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Recent progress of SPIDER: Aspects of subtractive approaches to existing building's performance improvement

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Abstract. This contribution reports about methodology, progress and preliminary findings of a recent exploratory Research and Development project, pertaining to the (semi-)automated thermal retrofit of existing building's envelopes. Thereby, the potential of robots, which autonomously identify areas of facades that can be used for inserting openings into the existing wall material, is examined. The idea is based on the fact that masonry walls of historic masonry walls (especially of *Gründerzeit* buildings built between 1850 and 1918) often have been structurally over-dimensioned. As such, the spare thickness of the walls could be used for thermal insulation purposes. The initial idea to implement air cavities for insulation purposes is in correspondence with the predominant functional principle of most insulation materials.

Actually, Vienna is growing at a similar rate as it did in the last third of the 19th century. A period that is referred to as *Gründerzeit* in Vienna.

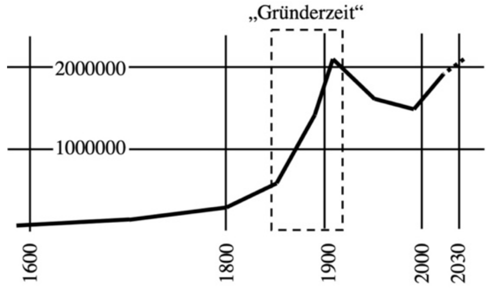

Fig. 1. Population of Vienna, graphic based on STATISTIK AUSTRIA and [1]

After the fall of the iron curtain in 1989 and Austria's accession to the European Union in 1994, the country and especially Vienna experienced a new heyday and a significant increase in population. Not only will Vienna soon exceed a population of 2.000.000 inhabitants again, it also grows at the same rate, as it did in the days of the *Gründerzeit*, see Figure 1. Lacking green sites for new developments on the one hand and on the other hand providing lots of apartments within the old 19th century fabric, this growth will partly be countered by vertical expansion of these old buildings. Attics and additional stories provide attractive new living spaces with great views, terraces and a most modern standard of energy efficiency and thermal comfort. The apartments below usually also benefit from these expansions, be it through the installation of elevators or through the repair of risers or the facade. However, part of the charm of these old quarters, largely being under heritage protection by now, is due to the ornamented facades. These facades cannot be thermally renovated in a conventional manner without destroying them. Conventionally, an Exterior insulation and finish system (EIFS) would be applied to a brick wall. This is only possible, if the ornaments of the façades are removed. The façade would be flattened and usually no money would be spent on a design with equal or higher quality. A design conscious approach has been shown in a house in the 6th district, see Figure 2 and [2].

Fig. 2. Peter Sandbichler, façade design, Mariahilfer Straße / Getreidemarkt, Vienna, 6th district, 2017, photograph copyright: Günter Richard Wett, published online [2]

1. Urban context and relevancy

The city of Vienna estimates the number of apartments from the *Gründerzeit* era at 351.000, inhabited by an average of two people [1]. These apartments typically show a heating demand of 150 kWh/m2a [3] and cause CO_2 emissions of about 247 g/kWh, resulting from their energy demand [4]. Given a typical apartment size of around 100 m2 gross floor area, this results in a total yearly heating energy demand of 5,27 TWh and a total of CO2 emissions of 1,3 Mt.

Fig. 3. predominantly *Gründerzeit* housing zones, MA 18; Referat Stadtforschung und Raumanalyse (Zahlen: Stand 1.1.2017) coloured or dark areas [1]

The heating demand of these buildings historically has been met by coal and wood and meanwhile is basically covered by natural gas. According to the OIB, the Austrian Institute of Construction Engineering, the total amount of natural gas required for heating and warm water is 16,5 TWh per year. From this appr. 13,7 TWh is used for heating, the rest is for warm water [5]. The Viennese Gründerzeit apartments therefore consume 38% of Austria´s gas-covered residential heating demand. Given recent efforts to improve and renovate buildings all over Austria this percentage will increase, if no measures are taken. Decreasing the heating demand to contemporary standards, that is a quarter of the given demand, resulting in a consumption of 4 to 5 TWh would be necessary to bring alternative energy sources into reach to cover the demand. However, given the significant share of heating energy demand in the national context and being aware of the difficulties and the long-term perspective of getting the energy supply of these buildings away from fossil fuels, any improvement should be investigated that can be implemented economically and without major organizational difficulties. Organizational difficulties will occur with any measures taken on the inside of the apartments and with cost intensive measures as many of these buildings are co-owned by different often private proprietors.

