INTERDIURNAL THERMAL ANALYSES OF INNER COURTYARDS BY MEANS OF AIRBORNE REMOTE SENSING

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ABSTRACT

Urban areas are heavily modified in terms of surface temperatures (UHI: Urban Heat Island) relative to their rural environment. By means of airborne or satellite-based Earth observation, it is possible to find out changes in radiation and energy flux densities in the mesoclimate of the city. Land cover utilization and sealing aspects play a significant role in the modification of surface temperatures in a city. In the present work, the surface temperature data, derived from the thermal scanner surveys of the years 1986, 2004, 2011 and 2021 as well as the degree of sealing, the land use, the land cover and the climatopes, were summarized in a geodatabase. With this GIS-based information, it is possible to analyze the thermal behavior of different inner courtyards according to their underlying surfaces as well as their size. In addition to the description of the climatological features of the Graz urban area, a part of the paper is dedicated to the data preparation and methodology development, following by the analysis of results based primarily on statistical evaluations. After successful creation of the database, the results indicate a strong correlation between sealing degree and thermal behavior of inner courtyards. The temperature increases with higher sealing degrees whereas the opposite greener areas – lower temperature was recognized as well. Additionally, thermal characteristics vary depending on their location within the city according to climate conditions. Almost no strong correlation referring to their size was identified.

Keywords: Thermal Remote Sensing, Surface Temperature, Inner Court Yards, Urban Climate

INTRODUCTION

According to the United Nations, in 1950 less than 30% of the world's population was resident in urban Areas, at the end of the second century the number grew up to 50%. Already 2015 the number increased to 70% [1]. Although urban areas cover only 0.2% of the earth's surface, they contain most of the world's population, why a future-oriented, sustainable city development is unalterable [2]. In the last years (decades), satellite, as well as airborne remote sensing techniques, got recognized as a handy tool for analyzing urban structures.

Urban areas change the earth's surface, the atmosphere above, compared to their surrounding they have a strongly modified climate because of a different urban-type settlement with an increased number of housings, transportation and so on. They have a stronger intensity of development, a much higher degree of sealing and a lack of green areas and vegetation [3]. Thereby the city climate differs to their surrounding in several

conditions. An increased surface and air temperature, which often leads to the development of a heat island can be observed and the wind can be strongly modified [4]. All this leads to an anthropogenic caused climate modification, changing the climate and air conditions in the city environment [5]. It concerns not only metropolis regions with millions of inhabitants but also the climate conditions of small cities like Graz with about 300.000 inhabitants are already different. Remote sensing can provide answers about the complexity in varying degrees of detail and from different backgrounds. Fully comprehensive data collection enables the quantitative description of the earth surface, its parameters, and dynamics. Remote sensing developed to an ancillary discipline within city climate and plenty of other disciplines [4].
The comprehensive data collection of airborne thermal scanner flights makes the map and monitor process of the different physical properties of structures and forms used in the city environment possible [6]. In urban areas thermal Remote Sensing is defined as the measurement of the surface temperature and their properties, which correspond to the land use and land cover. Those datasets are available in different spatial and temporal resolutions [7]. The urbanization process has a strong influence on the earth surface and the land use change. The advantage of the thermal Remote Sensing technologies, compared with in-situ temperature measurement on the ground is the delivery of surface temperature information's [8]. Those are comprehensive and simultaneous records taken by airplanes or satellites, which are of primary importance for detailed investigations. They make a further survey of the Land Surface Temperature (LST) or the Urban Heat Island (UHI) or other phenomena in the city possible. Additionally, a temperature analysis of the close urban-rural space is practicable, whereas further statements for the city climate can be made [9]. In-Situ measurement methods are because of different interpolations in comparison error prone. To compare the thermal behavior of inner courtyards of the foundation period (Figure 1) through data taken by airborne thermal scanner flights, the use of statistical parameters like the mean value and standard deviation, can be helpful. The area density describes the center of a distribution, while the standard deviation makes a more precise quantification of the amount of variation of the available data set possible [10], [11].

STUDY AREA, DATA AND METHODOLOGY

Study Area

In this paragraph, an overview of the location as well as the climatological features for the investigation area Graz, the capital of the province of Styria in Austria, will be described. For a consistent size of the study area and the used data sets, the city boundary with an area of 12.756 hectares was used. Graz has a river called "Mur" flowing through and splitting the city up into two parts. One is on the left bank in the "Riedelland" while the right bank has the "Plabutsch-Buckhogel" range with 763 m above sea level. The climate character can be described continental with a strong influence on the precipitation, having a small amount of snow during winter, while in summer the thunderstorms frequency is high. Situated in a valley basin with asymmetry and its location southeast of the Alpine ridge, the city is recording a low amount of wind, which increases especially during winter, the possibility of inversions and fog. This causes many disadvantageous for air pollutant and forces four local wind circulations differing during the day [12], [13], [14], [15], [16].

Regarding the temperature, there are different patterns within the city. The tributary valleys in the east show the highest variations in daily temperature differences, the Grazer Feld (in the south) has very moderate temperature and records much fog. The city center is warmer because of the densely built-up area also resulting in a heat island. Two different types of heat islands with different structures, depending on the Murvalley wind system can be formed. A very balanced climate can be found on higher parts of the crests that are called "Riedel" because of the existing inversions in this area [17], [18].

Data and Methodology

In this analysis, the land surface temperatures derived from the airborne thermal scanner flights of the years 1986, 2004, 2011 and 2021and the respective data for the land cover, the land use, the predefined climatopes and the sealing degree of each year of the city of Graz were used to identify modification of the land surface temperature of the inner courtyards [10].

