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Comparison of building modelling assumptions and methods for urban scale heat demand forecasting

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Abstract

Building energy evaluation tools available today are only able to effectively analyse individual buildings and usually either they require a high amount of input data or they are too imprecise in energy predictions at a city (district) scale because of too many assumptions made. In this paper, two tools based on 3D models are compared to see whether there is an approach that would probably be able to fit both – the amount of data available and the number of assumptions made.

A case study in the German town of Essen was chosen in the framework of the research project WeBest, where six building types representing the most important building periods were analysed. The urban simulation tool SimStadt, an in-house development of HFT Stuttgart, based on 3D urban geometry, is used to calculate the heat demand for both single building scale and city district scale. The individual building typology results are compared with the commercial dynamic building simulation software TRNSYS.

The influence of the availability and quality of data input regarding the geometrical building parameters on the accuracy of simulation models are analysed. Different Levels of Details (LoDs) of the 3D building models are tested to prove the scalability of SimStadt from single buildings to city districts without loss of quality and accuracy in larger areas with a short computational time.

Keywords: Heat demand simulation, 3D city model, CityGML, Scalability of urban models

Introduction

The building sector has a large potential in the EU-economy for energy efficiency gains and CO_2-reductions and is thus a priority area for achievement of the ambitious climate and energy targets for 2020 and 2050 [1]. In order to reach a 2% energy refurbishment rate promoted by the European Union and to realise long-term climate neutral communities, a change of rhythm and of scale is highly required.

Building energy evaluation tools available today are either only able to effectively analyse individual buildings and require a high amount of input data or they are too imprecise at a city (district) scale because of too many assumptions made. Therefore, there is a strong need to develop tools to precisely and easily perform a forecast of heat demand for different scales from single buildings to an urban (district) level.

3D city models might be a solution to master this balancing act as they can be used for urban simulation, but allow an analysis for individual buildings, too. Until now, 3D city models were mostly used for visualization purposes, but more and more studies attempt to utilize 3D city models for other purposes beyond visualization.

Biljecki et al. [2] carried out a systematic survey on documents related to the application of 3D city models. They identified 29 distinct use cases in several application domains, like e.g. estimation of solar irradiation, energy demand estimation, urban planning etc. Zhang et. al [3]. investigated the applications of 3D city models to urban design. Virtual city models, which store geometrical and semantic data of whole cities, are also a good solution in order to perform urban energy analyses, like e.g. in Karlsruhe and Ludwigsburg [4] or in Berlin

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[5] and other cities [6, 7]. The urban simulation platform SimStadt [8] was developed for such urban heat demand simulations using precise dimensions and building geometries that support accuracy in heat demand calculation [9]. In recent years, especially in Germany researchers have analysed the applicability of 3D city models for energy demand estimation purposes [10–14]. Most available methods use the volume of buildings, number of floors, type of the buildings and other characteristics to forecast the energy demand for heating or cooling.

A general applicability of 3D geo-information systems to solve industrial and research problems does not exist. Depending on the application, specific data are required. The data quality of the city models varies, depending on the available public databases and the information collected on-site. Nouvel et. al [15]. present a methodology of urban heat demand analysis that enables the investigation of the uncertainty of the model, analysing the influence of the building information (geometrical and semantical) on the simulated heat demand. The work of Carrion [5] showed an average error of 19% between the calculated and measured data of heat demand/consumption. Kaden & Kolbe [16] recognised that these errors are mainly caused by the fact that in most available data sets the actual building rehabilitation state is not known city wide, so that the estimates are mostly based on energy characteristic values or heat transfer coefficients as a function of the year of construction.

In this work, a refurbishment scenario based on actual refurbishment states as an application of the software SimStadt will be analysed and compared to monitoring data.

Previous works by the authors analysed the deviations between measured and calculated values for a new build low energy city quarter of Scharnhauser Park/Germany, in which the buildings had high energy efficiency standards and were built over a period of approximately 10 years. That is why the building characteristics are quite well known and the rehabilitation state could not have an influence on these deviations [11]. The analysis done showed a reasonable correlation for many buildings, but there were also many buildings with extreme deviations between measured and simulated heat demand larger than 100%, which led to an average deviation between 30 and 40%. These high deviations were mainly caused by the lack of detailed geometrical information regarding the building height for many buildings. This fact encouraged the author for further analysis within this paper.

