Identification and quantification of urban planning related framework conditions on energy and resource-efficiency of urban building developments

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Abstract. Energy efficiency in buildings undeniably plays a vital role in addressing climate change. At the level of building planning, a thorough analysis with thermal dynamic calculations can be carried out to assess energy demand and resulting CO₂ emissions of buildings due to the high level of detail usually provided at this stage. In urban planning design on the other hand, energy and resource-related parameters are usually not quantified, as at this stage of the planning process other urban planning factors predominate the concepts. However, numerous aspects that are determined at the stage of urban planning cannot be changed anymore later on in the process even though, they can have a significant impact on the energy demand. This includes the structuring of the building blocks, density and height of the buildings, orientation and inclination of the surfaces as well as greening of the outer shell and availability of direct solar radiation. This paper describes the analysis of parameters, which have a significant influence on energy and resource consumption of urban developments. This includes new developments as well as the existing building stock in order to provide quantifiable indicators for refurbishment and densification measures. The simulation tool CityCalc, which has been developed in a previous research project provides the environment for the analysis. To validate the approach, the identified parameters are analysed in an exemplary case study for a Viennese urban development area. The results aim at identifying and quantifying the key influencing parameters of urban planning design on the energy and resource efficiency of new and existing urban development areas in order to gain essential insights for the integration of climate-relevant factors for future planning processes.

1. Introduction

Population growth in European cities has slowed down, but nevertheless capital regions within the European Union are expected to continue to grow by 4-6% over the next decade, leading to an increased demand for new developments in cities [1]. Given the fact that in the European Union, buildings account for 40% of total energy and are responsible for 38% of CO₂ emissions [2] achieving the Sustainable Development Goal (SDG) of sustainable cities and communities and implementing plans towards resource efficiency is inevitable to avoid negative effects of the increasing urbanization. For this purpose, the current focus of policy and planning is predominantly on energy efficiency in the design and operation of individual buildings. The primary fields of action of European cities to reduce both energy consumption and greenhouse gas emissions concentrate on improving the energy efficiency of
individual buildings, i.e. the enhancement of thermal insulation of buildings, the use of more efficient lighting technologies and the promotion of new low-energy buildings [1].

At the planning level of individual buildings, many details are usually already known, allowing detailed analyses with thermal dynamic calculations to be performed. In urban planning design, on the other hand, parameters for energy efficiency are generally not quantified, as there are no general indicators to evaluate the energy efficiency in this early planning phase, nor is there a wide range of easy-to-use tools to simulate the energy efficiency of urban planning concepts [3]. Accordingly, other urban planning factors than energy efficiency (e.g. spatial relations, street alignments, views, green spaces, transport infrastructure) generally predominate the concepts. This concludes that although urban planning creates the framework conditions in which the design of individual buildings can subsequently operate the issue of energy- and resource efficiency is of subordinate priority in the early stage of planning.

While the actual impact of urban features on energy efficiency is not yet clearly identified, it is evident that the influence of building morphology and urban structure on the energy consumption of buildings derives from their impact on heat transfer and solar access [4]. Building morphology essentially describes the size and shape of a building. In addition to the compactness of the building, which is expressed as the ratio of its volume to its surface area glazing percentage and glazing distribution as well as the orientation of the building also have an influence on its energy consumption [5]. Urban structures on the other hand are characterized by the arrangement of different buildings and their distances from each other. Their impact on the resource efficiency of individual buildings derives from their influence on the availability of sunlight and daylight on building facades and the resulting solar gains [6].

Due to the possibility that these energy relevant parameters can be easily changed at a very early planning stage, urban planning competitions and urban planning projects have great potential to contribute to the goal of sustainable cities. Therefore the aim of this study is to investigate the potential for optimizing energy- and resource efficiency in changing urban planning designs as well as to find out which aspects and factors are the most important influencing parameters. For this purpose, different urban planning frameworks are tested in a theoretical model regarding their heating energy demand (HED) based on a current Viennese urban development area in order to gain essential insights for future urban planning processes.

2. Background

Vienna is the capital city of Austria and at the same time one of the nine Austrian provinces. With close to 1.9 million inhabitants [7], Vienna is the largest city in Austria and the sixth largest city by population in the European Union. Since the beginning of the 2000s, the city has experienced a strong phase of population growth with annual growth rates of 1.2%. Despite moderate growth between 2006 and 2010, the population of Vienna increased by about 327,000 people to 1,897,491 between 2002 and 2018. Until 2035 a further growth of the population by more than 180,000 people (+9.5%) to 2,105,119 is forecast [8]. In combination with the trend towards smaller households, this growth implies that more than 83,000 new private households (+9.2%) can be expected in Vienna by 2035 [9].