The land use is divided into several different land use categories and was used for the extraction of the foundation structure. This dataset contains 30 different land use structures appearing in the urban area of Graz and were predefined in [12], [16], [17]. For example, the agricultural areas like vineyards or forest and artificial surfaces like industrial or commercial units or green urban areas were distinguished. It also contains the layer foundation structure, which is essential for the underlying work and did almost not change over the years what makes sense, as it is an old structure from the 19th century. The slight change from 1986 to 2011 concerns around 2.5 hectares, which results in a decrease of the area from 274 to 271 hectares and is influenced only by the data collection and not an underlying change itself. Also, the other datasets, like the sealing degree, the land cover and the climatopes were predefined [15], [19], [20]. One challenge of this work was moreover to merge the big datasets to extract several layers in one with a uniform reference system. Figure 1 represents the spatial contribution of analyzed court yards in Graz.

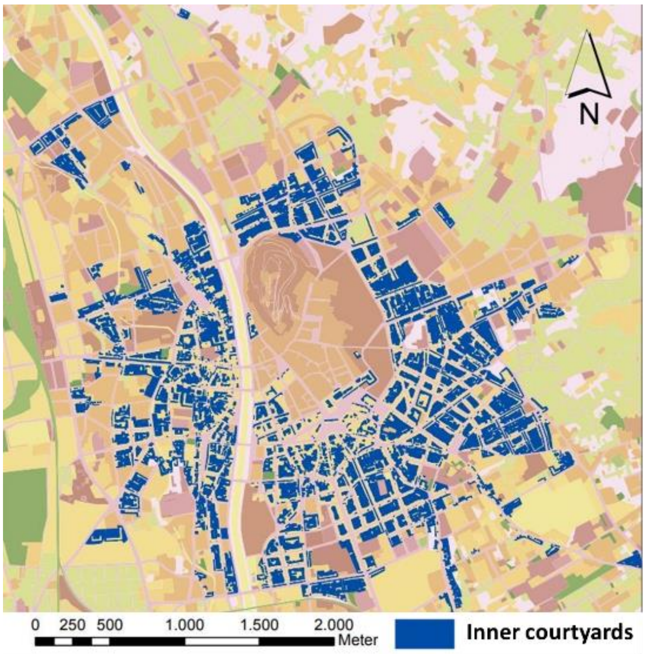


Figure 11. The location of the selected inner courtyards in Graz.

Because of the different sensors, different pre-processing steps and diverse data formats used for collecting the surface temperature and the other information, some additional pre-processing steps were necessary to homogenize the data before importing all into one geodatabase. Through an intersection, it was possible to keep the spatial reference of the data and thereby manage, save, reprocess, and analyze them.

Figure 2 shows examples of used data (LC/LU, Image representation and thermal coloured information). As seen in Figure 3 an overview of the workflow is depicted before the data was finally transformed into vector data.

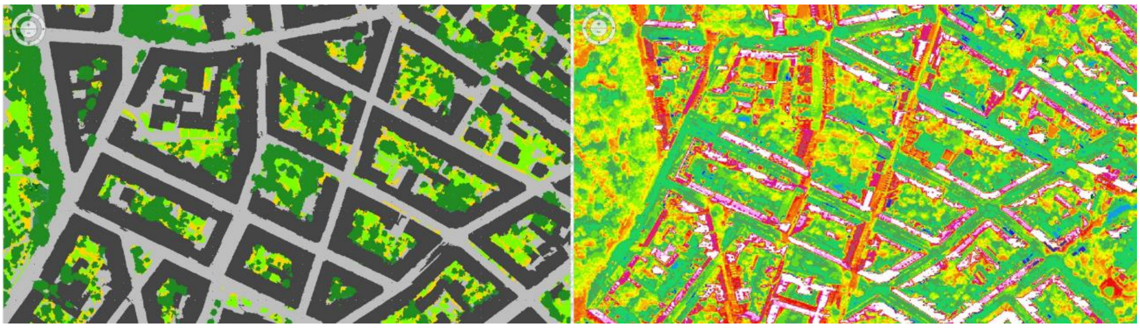


Figure 12. Landcover structure left (black: buildings, grey: sealed areas, dark green: trees and bushes, light green: grass) and thermal image representing the surface temperature right (2021 midday) of the foundation area in Graz.