Data description

The city of Essen as the coming European Green Capital 2017 is very committed to climate protection issues and delivered the initial data for the present study, which is divided in a two-stage analysis; the first one is based on six single buildings, the second one on four city districts in Essen.

Single building analysis

The single building analysis is based on six case study buildings representing different building categories and years of construction (see Table 1). Each of the buildings represents a typical building decade of Essen.

Geometrical data

The case study buildings were geometrically modelled in the CityGML (http://www.opengeospatial.org/standards/citygml) standard. Such three dimensional models are widely available in Germany. Combined with further building information on age, usage type and construction type they represent a powerful database for urban energy demand estimation. CityGML as an OGC standard is a common information model to represent, store and exchange 3D city models. The models can be available in different Levels of Detail (LoD) defined as follows (see also Fig. 1, left):

- LoD1: Extrusion solid
- LoD2: Geometrically simplified outer shell and simplified roof shapes
- LoD3: Geometrically detailed outer shell represented by detailed outer surfaces and detailed roof shapes
- LoD4: Geometrically detailed outer shell and interior is represented by detailed outer and inner surfaces and detailed roof shapes [http://en.wiki.quality.sig3d.org/index.php/Modeling].

The city of Essen delivered CAD-files in LoD2 and LoD3 for all six case study buildings. Before using these files with the different software packages, they had to be transferred in the respective data formats. LoD2 and LoD3 models were extracted directly from the given CAD data sets. A LoD1 model was retrieved from the available LoD2 model: The LoD1 building model uses the mean-height bounding box of the LoD2 building

Table 1 List of reference buildings

Building no	Building type	Year of construction
1	Multi-family house (MFH)	1907
2	Multi-family house (MFH)	1954
3	Multi-family house (MFH)	1910
4	Multi-family house (MFH)	1955
5	High tower (HH)	1974
6	Single-family house (EFH)	2004

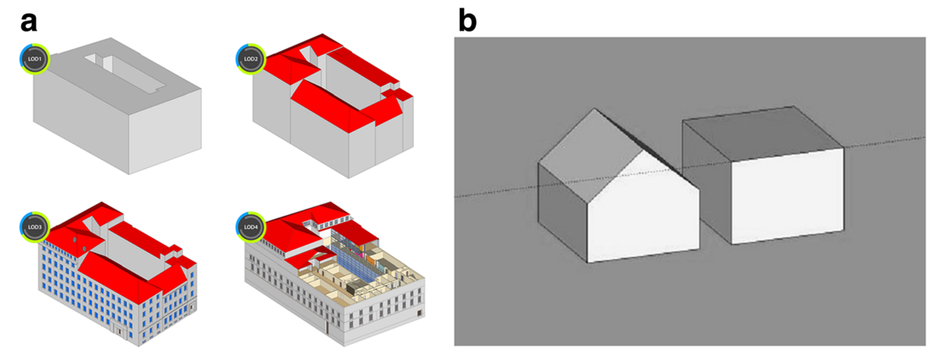

Fig. 1 Levels of Detail (*left*); Creating LoD1 out of LoD 2 (*right*)

model, i.e. the arithmetic average between eaves and ridge height (see Fig. 1, right).

The authors have already carried out a range of studies in urban areas to compare the monthly energy balance method with monitoring data (Karlsruhe Rintheim, Ludwigsburg Grünbühl, Rotterdam, Scharnhauser Park Ostfildern and others). It has been shown that on a city quarter level, the difference between simulations and monitoring is typically below 10%, but can be higher on an individual building level [12].

Physical data

The building physics properties like U-values (heat transfer coefficients) of the building elements were assessed from the IWU building typology library [17] further developed in the TABULA [18] project. Here buildings are classified as to their type (e.g. multi-family house, single-family house or high tower) and building age class. Building age (or year of construction) and building type for the six reference buildings were delivered by the city of Essen to link the buildings to the respective building typology library.

Usage and operating parameters (occupancy time, air change requirement, set-point temperatures, etc.) have been determined by mapping building function codes from ALKIS (Authoritative Real Estate Cadastre Information System [http://www.adv-online.de/icc/exteng/nav/443/4431019a-8c61-b111-a3b2-1718a438ad1b&sel_uCon=7f770498-bd6a-ef01-3bbc-251ec0023010&uTem=73d607d6-b048-65f1-80fa-29f08a07b51a.htm]) with the reference building usages of building energy norm DIN V 18599 (ISO 13790).