2. Thermal performance

The buildings of the *Gründerzeit* era usually find themselves in the urban context of the perimeter block design. According to the city of Vienna the most characteristic block typology shows a street width of appr. 15 m and a block size of 90 x 90 m with 4 to 5 stories [1].

The heating demand decreases with the thermal transmittance of the enclosing surfaces of a conditioned zone. This relation is in a direct linear proportion.

The block typology means that heat losses are predominantly determined by the facades to the street and the courtyard. The facades to the neighbors usually can be assumed as adiabatic. The topmost ceiling and the basement ceiling have less influence, on the one hand due to the geometry of these buildings, on the other hand, they face either an unheated attic or an unheated basement. According to the Austrian Standard ON B 8110-6[1] the heat loss towards an unheated attic can be considered as 10% less and towards an unheated basement as 30% less than towards the exterior.

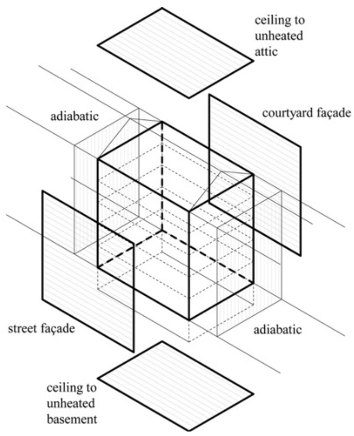

Fig. 4. Heat loss of a perimeter block building

For a quick estimation that means for a (typical) building, 17 m long, 12m wide,17,5 m high:

Table 1. influence of the different building skin elements

Element	Area x temperature correction factor	percentage
street façade	297,5 x 1,0 297,5	32,3
courtyard façade	297,5 x 1,0 297,5	32,3
topmost ceiling	204,0 x 0,9 183,6	20,0
basement ceiling	204,0 x 0,7 142,8	15,4
total corrected heat loss area	921,4	100,0

[1] and also according to the German DIN 4108-6 and other monthly calculation methods

The two façades are responsible for nearly two thirds of the total heat loss. This is of course just a quick estimation. On the corners of such a block, the street façade is considerably larger than the one to the courtyard. Where the courtyard façade can be easily improved by a classic EIFS system, the heavily and sculpturally ornamented street façades call for alternative solutions.

Construction

In Vienna in the 19th century and the beginning of the 20th century, masonry usually was built up by bricks of 29 by 14 by 6,5 cm. A cubic meter of wall usually was composed of 300 pieces [6].

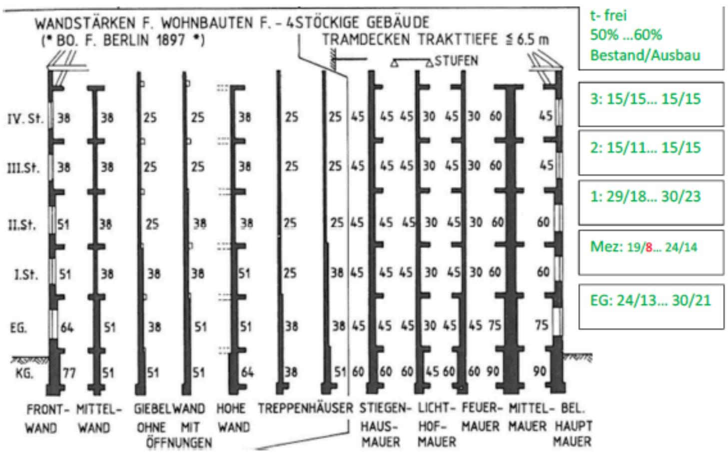

Fig. 5. Technical regulations, Wien, Berlin. Kolbitsch 1989 [6]

At least 15 cm of such masonry with an average depth of 45 cm is redundant and can thus be used to improve the thermal performance of building. Previous calculations of the authors have shown that partly even 50% of the masonry would be available. The structural performance has been investigated on an exemplary building.

Example. The exemplary building chosen is located in Vienna´s first district, located on the corner of *Fichtegasse*/*Kantgasse*. The building is a typical *Gründerzeit* construction with five floors and an attic.