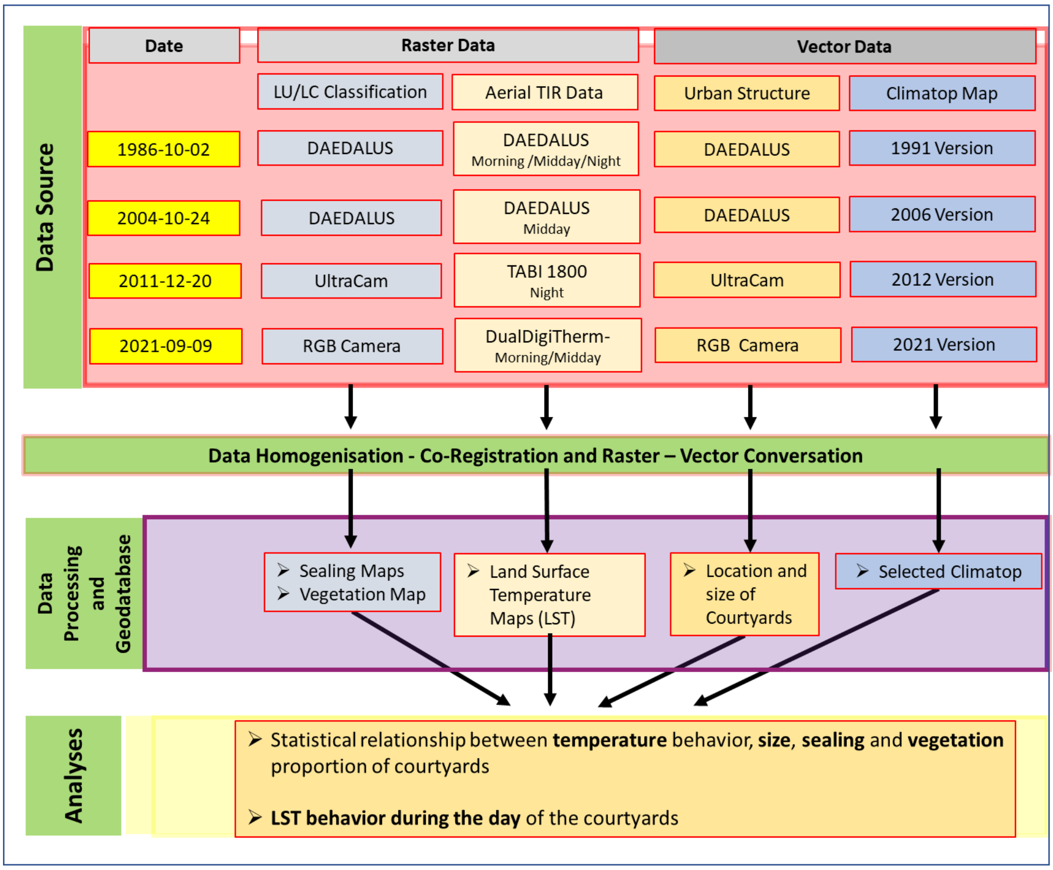


Figure 13. Workflow of creating the Geodatabase.

The surface temperatures were delivered in a format of different bit depths. 1986 had 8 bit, 2004 and 2011 had 32 bits. In order to homogenize the data, the data of the flights of 2004 and 2011 were rounded to integers of 8 bit. The comparison was easier having all the data in 8 bits, the data loss was reasonable, especially considering the already achieved file size of 16 gigabytes. Otherwise, the computing time, which already demanded several hours at each step, would have been considerably longer. In the last step, before transforming into vector graphics the thermal scanner flights from 2004 and 2011 were split into four and 16 parts to avoid an exceeding the two-gigabyte limit of the shapefile type. If the size limit is crossed the output file is empty after the process. Then the data was combined in several consecutive steps starting to merge all data without the surface temperature, which was added at the end.
After successful creation of the database, including now the degree of sealing, the land use category for the foundation structure, the surface temperatures and the climatopes, one for every year, the weighted average and the standard deviation were calculated and exported for every polygon. This made a further calculation of different statistics possible to determine correlations between the surface temperature and either the size or its sealing degree.

RESULTS

According to [13], [14], [21] the climate of inner courtyards is determined mainly through ventilation conditions which in order are primarily influenced by the size and the number of floors. It is being evaluated if, based on the available data, a relation between thermal behavior of inner courtyards and their size as well as their sealing degree can be identified. Not discussed in this context will be the influence of the number of floors.

Distribution of inner court yards

The area of the inner courtyards has reduced by the value of three hectares over time, which can be neglected and has been regarded as constant over the years. The degree of sealing increased in Graz by 5%. Against the general trend, the inner courtyards registered a decrease of sealing degree of 12%. As seen later, a lower density has a strong effect on thermal behavior leading to lower temperatures.
In Figure 4 the inner courtyards of 1986 were categorized into classes of 0,1 hectares, showing for each class the number of inner courtyards and their relative occurrence. Because of the constancy of this structure type within the city area over the years, there is no need for further consideration of the following years. Thirty-nine inner courtyards between 0,3-0,4 hectares cover 11,2% of the foundation area. Following that, 19 inner courtyards with the class size 0,6-0,7 hectares are covering 10,2% of the area. The biggest one has 2,6 hectares and represents 2,2% of the area.
As shown in Figure 5, the inner courtyards have according to their location in the city very different structures in terms of size and shape. It is a result of historical development due to different reasons. The ones located on the right part of the river “Mur” (Figure 5 left) are disrupted, have small houses or other barriers in between and no permanent open space at all. Those on the left side (Figure 5 right) are very homogenous and well defined. While analyzing the influence of the size of the inner courtyards on their temperature behavior, those circumstances need to be considered to get meaningful results. Consequently, just the coherent inner courtyards of the left side of the river were taken into consideration.

