, are converted into a geodata set, to link building height maxima derived from the "Bauklasse" (building height class) spatially to the current building footprints. The densification scenario has been carried out by extending the buildings to their allowed building height limit, resulting in a new 3D city model representing the entire densification scenario. Height differences between the building height limits and the observed building heights allow, assuming a 3 m floor height which is standard for new buildings and building extensions, for estimation of the additional number of floors and the additional gross floorspace. Further additional floorspace gained through rooftop extensions and attic conversions, which can exceed the height limits when receding towards the building's eaves, is considered as 50% of the buildings' footprints.

Figure 3 depicts the densification potential of central Meidling by extending the height of the current buildings according to the building height limits. The 3D view gives only a general impression of the spatial effect of city-wide densification. Rooftop extension and attic conversions are not shown, as no roof surfaces are added to the 3D model.

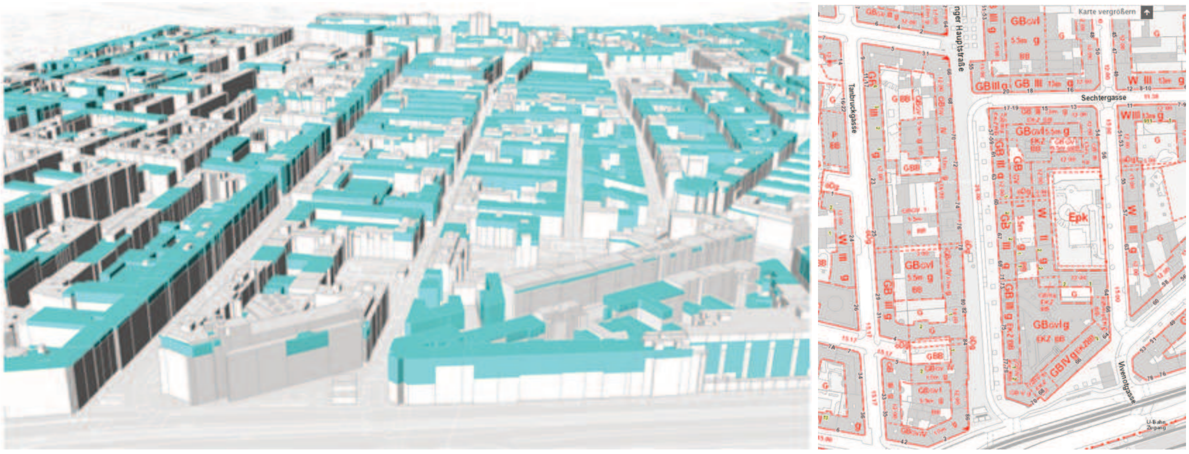

Figure 3: Densification potential of Vienna's 12th district around Meidlinger Hauptstraße according to the building height limits of the Vienna zoning plan. The zoning plan of this area with "Bauklassen" border lines and signature annotation are shown on the right side (Sources: 3D model, densification scenario processing: AIT, height zoning map: City of Vienna)

The overall floorspace extension potential has been quantified for the residential and mixed-use buildings by taking current building height, building height limits, and building footprint area from the building geo-database. Hypothetical height extensions are only considered, if the (residential and mixed-use) buildings' footprint area exceeds 100 m2, which is around the gross floorspace required to build an additional flat. Backyard buildings are only included for height extension if their current height is above 4 m, otherwise they are considered as workshop buildings and backyard sheds, which are not feasible for residential floorspace extension.

In the City of Linz, a process has been initiated with city planning experts to identify the most relevant and urgent issues in the context of climate change and urban planning. As the panning policy target for Linz is to grow through new development areas, as well as through new inner city high-rise buildings, it is important to know how high-rise buildings would influence the microclimatic state of the neighbouring areas and the entire city.