Meteorological data

The meteorological data used for the simulation are test reference years (TRY) weather data delivered by German Meteorological Service for the city of Essen, which are available in monthly as well as hourly time resolution.

Validation

As no reliable monitoring data were available for the individual buildings in the town of Essen, a simulation tool (see below the simulation tool description) comparison was used here to check the results. Validation with monitoring data was then done on a city quarter aggregation level. Care was taken on using the same input data for all models.

Software tools

The building scale analysis was done to check the accuracy of the urban modelling approach by comparing the SimStadt results with the simulation tool TRNSYS (http://www.trnsys.com/). The settings, like physical parameters, user behaviour etc. were kept the same in order to make calculations comparable.

SimStadt Since 2012, the urban energy simulation platform SimStadt, jointly developed by the research centers for Sustainable Energy Technology (zafh.net) and for Geo-informatics at the University of Applied Sciences Stuttgart and in cooperation with the companies M.O.S.S. GmbH (https://www.moss.de/) and GEF AG (http://www.gef.de/en/home/), aims at supporting urban planners and city managers with defining and coordinating low-carbon energy strategies for their cities with a variety of multi-scale energy analyses. Two particular features mark the SimStadt design: It is based on the open 3D city model standard CityGML and its workflow-driven structure is modular and extensible. SimStadt allows to automatically calculate the monthly heat demand of every building of a 3D city model, using the standardized steady state calculation (thermal monozone) of DIN V 18599 (ISO 13790). Mandatory input data are just the 3D city model itself and the building

Table 2 List of city districts

District number	Construction period	Characteristic
Webest1	until 1918	predominant Wilhelminian style buildings, multi-family houses
WeBest2	1949-1959	predominant post-war buildings, multi-family houses
Webest3	after 2004	predominant new buildings, single family houses
Webest4	1970-1977	predominant large residential units, multi-family houses

usage respectively the building function to link the buildings to the corresponding libraries.

TRNSYS TRNSYS is a modular simulation tool primarily used for transient system and building simulations with a history (of development) over 30 years internationally. In this study, TRNSYS was used for a dynamic building simulation used as reference for SimStadt. The geometry, building physics and also parameters like occupation and internal gains of each reference buildings were specified in the integrated building interface TRNBuild. For the transferability the same cubature (geometric data from the original CAD-datasets) as for the SimStadt simulations were used. Moreover, other parameters such as temperature set points and internal gains etc. were kept the same due to the comparability of both simulation methods.

Both simulation tools also used the same weather dataset (tmy3-hour).

City District analysis

The second part of the analysis represents an analysis of four city districts in Essen (see Table 2). By comparing aggregated measured consumption values and simulation results of heat demand, this analysis section also gives an indication on the accuracy of the urban simulation platform SimStadt.

Geometrical data

Analogous to the single building scale analysis, the reference districts were chosen according to their predominant building types to cover a large range (see Table 2).

The city of Essen also delivered 3D city models for the selected reference districts (see Fig. 2 below).