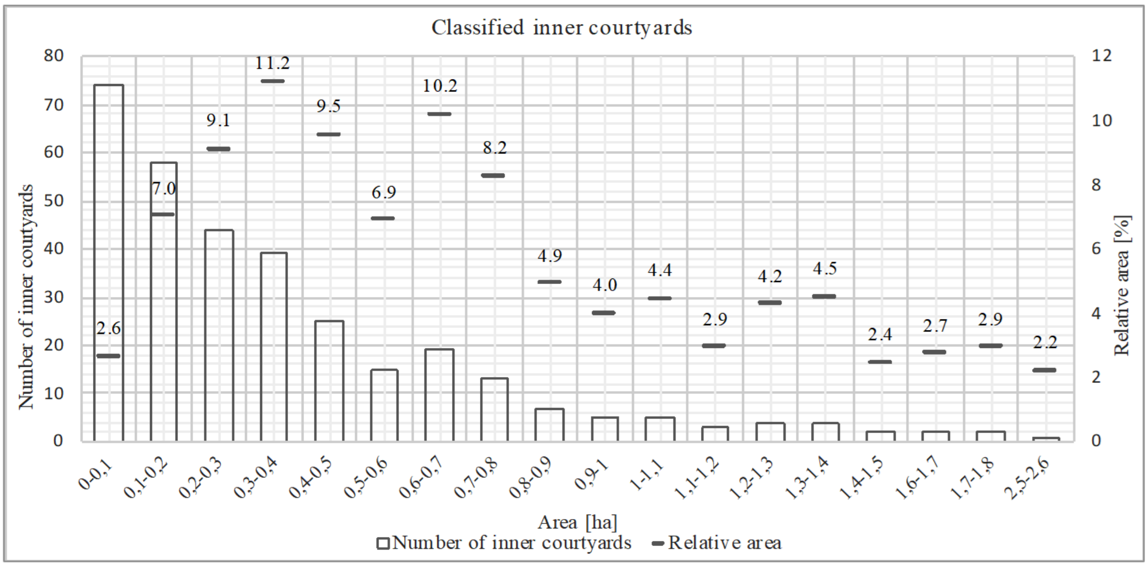


Figure 14. Area of inner courtyards of the foundation structure classified in ha of 0,1 and their corresponding number and relative area in % - 1986.

Temperature versus size of inner court yards

To validate a possibly existing correlation of the parameters, namely the size of inner courtyards and their temperature, the area was categorized into classes of intervals of 0,1 hectares. Subsequently, the area-weighted average of the classes was applied, and a linear regression was calculated. Through a linear regression, the trend of a possible correlation between parameters can be evaluated. In this work, for assessing the strength of an underlying correlation, the valuations were applied as seen in the Figures 6 - 11 the strongest correlation between the parameters can be seen at midday of 1986 with a coefficient of determination (R2) of 0,61. The data of the flight of December 2011 reveals a coefficient of R2 = 0,52. A weaker correlation can be seen in the night of 1986 with R2 = 0,44, and 2021 with R2=38., respectively at midday 2021 with the lowest value 0.00024. During the flights at midday 2004 as well as in the night of 1986 and 2021 no linear correlation between the characteristics can be seen. Because of the large temperature ranges of the individual flights a uniform y-axis was renounced.

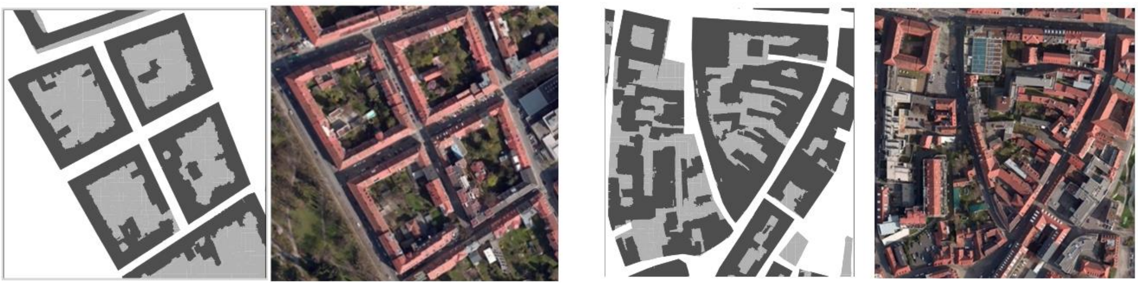
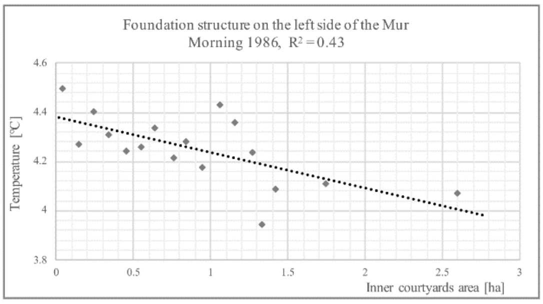


Figure 15. Inner courtyard of the foundation structure
(Dark grey: Building; Light grey: Inner courtyard, UltraCam 2015).



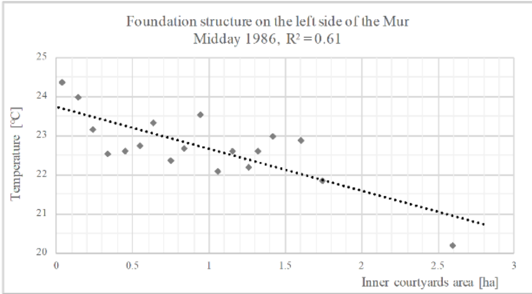
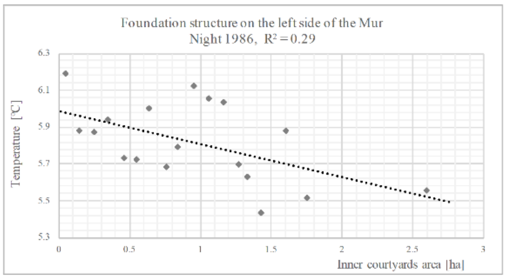


Figure 16 (left). Area of inner courtyards classified in ha of 0,1 vs. temperature in °C. The courtyards are located in the foundation structure of the left side of the Mur – Morning 1986.
Figure 17 (right). Area of inner courtyards classified in ha of 0,1 vs. temperature in °C. The courtyards are located in the foundation structure of the left side of the Mur – Midday 1986.