The Linz 3D city model has been generated based on CORINE land cover data, the Open Streetmap layer, the cadastre map with the building footprints, a digital terrain model and a Lidar data set – a point cloud of airborne derived 3D information - which has been related to the building footprints. Figure 4 shows the downtown area of Linz with the land cover, terrain- and streets and rivers and the simple 3D building shape extraction.

Figure 4: Linz downtown area; land cover, street network and terrain (left) and the final 3D model (right) (Sources: various layers: City of Linz, Open Streetmap, 3D model processing: AIT)

The derived 3D city model serves as a digital base to embed high-rise buildings as densification interventions – either as hypothetical assumption or as real property development. The following figure 5 shows the 3D model of the future "Tabakfabrik" development northwest of the city centre. The real estate investor will present the planning details to the public in early 2019. The mixed-use development (living, working, education) shall be finalized by 2023 (http://neubau3.tabakfabrik-linz.at/).

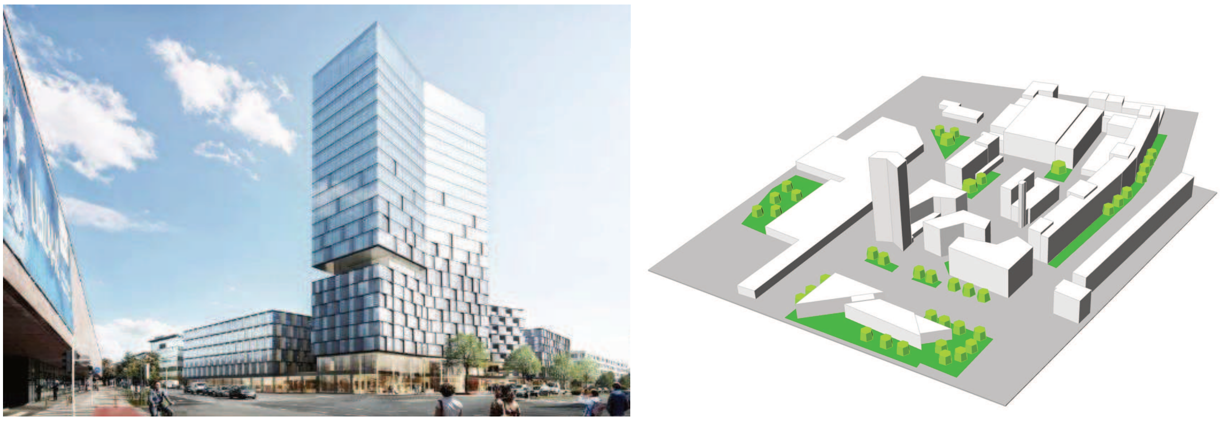

Figure 5: Tabakfabrik development area, Linz - rendering of the develoment plan (left), 3D city model with embedded office tower development concept (right) (Sources: expressive.at (left), 3D model processing: AIT(right))

Microclimate simulations presented here, are carried out by ENVI_MET ® and by Grasshopper ® with the Ladybug plugin. Both tools enable a comprehensive assessment of heat trapping and air circulation under different climate conditions.

ENVI_MET V4 ® was developed in the late 1990-ies and improved over the time (c.f. Bruse et al., 1998, Huttner, 2009). Now the tool is sold as commercial software (https://www.envi-met.com/). ENVI_MET is an integrated three-dimensional non-hydrostatic model, initially developed to model surface plant interactions, currently more often used to simulate microclimate dynamics in built urban environments to assess effects due to climate change. The model works with 3D arrays as gridded model input, describing building, vegetation and soil properties. The model's databases provide a variety of different vegetation options and materials for walls, roofs and surfaces to match the individual building surface - and open green space characteristics.

The typical horizontal resolution of the input data ranges from 0.5 to 5 metres. The vertical resolution is flexible – either all vertical grid levels, except the lowest five, have an identical vertical extension, or the vertical grid size expands as "telescoping grid" above the elevation of the highest buildings ranging up to 2500 m to enable modelling the vertical dynamics up to the urban atmosphere boundary layer. (Details can be found in: http://www.envi-met.info/doku.php?id=kb:verticalgrid).