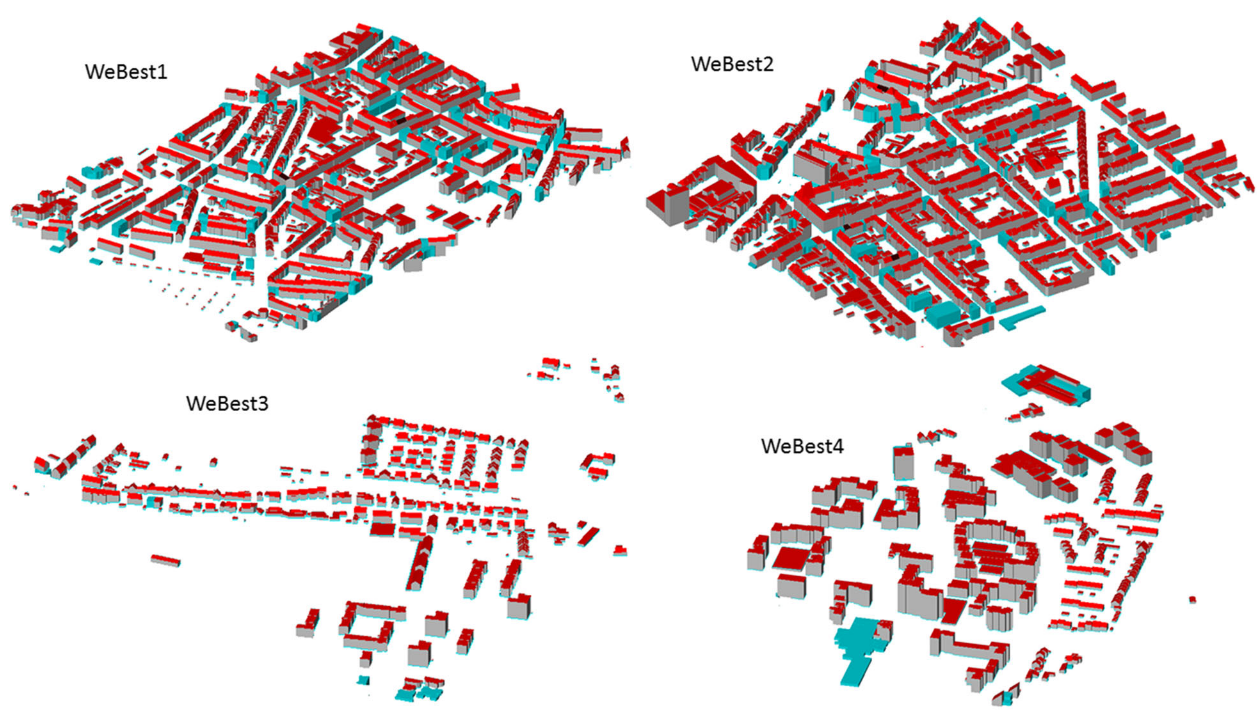

Fig. 2 CityGML- model visualization for four districts of Essen (using FZK-Viewer of Karlsruhe Institute of Technology KIT)

Physical data

Again, the building physics properties like U-values (heat transfer coefficients) of the building elements were assessed from the IWU building typology library further developed in the TABULA project.

Monitoring data

The city of Essen delivered measurement data across all reference districts. The data were provided as energy consumption values (gas and electricity in case of night storage heating systems) aggregated at building blocks. Due to reasons of data protection, the consumption values were pooled for each district.

Meteorological data

The meteorological data used for the simulation are test reference years (TRY) weather data delivered by German Meteorological Service for the city of Essen, which are available in monthly as well as hourly time resolution.

Software Tools

At district scale, SimStadt simulation results should be compared with measurement data. The database for SimStadt simulation on the whole does not vary between single building calculation and a large number of buildings, as SimStadt performs in terms of batch processing.

Results

Building scale

Influence of geometrical parameters (Levels of Detail)

The SimStadt platform was firstly used to compare the results for different Levels of Detail (from LoD1 to LoD3) regarding geometries. Figure 3 shows the comparison between LoD1, LoD2 and LoD3 for all case study buildings. LoD3 in this case differs from LoD2 only by the real window areas compared to standard values from the norms. Neither the real positioning of window areas nor overhangs and dormers have been taken into account in this study.

The deviations between LoD1 and LoD2 is obvious due to the varying wall/roof ratio. SimStadt automatically assigns U-values from its building physics library for different roof forms depending on the respective geometry. A building model in LoD1 in this context gets another U-value assigned as e.g. a saddle roof. Similar considerations apply to internal gains. That is why (SimStadt) simulation results improve in accuracy using LoD2 compared to LoD1. However, the deviation between LoD1 and LoD2 is smaller or equal to 10% except for building 5 (no deviation is seen as this building has a flat roof).

This corresponds to the results of a study in Ludwigsburg, Germany where the Mean Absolute Percentage Error (MAPE) of all building Energy Reference Areas reached 9.2% between LoD1 and LoD2 [12].