In order to cope with the rising housing demand without compromising the availability of unsealed land, the city has set itself the goal of primarily using existing building land reserves. Particularly parts of the urban landscape that were formerly used as industrial or traffic areas are of great importance for the further development of the city. The former railway station Nordwestbahnhof, which is used as exemplary case study for the theoretical models of this work, is one of these large areas that will be upgraded to new urban quarters [10]. The former freight terminal is located between the city center and the Danube River and is about 44 ha in size. The urban planning approach developed in 2008 envisages the development of a central multifunctional green open space with predominantly residential use at the perimeter. In addition, areas for offices, retail, leisure, culture and education are planned. In the coming decades, this will create space for 11,800 inhabitants and 5,100 workplaces [11].
3. Methodology

To achieve the research objective formulated in Chapter 1, various urban planning conditions were tested in a theoretical model with regard to their HED based on the current Vienna urban development area Nordwestbahnhof. The study is thereby structured in four steps (figure 1).

The first step covers research on urban planning framework conditions that have a relevant influence on the energy efficiency of building developments. Literature on urban planning in connection with the effects on resource consumption was screened and the identified parameters were summarized. In the second step the previously identified parameters had to be selected and combined with each other. For this purpose, parameters concerning the building morphology were used to define four building types for a 1.8 ha plot of the Nordwestbahnhof, using only structures that are already typical for the Viennese cityscape. In addition to the perimeter block development outlined in the urban planning approach, these include row structured buildings, point blocks and a high-rise building (figure 2).

To be able to focus on the effects of different urban planning designs, certain parameters were chosen to remain unchanged in the simulations. Accordingly, the gross floor area (GFA) and the share of residential and commercial use, which are pre-defined by the urban planning development guidelines,
are kept identical for all building types created whereby differences in the required circulation space were not taken into account. The building types differ therefore in terms of their compactness, expressed as the ratio of surface area to volume (SA:V) and their site coverage (table 1).

Table 1. Characteristics of the developed building types.

| Building type          | Gross floor area (GFA) (in m²) | Commercial use (in m²) | Compactness (1/m) | Site coverage (in %) |
|------------------------|---------------------------------|------------------------|-------------------|---------------------|
| Perimeter block        | 43,800.00                       | 2,064.00               | 0.25              | 39.74               |
| Row structure          | 43,800.00                       | 2,064.00               | 0.26              | 30.15               |
| Point block            | 43,800.00                       | 2,064.00               | 0.22              | 40.18               |
| High-rise building     | 43,800.00                       | 2,064.00               | 0.14              | 7.70                |

In order to develop the relevant scenarios, the building types were enhanced by the following influencing variables relevant for energy efficiency.

- Building orientation: eight orientations - aligned to plot and cardinal point
- Glazing percentage: 20%, 30%, 40%
- U-Value Windows: 1.4 W/(m²K), 0.8 W/(m²K)
- U-Value Walls: 0.35 W/(m²K), 0.15 W/(m²K)

Figure 3 shows in a graphical representation how the four building types were combined with the other parameters resulting in 288 different scenarios.

In the third step the scenarios were then evaluated with regard to their HED, whereby findings from first results were used to optimise the scenarios developed in step two. The calculations were performed using CityCalc, an evaluation tool in the form of a SketchUp plug-in that can be used to prepare geometric building models from Trimble SketchUp for the Archiphysik calculation software that is used in Austria to calculate energy performance certificates. The evaluation is based on the volumes and surfaces of the individual building parts, but also takes into account the mutual shading and the inherent
shading of the individual buildings. In addition, it is possible to determine how buildings or parts of buildings are used (residential or commercial use) [12]. As a result, the simulations provided calculations for HED for all modelled scenarios. In a final step, the most important results of the simulations are summarized, and the effects of the influencing factors derived from the scenarios are analysed.

4. Results
The results of the simulations show that, with the same GFA, different urban planning conditions can help to reduce the HED of the respective buildings by up to 42% from a maximum of 34.54 kWh/m²a down to 19.73 kWh/m²a. In the simulations the best values in terms of energy efficiency were achieved in the scenarios of high-rise buildings and point blocks. Perimeter block and row structures performed significantly worse. As expected, compactness has proven to be the determining factor for HED.