The typical time frame in which ENVI_MET calculates atmospheric dynamics is 24 to 48 hours with a time step of 1 to 5 seconds. For the applied test cases input data sets with 2m resolution have been prepared. This resolution allows to analyse small-scale interactions between individual buildings, surfaces and plants which enables to investigate urban heat island phenomena and the impact of related adaptation measures by extracting horizontal and vertical sections from the 3D output array.

The disadvantage of ENVI_MET is the long calculation time (depending on the hardware specifications): e.g. despite the small area of the Tabakfabrik test site, the simulation takes a week to model the microclimate dynamics by providing hourly results for one day (applying a computer with i7 processor with 16GB RAM).

Grasshopper ® (https://www.grasshopper3d.com/) is a graphical algorithm editor developed as a part of Rhino's 3-D modelling environment, originally applied for parametric design studies. Grasshopper users have developed a wide range of open source plugins – tools which carry out various modelling applications related to building design analysis. Ladybug Tools plugin is among the most comprehensive plugins in Grasshopper supporting environmental design assessment. One feature of Ladybug Tools is Honeybee, that connects Grasshopper to validated simulation engines. Specifically, it creates, runs and visualizes the results of daylight simulations using Radiance, energy flux simulations using EnergyPlus/OpenStudio, and wind simulations using OpenFoam (https://www.ladybug.tools/honeybee.html). All the components of the Ladybug tools collection inherit the physical principles and the functionalities of its underlying simulations engines (e.g. Radiance, EnergyPlus, OpenFoam). Input and output is linked between these engines and a visual scripting interface allows for comprehensive simulation and analysis of microclimate calculations, considering all related interactions within the model domain.

The Ladybug plugin allows the user to import and analyse standard weather data which enables assessing microclimatic effects to urban environments due to climate change. The plugin does not need a proprietary input format as it makes use of standard 2,5D ESRI shapefiles, depicting urban environments with building layout and vegetation property information. Various plugins allow to analyse small-scale interactions between individual buildings, surfaces and plants which enables again to investigate urban heat island phenomena and related adaptation measures to mitigate these effects.

As disadvantage of the Grasshopper/Ladybug plugin, the output - at least in our implementation – is not stored as a 3D array. Results are extracted on the fly as images, which do not enable further data analysis. A big advantage is, that the calculations are carried out much faster than by ENVI_MET: the microclimate simulations for 24 hours took for the presented test cases only a few hours simulation time. Grasshopper/Ladybug allows further a much finer resolution and more 3D building details integrating into the study domain. Additionally, with new Grasshopper plugins being developed daily by a vast community of users, this environment promises new and improved applications and a growing flexibility. Finally, Grasshopper plugins also allow for automation of tasks, thus enabling more efficient engineering of alternative design options and assessment of related environmental implications.

As main assessment indicator the mean radiant temperature (MRT) has been selected – which is calculated by various tools and can be easily monitored with black globe thermometers. The mean radiant temperature (MRT) is defined as the uniform temperature of an imaginary enclosure in which the radiant heat transfer from the human body is equal to the radiant heat transfer in the actual non-uniform enclosure (ISO, 1998). It can be regarded as the weighted sum of all long- and short-wave radiant fluxes (direct, reflected and diffuse components), to which a human body is exposed. (Walikewitza et al., 2015). If taken outdoors, MRT depends on the temperature of the sky, ground, vegetation and surrounding buildings (considering, distance, angle, size). (c.f. Rakha et al., 2017). The MRT is one of the most important meteorological parameters related to human energy balance and human thermal comfort (c.f. Fanger, 1970), being a critical physical quantity that indicates how human beings experience thermal radiation in their surrounding environment.