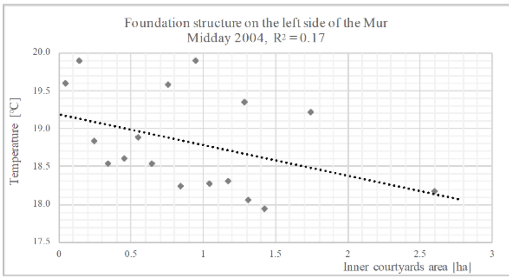
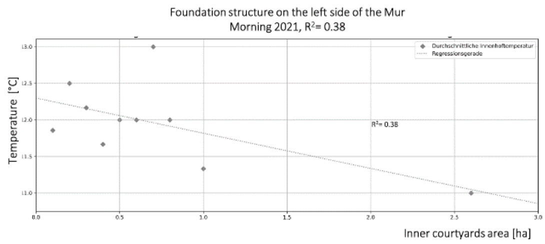


Figure 18 (left). Area of inner courtyards classified in ha of 0,1 vs. temperature in °C The courtyards are located in the foundation structure of the left side of the Mur – Night 1986.
Figure 19 (right). Area of inner courtyards classified in ha of 0,1 vs. temperature in °C. The courtyards are located in the foundation structure of the left side of the Mur – Midday 2004.



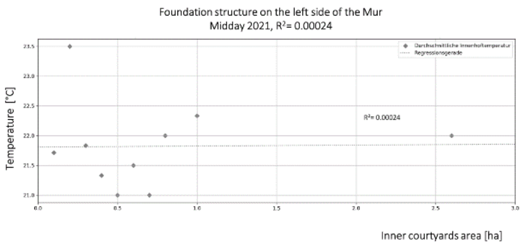


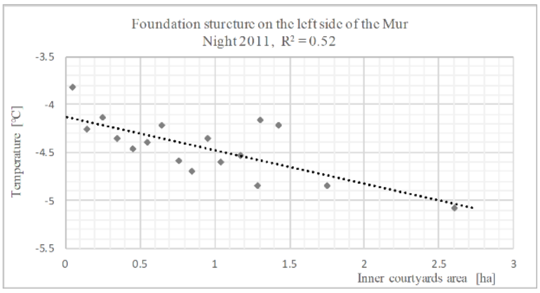
Figure 20 (left). Area of inner courtyards classified in ha of 0,1 vs. temperature in °C The courtyards are located in the foundation structure of the left side of the Mur – Morning 2021.
Figure 21 (right). Area of inner courtyards classified in ha of 0,1 vs. temperature in °C. The courtyards are located in the foundation structure of the left side of the Mur – Midday 2021.

Temperature versus degree of sealing

The sealing is an impermeable surface such as asphalt or concrete used for streets, pavements, parking and so on. As already remarked in the works of [4], [9], [22] those materials are changing and reducing processes and functions irreversibly within the landscape ecosystem. The degree of sealing describes the relations between the sealed areas compared to the whole investigation area. According to [23], the number of sealed areas is one of several micro- and mesoscale variables causing and influencing the city climate. Depending on the material of the sealed areas, they lead to a change of the thermic and hydrological properties and additionally to a decrease of vegetation.

Compared to humidity saving materials, dry asphalt or any other impervious surfaces heat up much more due to the lack of evaporation, for which an enormous amount of energy is needed. As a result, the additional, available energy is transformed into the long-wave range radiation as well as turbulent fluxes of the ground- and air heat capacity – which

leads to a warming of the atmosphere [23]. The evaporation process removes heat; this is why more continuous green cover areas like grasslands, forest or wetlands appear in thermal scanner flights as much cooler. Depending on the spatial extent and appearance of the sealed surfaces, the sensible and latent heat fluxes change to a certain amount, and thus, the urban climate is changed compared to its surrounding [9]. The distinction between different kinds of sealing materials was neglected in this analysis. The surfaces were separated into sealed and unsealed areas.
In the study area Graz, all datasets were uniformized by the city boundary to obtain a constant extent, and a total sealing degree of 23% was obtained. The central urban area has a value of 86%. Those significant differences appear because of the city center and a higher concentration of stores and entertainment – it is the geographical and political center of the town. In the surrounding, there are more green areas as forest, agriculture land as well as less dense neighborhoods with much green space.



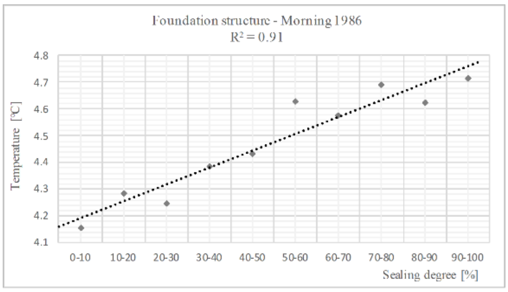
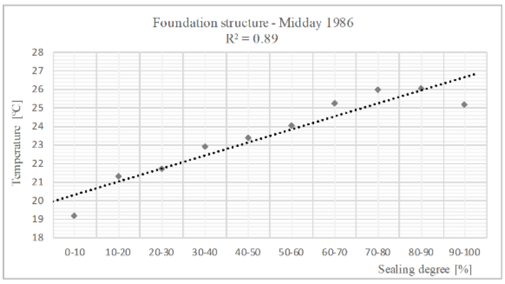


Figure 22 (left). Area of inner courtyards classified in ha of 0,1 vs. temperature in °C. The courtyards are located in the foundation structure of the left side of the Mur – Night 2011.
Figure 23 (right). Area of inner courtyards classified in sealing degrees of 10 % vs. temperature in °C of the foundation structure – Morning 1986.