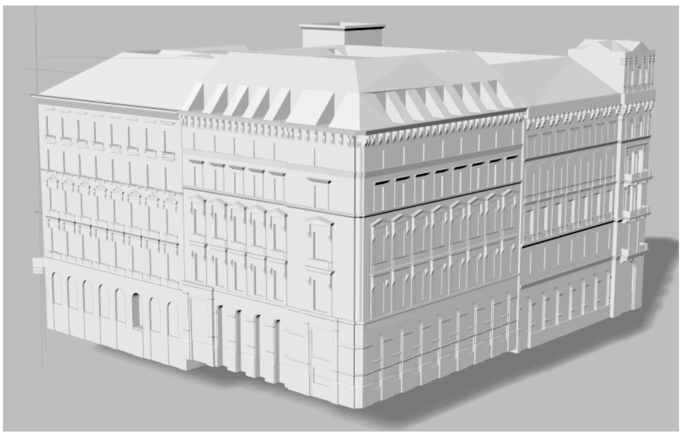

Fig. 6. Residential Building *Fichtegasse*/*Kantgasse*

Utilization. To assess the redundancy of the wall, first the utilization is calculated. The distribution of the cavities is distributed accordingly, see Figure 7. To preserve the ornamentation of the façade and to implement an automatized process, material will be removed by drilling. This method can also be carried out by small façade climbing robots.

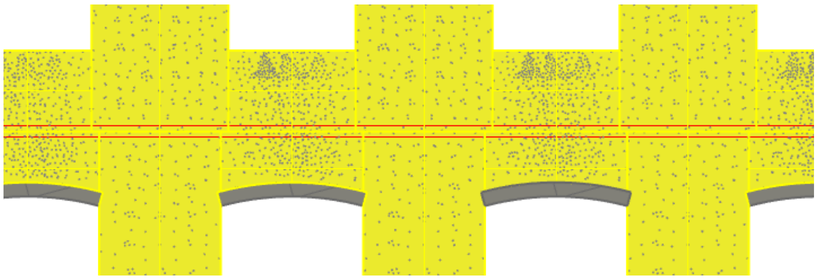

Fig. 7. bore hole distribution *Fichtegasse/Kantgasse*

Direction and geometry of the bore holes has been investigated. This is much depending of the available tools. A drilling direction of 45° increases the effect of the porosity. Another approach has been to apply more sophisticated drilling dips [7].

Thermal Performance

Material properties. While the Austrian Standard ON B 8110-8 for historic masonry recommends using modern values of about 0,69 W/mK for the thermal conductibility coefficient. The German Arbeitsgemeinschaft Mauerziegel quotes historic records that show thermal conductibility coefficients ranging from 0,6 to 1,1 W/mK [8]. These values refer to masonry, including mortar. Modern mortar is specified with 0,78 W/mK, the composition did not change significantly, so that we used this value. For historic brick no exact data is available, although a huge range of literature is available. The most plausible approach is to relate conductivity and density, as given in the ON EN 1745. For the following investigation a conductivity of 0,55 W/mK has been chosen, that corresponds to a brick weight of 1.800 kg/m3.

Thermal simulation. For the simulation of the masonry´s thermal performance, the authors used Antherm, a validated heat bridge simulation software [9]. Masonry with the parameters given above shows a U-value of 1,55 W/m2K which perfectly corresponded to standardized default values, given by the OIB [10]. All walls were calculated with boreholes of 8mm diameter, 15cm deep, arranged on a 11,5mm square grid.

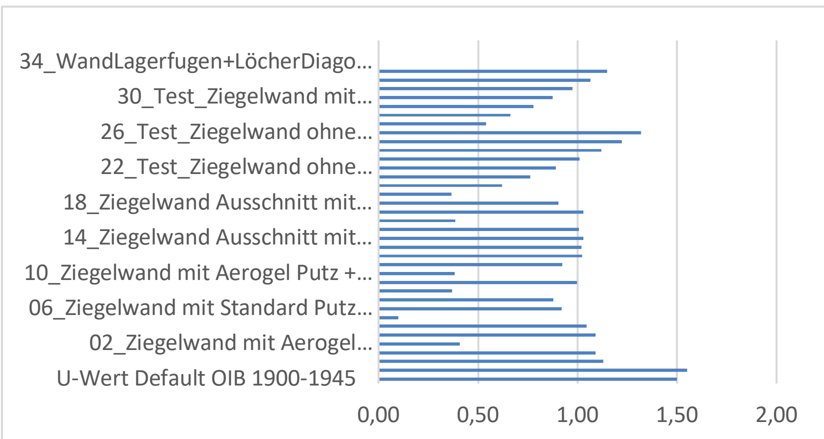

Fig. 8. Excerpt from the result list of the simulation results of the manipulated masonry

36 different borehole patterns and material combinations were investigated, see Figure 8. Unless additional measures were taken, such as the application of Aerogel plaster on the whole facades, the holes alone, without replacing the plaster, reduced the masonry´s *calculated* u-value down to 80%. Replacing the historic plaster by aerogel plaster brings the masonry from 1,55 to 0,4 W/m^{2}K, the boreholes added it goes further down to 0,35, which is the maximum value allowed for new wall components.