Comparing the simulation results of both tools ENVI_MET and Grasshopper/Ladybug allows to examine their uncertainty bandwidth: the daily average of the mean radiant temperature (MRT) turns out to be quite similar in both tools – differences in the MRT average are below 1 °C, the pattern of the horizontal MRT distribution is rather identical. Thus, we present here the Grasshopper results as Grasshopper allows faster processing to provide results for alternative input with respect to climate conditions, building layouts and adaptation measures.

4 RESULTS

Results referring to densification potential, obtained so far, show the feasibility to increase the gross floorspace of the existing buildings stock in already densely urbanized districts. Results regarding city - climate – interactions show a first assessment of the impact of densification on microclimate conditions.

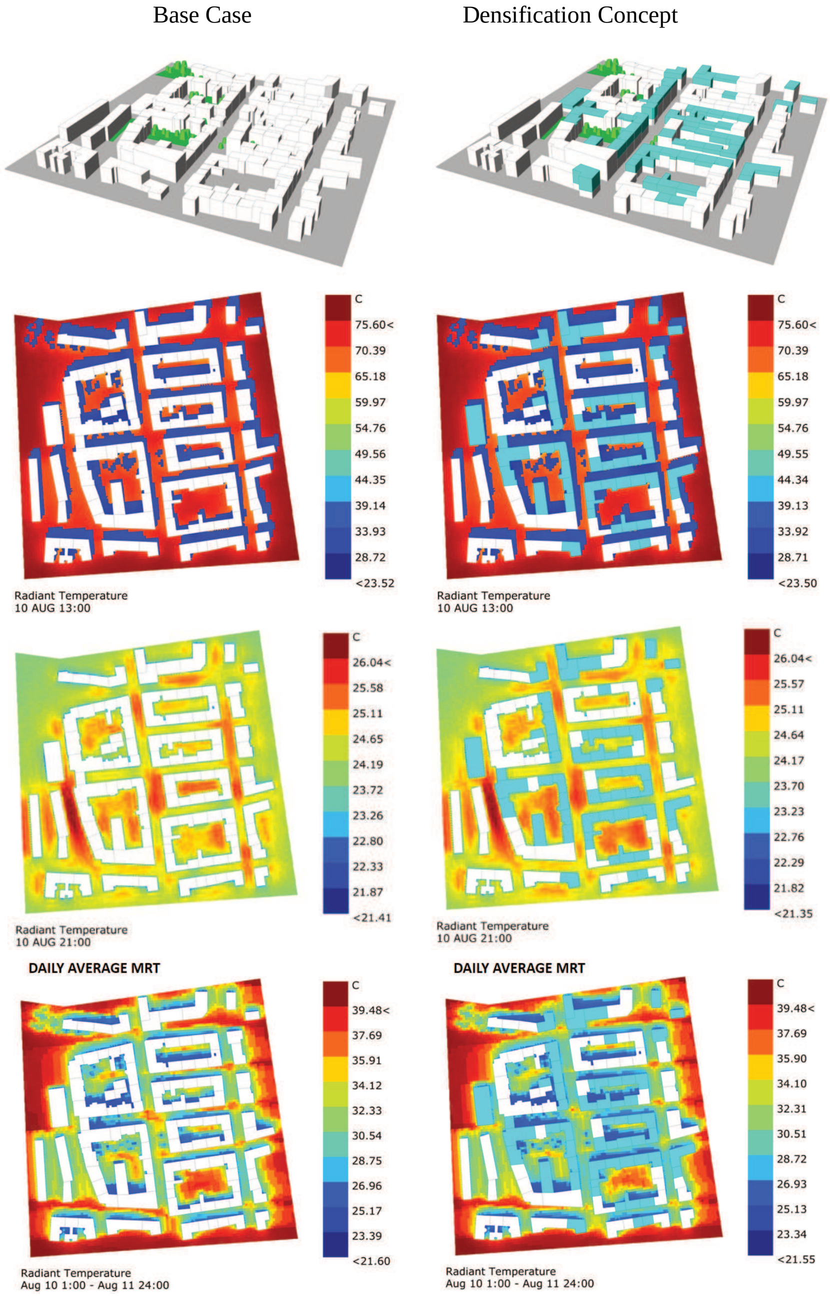

Figure 6: Case study area along Meidlinger Hauptstraße: 3D view (top row), heat exposure simulation for current state (left) and a densification scenario (right): Mean radiant temperature (MRT) at 13:00 h (2nd row), MRT at 20:00 h (3rd row), MRT daily average (4th row).

Compared to the actual building height distribution in Meidling, the height zoning regulations allow for a substantial extension of many buildings, who's heights are below the height zoning limits as shown in figure 3. The gross floorspace (GFS) extension potential of the current residential - and mixed-use buildings in densely urbanized central Meidling is estimated reaching 16 % of the GFS. By including rooftop extensions and attic conversions the growth potential sums up to around 25 % of the GFS of the residential - and mixed-use buildings (Current GFS: 2,8 million m2, GFS extension potential by adding regular stories: 467.000 m2, GFS extension potential including rooftop extensions and attic conversions: 701.000 m2). Thus, densification of residential- and mixed-use buildings in central Meidling would - considering an average flat size of around 94 m2 gross floorspace (and 66 m2 net floorspace) – allow for adding around 15 to 25% additional flats to the current building stock.

To better cope with such densification dynamics under changing climate conditions, the interaction of microclimate and urban fabric has been explored. Various microclimate simulations have been carried out for Vienna and Linz case study areas considering a very hot day (August 10th, 2014) as climate background condition.