While considering the thermal behavior of the inner courtyards the influence of the degree of sealing was analyzed in addition to its size. Therefore, Figures 12 -17 show the inner courtyards classified according to their sealing degree, using 10% intervals. In order to identify possible correlations, the degree of sealing was plotted against the area-weighted average of temperature. Evaluations show that the degree of sealing in the inner courtyards has a much stronger influence on the temperature than the size. The strongest correlations occur in the morning and during the night of 1986 with a coefficient of determination of R2=0,92 and R2=0,91, respectively. Also, in the night of 2011 and at midday of 1986 a coefficient, which is almost as high as the ones before can be seen. Just the results of the airborne thermal scanner flight from 2004 show a weaker correlation between the temperature and the degree of sealing with a coefficient of R2=0,59.



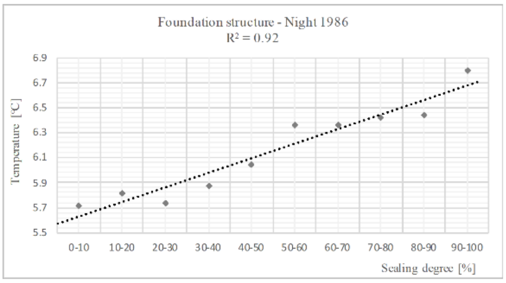
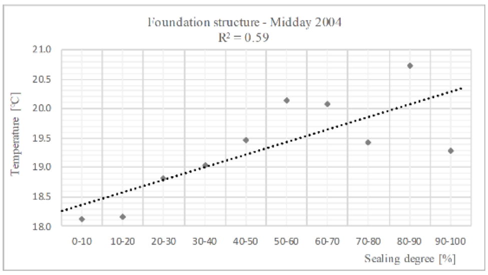


Figure 24 (left). Area of inner courtyards classified in sealing degrees of 10 % vs. temperature in °C of the foundation structure – Midday 1986.

Figure 15 (right). Area of inner courtyards classified in sealing degrees of 10 % vs. temperature in °C of the foundation structure – Night 1986.

Because of identifying such a strong influence based on the degree of sealing of the inner courtyards on the temperature behavior, an additional study was performed. The purpose was, to see if the trend visible in the previous evaluation is recognizable in an overall consideration of the sealed and unsealed surfaces of the foundation structure. In Table 1 each airborne thermal scanner flight is listed, and surfaces of the inner courtyards are divided into unsealed (0) and sealed (1) areas, whereby the degree of sealing in %, the weighted average of the temperature in °C of the area as well as the standard deviation in Kelvin will be further evaluated and compared to each other. The most significant temperature differences between the sealing and non- sealing surface were recognized during the midday flights of 1986 and 2004 with 2,9 Kelvin and 2,3 Kelvin. The other flights always present higher value for the sealed areas but not as high as the ones before mentioned. The standard deviation of the surfaces covered by sealing is always higher, which is the result of the higher variety of materials as well as the stronger albedo.



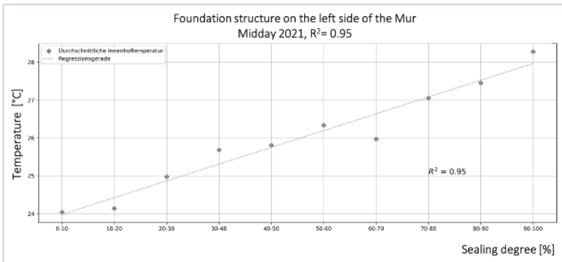


Figure 25 (left). Area of inner courtyards classified in sealing degrees of 10 % vs. temperature in °C of the foundation structure – Midday 2004.

Figure 26 (right). Area of inner courtyards classified in sealing degrees of 10 % vs. temperature in °C of the foundation structure – Midday 2021.

The inner courtyards with a higher degree of sealing as well as the sealed areas in the inner courtyards of 1986 are continuously warmer throughout all the results, although the temperature differences between the sealed and unsealed areas become smaller when the sealing degree increases, which might influence its close surrounding. The inner courtyard with the number 46 with the lowest degree of sealing (12%) has a temperature difference between sealed and unsealed areas of 0,9 K in the morning, 4,5 K at midday and 1,3 K during the night. Looking at the courtyard with the number 355 with the highest sealing degree (81%) the temperature difference between the sealed and unsealed area is 0,6 K in both cases and the temperatures are equal in the morning.

Table 6. Weighted average of the temperature in °C and standard deviation in K of the sealed and unsealed areas of the inner courtyards (0=unsealed; 1=sealed)

Year	**1986**						**2004**		**2011**		**2021**			
Day Time	Morning		Midday		Night		Midday		Night		Morning		Midday	
	0	1	0	1	0	1	0	1	0	1	0	1	0	1
Sealing degree (%)	53,7	46,3	53,7	46,3	53,7	46,3	62,6	37,4	64,3	35,7	49,5	50,5	49,5	50,5
Weighted average of temperature (°C)	4,4	4,5	22,2	25,1	5.9	6,2	18.2	20,5	-4,5	-4,2	11,9	12,5	24,1	26,7
Standard deviation (K)	1,3	1,6	7,1	8,2	1,5	1,8	4,1	7,8	0,8	1,2	1,1	1	3,9	3,5

Either from 1986 to 2004, the sealing degrees increased from 12% to 23% or they decreased from 53% to 40% and from 81% to 75%. Forest and green areas mostly replaced the impermeable surfaces. The temperature behavior of 2004 confirms in the inner courtyard with the number 352 the general trend that sealed areas are compared to vegetated surfaces warmer. The difference is with 5,1 Kelvin the biggest one, shown in this table. Because of an inversion of the temperature, a completely different picture was seen for the inner courtyards with the numbers 46 and 355. This phenomenon occurs rarely spread over the city but after monitoring the construction materials used for the house, as well as the alignment of it – no explanation for the observed temperature inversion could be found. Generally, it can be said that the weighted average of the temperature in degree Celsius of the houses was in the same order as the degree of sealing. The trend is: the higher the sealing degree the higher the measured temperature of the inner courtyard.