The deviation between LoD2 and LoD3 ("real" window/wall ratio) is also smaller or equal to 6% in case of all buildings as SimStadt overestimates the demand for LoD3 compared to LoD2. This surprisingly is due to the fact that LoD3 in this analysis throughout corresponds to lower window/wall ratios as in case of LoD2 with standard values out of the norms. This on the one hand leads to a lower median U-value for the whole building because wall constructions normally transmit less heat than windows do. However, that effect on the other hand is more than offset by lower

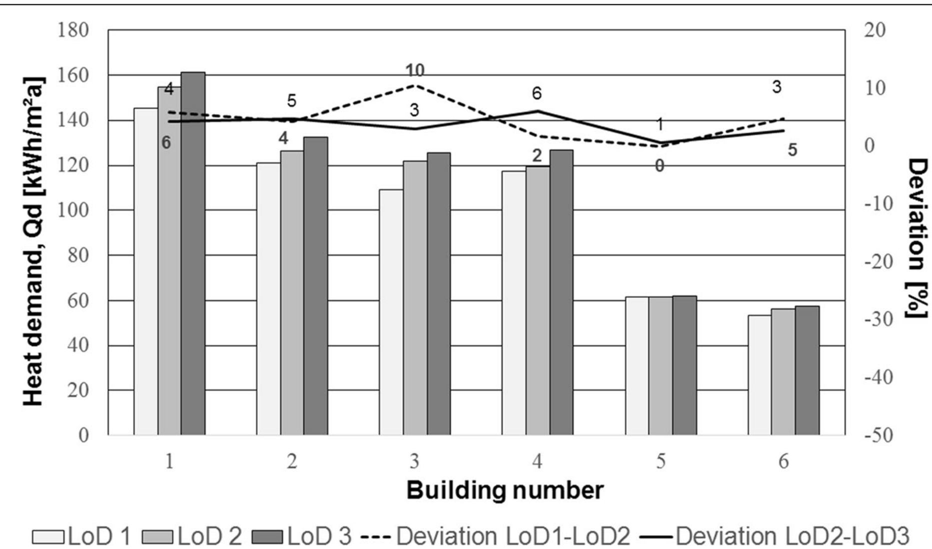

Fig. 3 Comparison of specific heat demand by varied LoDs using SimStadt

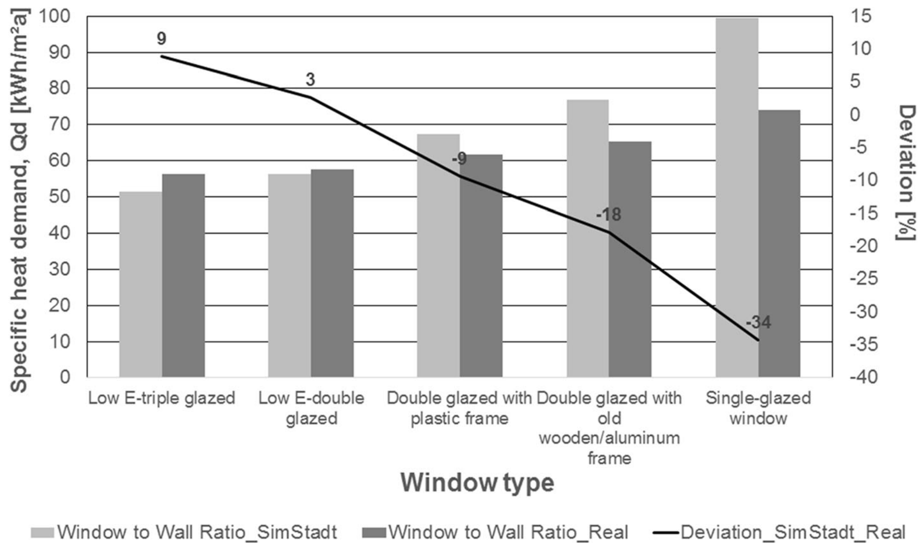

Fig. 4 Variations of the window to wall ratio and window type for the building 6

solar gains and results in an overall higher heat demand for LoD3.

The influence of the window/wall ratio as well as the window type is shown on the example of building 6 (see Fig. 4). Window to wall ratio here means the actual window to wall ratio taken from the construction files. Unless otherwise known, SimStadt uses standard default values corresponding to the German building typology.

Comparison between SimStadt and TRNSYS

SimStadt and TRNSYS differ not only in effort on entering input data or defining e.g. wall constructions within the models, but also in the modelling approach with monthly energy balances in SimStadt and hourly energy demand simulations in TRNSYS. Comparing SimStadt and TRNSYS for the less detailed building geometry models (LoD1), Fig. 5 shows the deviations obtained. Despite identical input data, results from TRNSYS and SimStadt differ by up to 17%.

The comparison between SimStadt and TRNSYS for more detailed building geometry models (LoD2) is shown in Fig. 6. Despite identical input data, results from TRNSYS and SimStadt differ by up to 24%.