In Situ. To control and complement the simulation, an in-situ measurement using the heat flux method [11] (using a gSKIN U-Value Kit set [12]) has been set up. The measured U-Value of 50 cm reference wall, situated in a narrow courtyard, facing North, was 1,5 W/m^{2}K, the improvement by the holes was a reduction of 21% down to 1,19 W/m^{2}K, although for practical reasons and considering a new concept described in the following chapter, the borehole diameter and distance was bigger: 18 mm diameter, 15 cm deep, arranged on a 10cm square grid, see Figure 9.

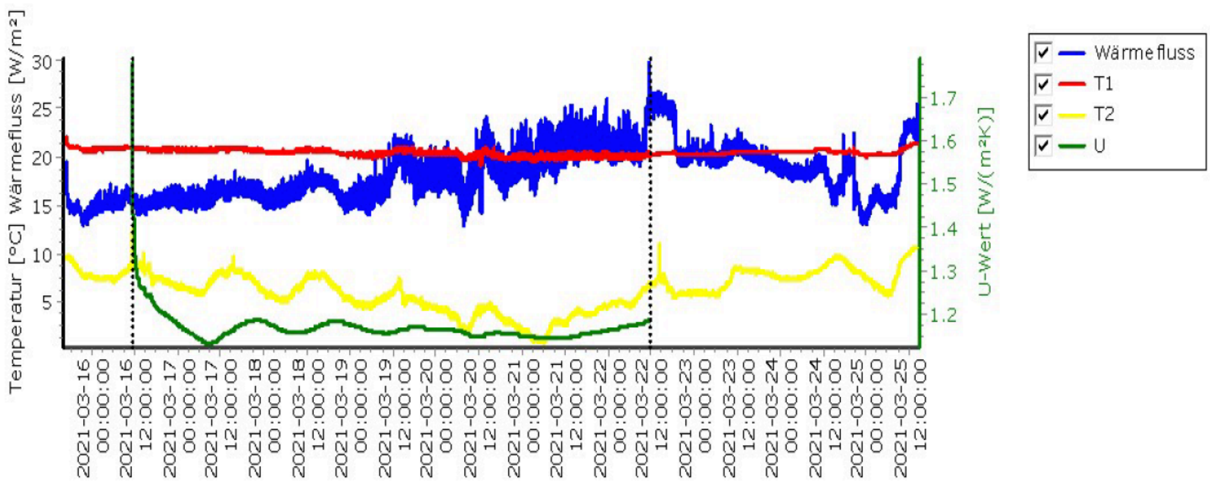

Fig. 9. in situ measuring of wall with holes

3. active insulation

Where the performance of the boreholes doesn´t show a powerful effect, the combination with a replacement of the plaster contradicts the idea to use autonomous robots doing the retrofitting. Therefore, the authors re-considered the concept of insulation: during the day, even in winter, facades are hit by solar radiation, at least by the diffuse part of it. If the arriving energy is bundled and stored for the night, it can be used to heat the wall from inside, increasing the component´s interior surface temperature. This is equivalent to an improved u-value.

Different methods can be applied to develop such heating rods, that can be plugged into the boreholes. Either solar energy is captured by a solar thermal panel and transferred to a phase changing material, melting it. During freezing that material would release the heat energy again. Or in a more technical but not necessarily more expensive approach, a photovoltaics panel can be used to load a small battery that heats filament during exactly specified hours and controlled by outside temperatures.

In the simulation the heat rods in the holes were powered by 5 mW, the results showed changes of the interior surface temperature resulting in *calculated* a u-value of 0,4 W/m^{2}K - lowering it from 1,55 W/m^{2}K. For one day, this sums up to 0,12 Wh. Thus, a minimum power of 20 W/m2 on the façade is needed. On an average day in December still 600 Wh/m^2 will hit the façade - just considering the diffuse radiation. This gives us 25 W/m^2. Of course, this is not a match, considering the efficiency of a PV panel of around 15%. However, as during the whole year the average is five to six times higher and given the capacity of the battery and the heat capacity of the PCM, supply and demand finally will be balanced.