In the year 2011, the weighted average of the temperature in degree Celsius is again aligned with the sealing degree of the inner courtyards. The temperature increases from -4,6°C to -4,4°C -4,2°C with the sealing degree of 30%, 35% and 47%. The differences are, compared to the previous years, much lower, what is reasonable regarding the time of year. The incoming radiation, thus the roof-, wall heat-, and ground heat capacity are much lower, and hence the surfaces are not heating up and saving as much energy as they do during the flights of 1986 or 2004. By comparing the temperature differences between the sealed and unsealed surfaces of each inner courtyard, twice the impervious surfaces are warmer, the differences amount 0,6 K and once just 0,1 K. The courtyard with the number 352, which is with a sealing degree of 47% almost half-sealed, shows a temperature, which is balanced between the different surface areas. For 2011 a clear tendency, the more sealing – the higher the temperature is visible, although additionally within each inner courtyard the temperature differences according to their degree of sealing were seen as well.

For each inner courtyard a clear trend, a higher degree of sealing leads to higher temperatures, is visible. Especially while comparing the flights of 1986 a strong correlation at midday was approved which extracts and confirms again how strong the positive radiation influences the temperature of those surfaces. After the results of this additional analysis of comparing single inner courtyards, a deductive conclusion is reasonable, saying the higher the sealing degree of inner courtyards the higher the temperature. It underlines the already seen tendency of the previous study, where the analysis was applied for all the inner courtyards of the foundation structure.

In the previous section, correlations between temperature and degree of sealing were evaluated for the foundation structure as well as for individual inner courtyards, to distinguish if a deductive conclusion can be drawn. To further assess city temperature patterns of this structure, an additional analysis was done to evaluate if the impervious surfaces show different temperatures depending on whether they are on the right or the left side of the “Mur”. The combination of these existing datasets combined in one geodatabase supports a convenient way to extract the inner courtyards from different parts of the city. The results show a weighted average of the temperature of 21,9°C on the left and 23,3°C on the right side of the river what gives a difference of 1,3 K between those two observed parts. The corresponding aspects here for can be attributed to the fact of having the tributary valleys east of Graz, which generate, lower temperature down-valley winds, and perform as a fresh air supply for this part of the city. Additionally, and maybe more important are the lower sealing degrees of the inner courtyards on this side of the Mur [8], [18].

The results of this chapter strengthen the idea that the sealing degree is the primary active influence on the temperature of the inner courtyards. This final section is dedicated to the investigation of establishing the inverse correlation of a higher degree of green areas and a lower temperature in the inner courtyards. Analogous to the previous conclusions the coherence between the features, green areas and the thermal behavior has to be visible throughout all the flights. For this analysis, the in the geodatabase integrated land use information was applied to extract for 1986 green areas, for 2004 the categories green areas and forest and 2011, due to a new subdivision, the classes broadleaf’s, conifers, and bush layer. As already presented in the previous analysis, the inner courtyards were separated into classes with 10% intervals of green areas.

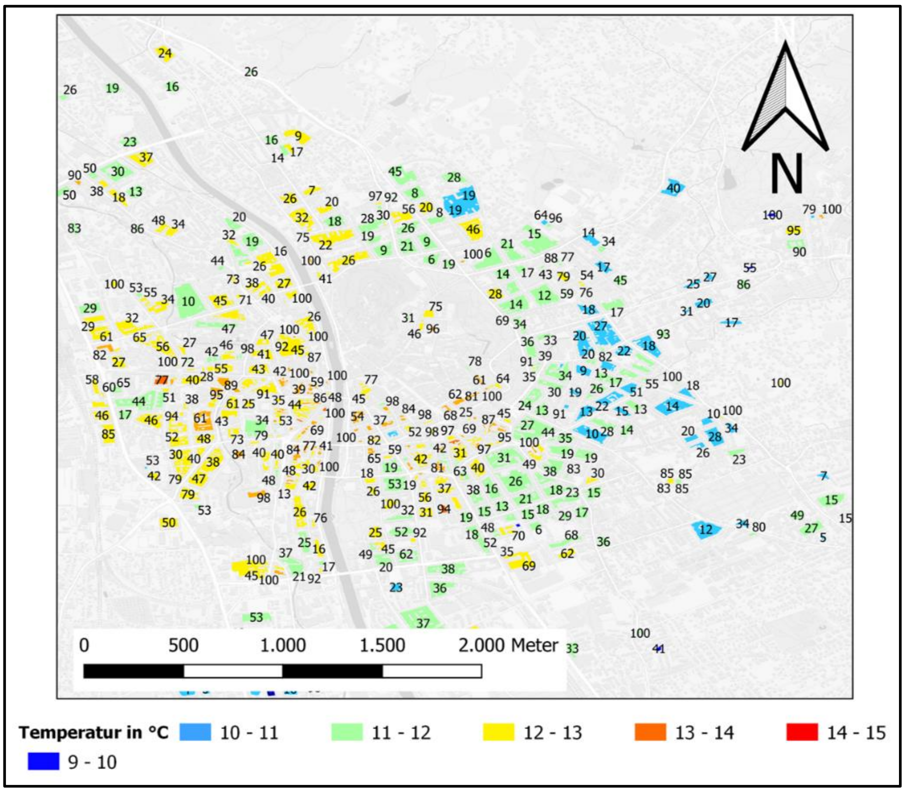


Figure 27. Foundation structure with sealing rates and average Temperature in °C (Morning, 2021).