4.1. Influence of compactness
The results of the simulations confirm the expectation that building compactness is by far the urban planning parameter with the greatest influence on the HED of buildings. A comparison of the energy efficiency of the simulated scenarios with the compactness of the respective building type illustrates the importance of this indicator for resource consumption and shows that the development of HED strongly follows the compactness of the respective building type (figure 4). Given identical orientation, thermal insulation and the same glazing percentage, the HED of the most compact building type is on average about 33% lower than that of the building type with the least compactness over all the scenarios modelled. To compare the influence of compactness with that of thermal insulation, the least compact scenarios with improved insulation were compared with the most compact scenarios with less insulation. The result indicates that the HED of the building types of different compactness do not show any significant difference afterwards. Accordingly, a building with insufficient compactness cannot exceed the energy efficiency of compact designs even with improved thermal insulation.

![Figure 4. Relationship between HED and compactness of buildings.](image)

Additionally, it was investigated whether the influence of compactness on the HED decreases with improved insulation of the outer shell. For this purpose, the simulation results for row structure and high-rise buildings with 30% glazing percentage and different U-values for windows and walls were analysed. Subsequently, the difference (in %) in HED for all orientations between the two building types per scenario was compared (figure 5.). The results once again confirm the importance of adequate
compactness, because although the initial value of the HED was lower in the compact building type, the improved insulation changed the value to the same extent as in the less compact building type.

4.2. Influence of glazing percentage

The variation of the glazing percentage of the buildings shows that the effects are, as expected, strongly dependent on the thermal transmittance of the windows (figure 5). With a window U-value of 1.4 W/(m²K), the increase in glazing percentage results in a higher HED. The simulations show that the increase of the glazing percentage from 20% to 30% and from 30% to 40% results in an average 4.5% higher HED. Under these conditions, the additional solar gains are therefore not sufficient to compensate for the increased transmission losses. However, if the thermal transmittance of the windows is improved, this correlation can be reversed. The simulation of the identical scenarios with a window U-value of 0.8 W/(m²K) leads to a reduction of resource consumption due to a higher glazing percentage. Increasing the percentage of windows from 20% to 30% and from 30% to 40% can reduce the HED in these scenarios by an average of about 7%.

Figure 6. Influence of glazing percentage on HED.
4.3. Influence of orientation
The simulation has shown that orientation is the parameter with the lowest influence on the energy efficiency of buildings. Over all scenarios, the HED changes by 2.3% on average depending on the orientation. As expected, the east-west orientation, with the long side of the facade facing south, proved to be the most effective orientation for energy efficiency. Accordingly, the worst results were achieved in buildings with north-south orientation. Especially buildings with low compactness and correspondingly high HED react only to a very limited extent to changes in their orientation (figure 7-9). The influence of orientation only gains importance when energy efficiency is already very high due to the optimization of other parameters. Accordingly, in the building type high-rise building the greatest influence of orientation can be observed (figure 10).

Figure 7. Influence of orientation on HED of perimeter block.

Figure 8. Influence of orientation on HED of row structured buildings.

Figure 9. Influence of orientation on HED of point blocks.

Figure 10. Influence of orientation on HED of high-rise building.
5. Discussion
The analysis of different urban development scenarios with regard to their HED has shown that urban planning design can make a significant contribution to reduce the resource consumption of future urban development projects and to contribute to the goal of sustainable cities. The most important influencing factor that needs to be considered in future urban planning processes at an early stage is the compactness of the buildings. The other influencing factors and their impact on the HED cannot be considered in isolation from each other, and only in the context of the respective plot of land on which the buildings are located. In this context, no general recommendations for the optimisation of urban development designs regarding HED can be derived from the results for these parameters. In follow-up studies it will be necessary to include further aspects such as the cooling energy demand, the solar potential, the conditions for the integration of renewable energy sources as well as possible interactions between the different aspects in the assessment of these influencing factors.

A limiting factor for the applicability of the results of this study is the fact that the knowledge gained is limited to the climate prevailing in Vienna, where the energy efficiency of buildings is primarily determined by HED. Although other geographical regions with different preconditions regarding the resource consumption of buildings cannot directly benefit from the generated knowledge, the method used can be applied to other cities, as long as adequate weather data is available.

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