In both comparisons, the deviations by older buildings (Building 1 to Building 4) are much lower than in case

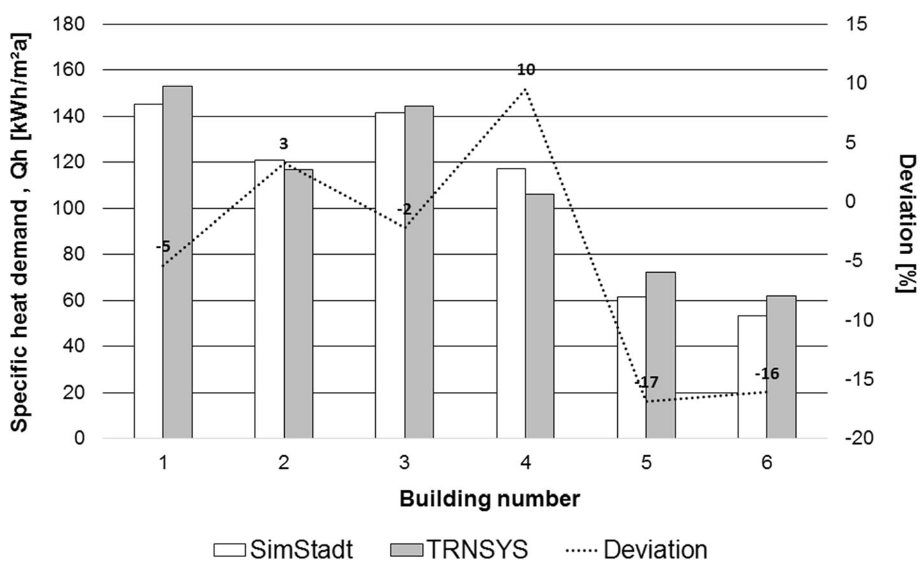

Fig. 5 Comparison between the SimStadt and TRNSYS simulation for the specific heat demand (LoD1 geometry)

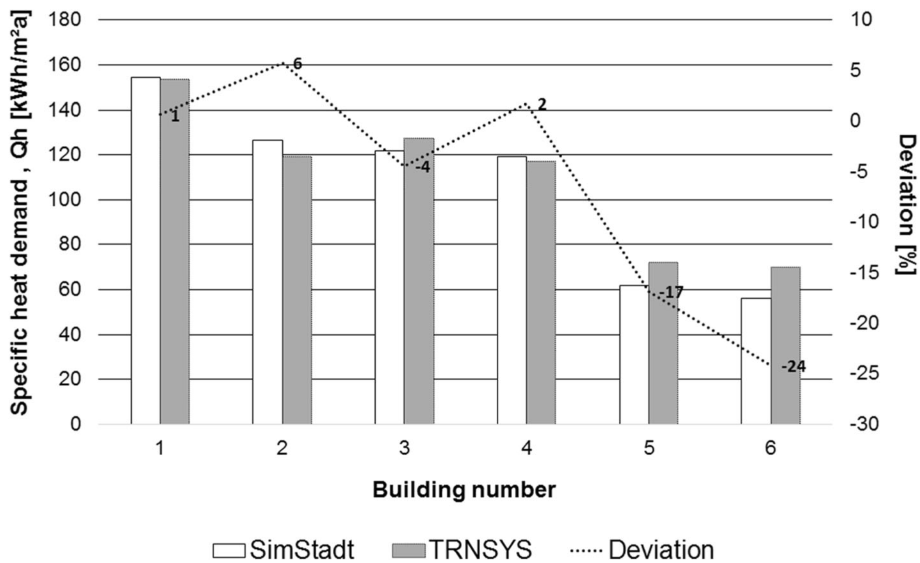

Fig. 6 Comparison between the SimStadt and TRNSYS simulation for the specific heat demand (LoD2 geometry)

of new buildings (Building 5 and Building 6). This is in keeping with the views that the monthly energy balance in general overestimates heat demand for older buildings whereas it underestimates heat demand for more efficient buildings. Monthly simulation values underline the impression that the monthly energy balance method underrates heat gains in older buildings (see Fig. 7 for building 1 built in 1907) and credits them too much in energy efficient buildings (see Fig. 8 for building number 6 built in 2004).