Figure 6 shows the mean radiant temperature (MRT) at street level in a sample area along Meidlinger Hauptstraße without ("base case", left) and with building height extension up to the height zoning limit ("densification scenario", right) during a day-time and night-time hour and as daily average. (The top row shows the test area, the building footprints on the right side, marked in cyan, indicate those buildings where a building height extension is assumed.)

Comparing the microclimate simulation results for the base case and the densification scenario in the northern part of Vienna's 12th district around Meidlinger Hauptstraße, show differences in the daily average of the mean radiant temperature between +7 and -7 ° Celsius MRT (fig. 6, 4th row), depending on increase or decrease of shading and heat storage effects due to densification.

During day-time hours the sunlit street- and backyard areas show around 13:00 h a heat exposure of up to 70°C MRT, while the areas shaded by trees and facades show a heat exposure below 40 °C MRT (fig. 6, 2nd row). During the night-time hours (e.g. 21:00 h, fig. 6, 3rd row) narrow street areas show heat trapping effects with a temperature exposure above 26 °C MRT, while more open areas show a temperature exposure of only 24°C MRT. Areas close to extended buildings show positive effects during day-time, because of more shade and negative effects during night-time, especially when street canyons or backyards are narrow. Temperature exposure in areas below trees show, compared to sunlit areas, differences in MRT of up to 30 °C. During night-time the temperature below trees shows little to no difference in MRT compared to open backyard- and street space. (The areas along the borders of the study domain shall not be considered for interpretation as they don't show valid results due to the missing neighbouring blocks beyond the study domain.)

In Linz the impact of the planned Tabakfabrik development on microclimate conditions has been explored and initial climate adaptation options tested.

Figure 7 shows the current and future state of the building layout after the property development intervention (top row) and the differences in mean radiant temperature (MRT) at street level for the current state ("base case", left) and after property development ("densification concept", right) during a day-time and night-time hour and as daily average (rows 2 to 4).

Microclimate simulations (for August 10th, 2014) applying the current building layout and the densified layout of the Tabakfabrik neighbourhood, show (comparing the results in figure 7, row 4) significant differences in the daily average of the mean radiant temperature between -1 and -7 °C MRT due to the increase of shading cast by the 81 m high office building.