Such a device, composed of a PV cell running filament into a glass tube containing wax, has been prototypically built, see Figure 10. It was mounted in the middle of 9 holes, arranged 10 by 10 cm. The heating device was run, replacing the PV cell by an external power source, providing 2 W during a 72 h measuring. However, there was no pre-heating and of course the whole wall was influencing the measuring. The u-value showed a reduction of 27% of the *measured* u-value, down to 1,1 W/m^{2}K. The glass tube influenced the thermal performance negatively; when removing that influence the improvement was 43% resulting in a re-calculated u-value of 0,855 W/m^{2}K. This can be seen as proof-of-concept. With a different geometry, the very low u-values from the simulation seem to be realistic.

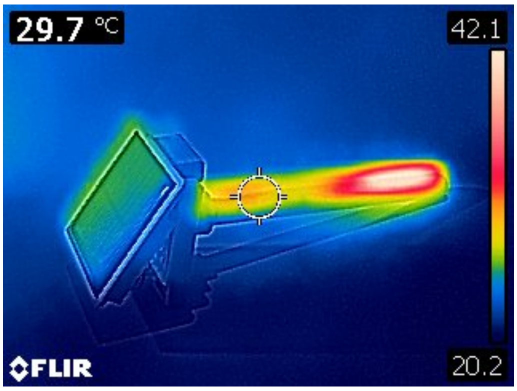

Fig. 10. infrared image of a heating rod, powered by a small PV panel

4. Robotics

The SPIDER project has been set up in the context of recent progress in robotics and autonomous devices. This also includes the use of photovoltaics as a power resource. With this as a background, the duration of a building activity is put in a different perspective and becomes depended on local weather conditions. Parallel to our efforts to find feasible methods of porosification of historic brick walls, the research team also investigates the design of robots, capable to climb walls and drill holes but also to fill the holes with aerogel or to insert actuators.

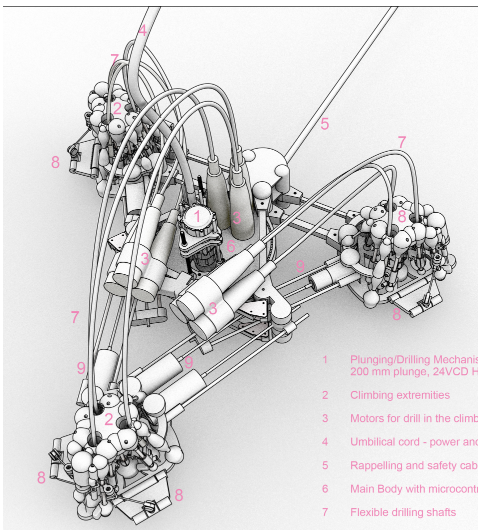

Fig. 11. latest design efforts of the prototype that will be built and applied in the course of this project.

5. Relevance

Finally, the relevance of the improvement has been reviewed by reading out data of the relevant buildings and their geometry from open government GIS. Thus, the energy performance from all the Gründerzeit buildings of Vienna could be calculated at once and the improvements by retrofitting the facades in the proposed way could be shown, immediately. Retrofitting the exterior street façades only from 1,5 W/m^2K down to 0,4 W/m^2K by the proposed method and retrofitting the other, non-ornamented façades by EIFS systems to the same value, the heating energy demand would be reduced by one third, the CO_2 emissions accordingly. Together with the improvement of the windows (to 1,0 W/m^2K), and the renovation of roofs and ground floor slabs, a heating demand of less than 50 kWh/m2a can be achieved, thus showing a reduction of nearly two thirds of the initial demand. Finally, these buildings can be heated by renewable sources and hooked off fossil fuels, further reducing CO_2 emissions.

6. Conclusion

This research sets out fundamental consideration of new methods to retrofit historic buildings. It demonstrates that the redundancy of masonry could be used for thermal improvement and it shows new ways to use robots for retrofitting. The most promising approach seems to combine the method of porosification with a kind of "active insulation" that uses the power of the sun radiation on the façade for heating the walls, reducing heat losses by a higher interior surface temperature. The proposed "active" device must be further developed, especially regarding the applied materials.

Using seasonally driven robots could facilitate retrofitting, especially in buildings where owners oppose work within their apartments to apply interior insulation and where there are little alternatives to otherwise preserve the ornamentation of the façade.

The ultimate goal is to finally lower the heating demand to a level that allows for alternative renewable fuels to heat the Gründerzeit quarters of Vienna.

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