Additionally, the weighted average of the temperature was employed. The coefficient of determination of every single flight measures the correlation of the summarized green areas and the temperature of the inner courtyards. The correlation coefficient of the conditions is permanently high, although in the morning and during the night of 1986 the values achieve with R2=0,91 and R2=0,92 peak values. The midday flight of 1986 and the night flight from 2011 indicate a strong linear relation with R2=0,88 and R2=0,89. Only the flight of 2004 tend to be lower, whereas with an R2 of 0,75 still a clear relationship between the variable's green areas in % and temperature in °C for the inner courtyards was visible. The arrangement of the coefficient of determinations of each flight is comparable or almost the same as before while extracting the correspondent part the sealing degrees. Once again, it can be strengthened that the temperature of the courtyards is strongly influenced by the amount of sealing and green areas (see Figure 18 and Figure 19).

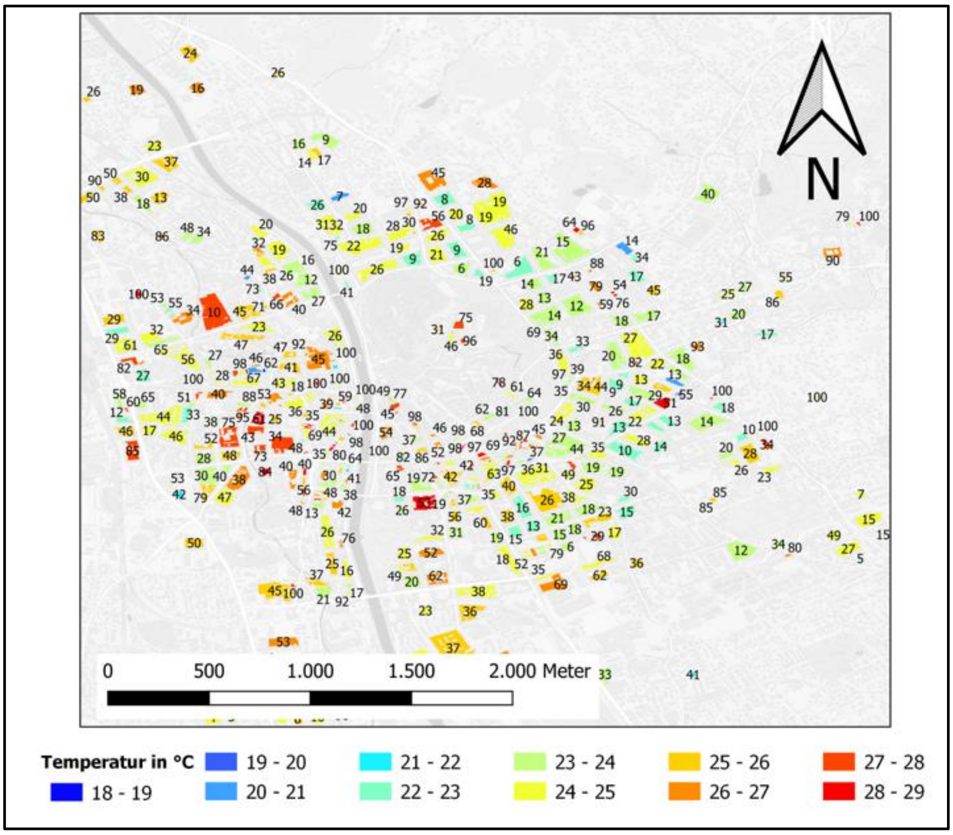


Figure 28. Foundation structure with sealing rates and average Temperature in °C (Midday, 2021).

CONCLUSION

Through remote sensing technologies as used for this analysis, it is possible to derive surface temperatures and detect temperate patterns or even temperature behavior in smaller scales for the city environments. Those surface temperatures, already collected in a very sophisticated way, need to be combined with other information. In the current analysis the land use, the land cover, the predefined homogeny climate areas, and the degree of sealing were, with the help of geographic information systems, combined to determine the temperature behavior of inner courtyards of the foundation structures. With

the creation of the geodatabase and the intersection of all the datasets thermal characteristics, influenced by the underlying surfaces, can be extracted, and analyzed in their different behavior.
The results indicate that not the size of the inner courtyard is the main influence on thermal behavior; it is the degree of sealing as well as the opposed green areas. Strong correlations could be seen during all flights. Because of the increasing number of inhabitants in cities, future urban planning should consider more green areas to increase the welfare of human beings.
Green inner courtyards in the heart of the city have a positive effect on the microclimate. The plants evaporate water and have a cooling effect in summer (see midday 2021). Permeable soils instead of asphalt and concrete can absorb and store (rain)water, thus relieving the burden on the sewer system. The urban influence (urban heat island, lower humidity) is mitigated by the green structure. Other positive side effects of a high proportion of vegetation include reduced wind speed, reduced pollution, and noise protection.
Green courtyards enhance the quality of life. They provide retreats from the hustle and bustle of city life and offer habitats for plants and animals. Especially in densely built-up urban areas, green courtyards act as a true oasis of calm.

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