Heat storage effect at street level plays less role as the building footprints of the buildings are smaller than the current ones, releasing less nocturnal heat radiation and allowing better ventilation between the buildings. The planned solitary office tower will provide additional shading from morning to peak hours. Some new narrow building facades will cause heat trapping effects during night hours. Larger areas shaded by the now taller facades show temperature exposure below 35°C MRT around 13:00 h while sunlit surfaces show temperature exposure up to 50 °C MRT (fig. 7, 2nd row). During the night-time hours (20:00 h, fig. 7, 3rd row) narrow yard areas show heat trapping effects with temperature exposure above 26 °C MRT, more open street areas show temperature exposure of 24 - 25 °C MRT. (The areas along the borders of the study domain shall not be considered for interpretation as they don't show valid results due to the missing neighbouring blocks beyond the study domain.)

5 CONCLUSIONS AND OUTLOOK

Urban densification is a potential solution to allow for sustainable urban growth without sealing additional land: The case studies show that floorspace can be increased up to 15 % by adding additional stories to buildings who's height is one story or more below the related zoning height limit, and can be increased up to 25 %, if rooftop extensions and attic conversions are added to all buildings (considering 50% of the footprint space as usable for new floorspace). These numbers are valid for the densely built up area of Meidling and

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even for the entire district Meidling. Thus, it can be assumed that the results can be transferred to all densely urbanized parts of Vienna's outer districts with similar building structure (at least the 10th to 20th districts).

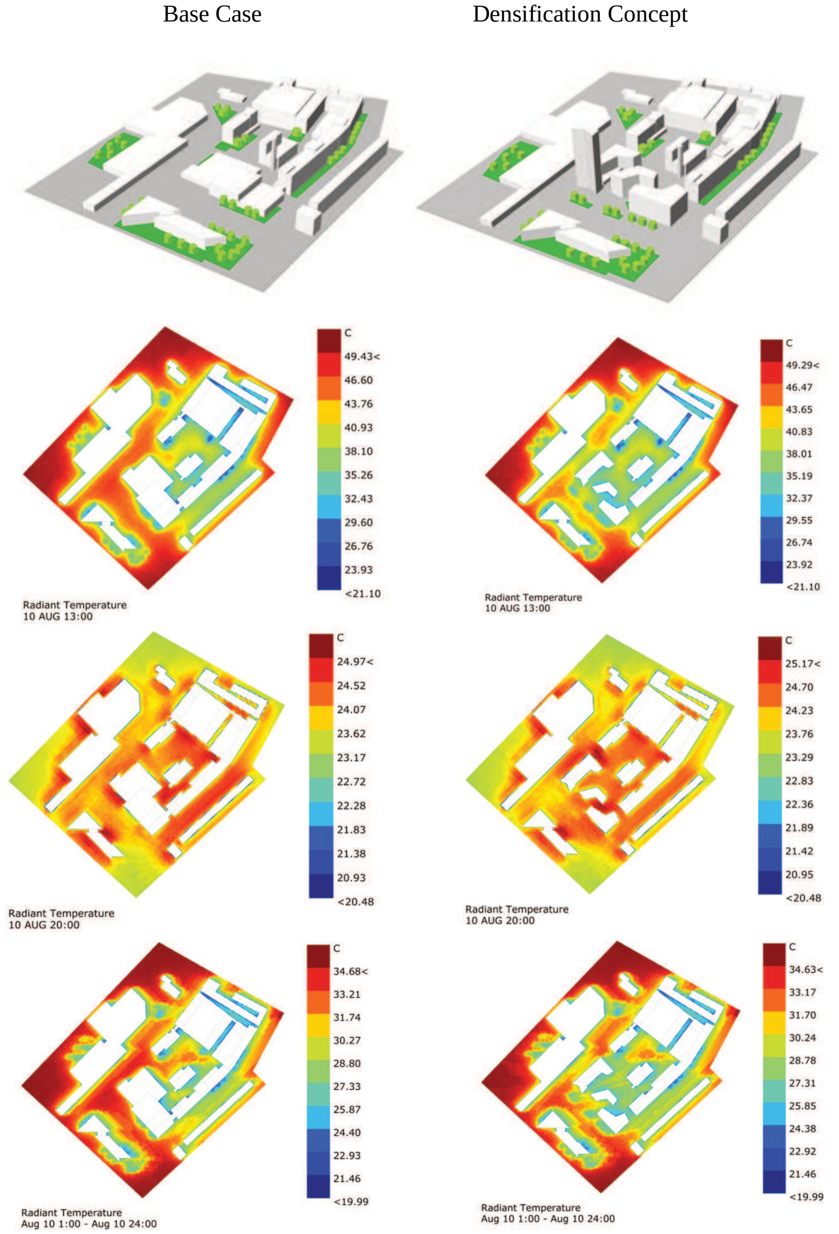

Figure 7: Case study area Linz Tabakfabrik development: 3D view of current and future building state (top row), differences in heat exposure for base case and the densification concept: Mean radiant temperature (MRT) at 13:00 h (2nd row), MRT at 20:00 h (3rd row), MRT daily average (4th row).

Densification interventions show distinct effects on temperature exposure: MRT decrease is observed on streets and backyards during the day as higher buildings cast more shadows. MRT increase is observed during the night because of heat trapping caused by heat storage in and heat dissipation from these higher, larger buildings. High-rise buildings show during day-time and night-time positive effects, because of casting more shade and show little nocturnal heat storage effects. During day-time the temperature exposure below trees is significantly lower. Differences in heat exposure between sunlit and shaded areas during sun peak hours reaches 15 to 30 °C MRT. During night-time the temperature exposure below trees shows little to no difference in MRT compared to open spaces. Until now the rooftop temperature exposure has not been analysed.

At these projects' stages, it can be concluded, that moderate urban densification would be an appropriate and feasible instrument to improve land use efficiency, which would avoid occupying and sealing additional land and would eventually reduce the single inhabitant's contribution to urban traffic load in vertically growing cities. It can be further concluded, that a limited number of high-rise buildings have less heat trapping effects at street level than building rows with overall extended building heights, as far as those towers are designed slim and are not concentrated in a few areas within the city. The microclimate simulations show further that trees covering open spaces have a positive effect to reduce day-time heat exposure especially during sun peak hours and have no reasonable nocturnal heat trapping effects.

In later stages of the two projects, further climate adaptation concepts with respect to urban growth and densification will be tested.

One further impact of densification refers to wind comfort at street level. High-rise buildings and certain configurations of low-rise buildings may have negative impact on how wind is perceived by pedestrians in public open space. On the other hand, clustered high-rise buildings may serve as barrier for ventilation. Therefore, large scale ventilation analysis at district or city level as well as local wind comfort analysis at neighbourhood level and counter measure development to mitigate negative impact of densification interventions on wind characteristics will be carried out.

At the local scale, vertical extensions of selected buildings will be additionally tested for the Vienna case study, considering different construction types, thus distinguishing between densification carried out with high or low thermal mass. The type of construction will on the one hand be influenced by the structural soundness of the considered buildings, on the other hand, the choice of construction material will affect the thermal and subsequent energy related behaviour of the overall building influencing heat storage and nocturnal heat radiation.

Temperature exposure at rooftop levels will be further analysed considering the current building layout, extended building layout with high and low thermal mass. In addition, greening of façades and roofs will also be tested to better adapt to climate change, as they influence the microclimatic conditions and performance of the buildings.

Further feedback loops will be set up to the planning process involving city planning experts and property developers to identify appropriate climate adaptation activities – discussing open space design and greening as well as densification to better cope with future climate conditions as well as urban growth requirements.

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