Comparing both software packages (SimStadt and TRNSYS), there are some advantages for the urban simulation platform SimStadt:

- SimStadt can provide an automatic calculation (static energy balance) of heat demand at urban scale as well as at single building scale (scalability without loss of accuracy because of batch processing), while TRNSYS enables detailed dynamic simulation but only for single buildings

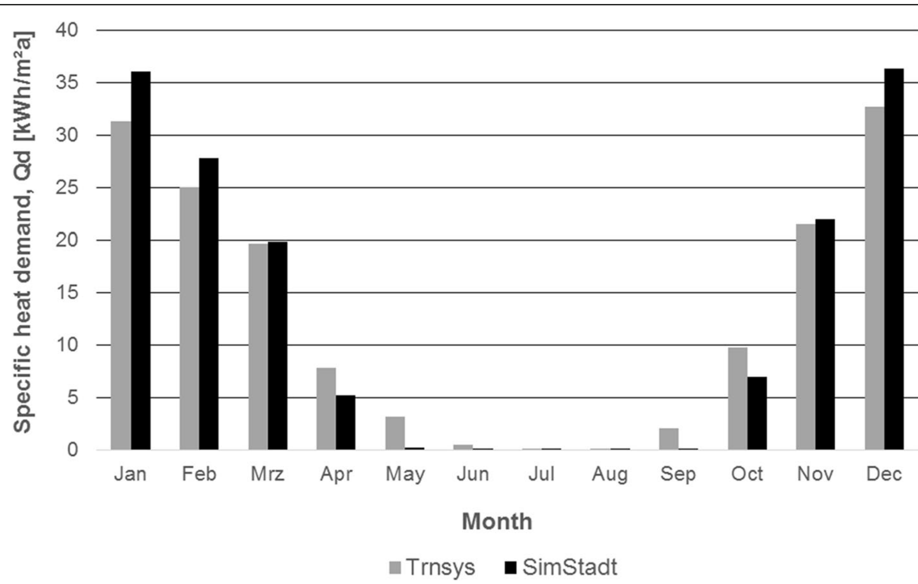

Fig. 7 Monthly comparison between SimStadt and TRNSYS for Building1 (LoD2)

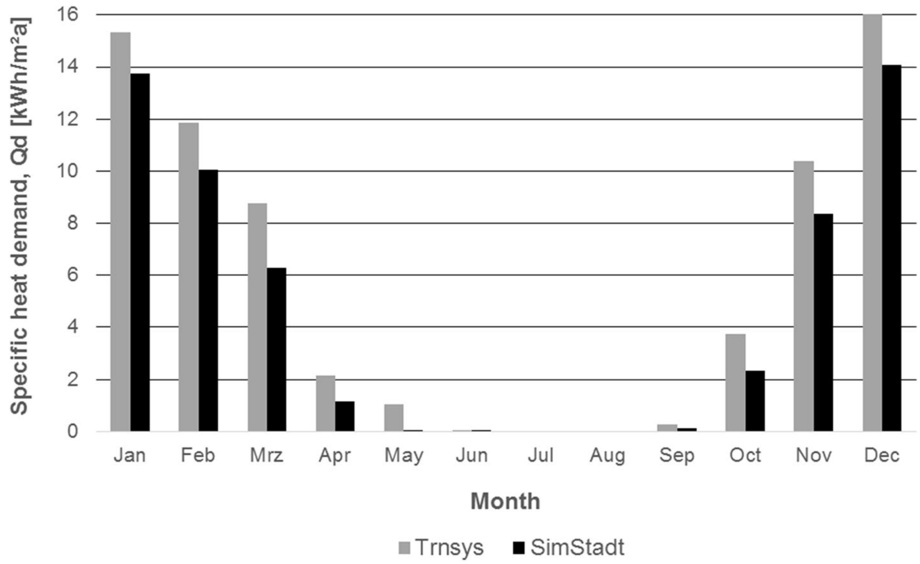

Fig. 8 Monthly comparison between SimStadt and TRNSYS for Building1 (LoD2)

with higher accuracy because internal storage capacities are more adequately modelled.

- Data input preparation in SimStadt is reduced to preparing the CityGML file with information regarding building age and building usage; in case of TRNSYS, all data inputs must be put manually in detail which is time consuming. In an application over several buildings or whole districts, SimStadt performs much faster.

District scale

Following, the analysis of four districts in the city of Essen with regard to the year of construction, building usage/typology as well as number of floors was done in

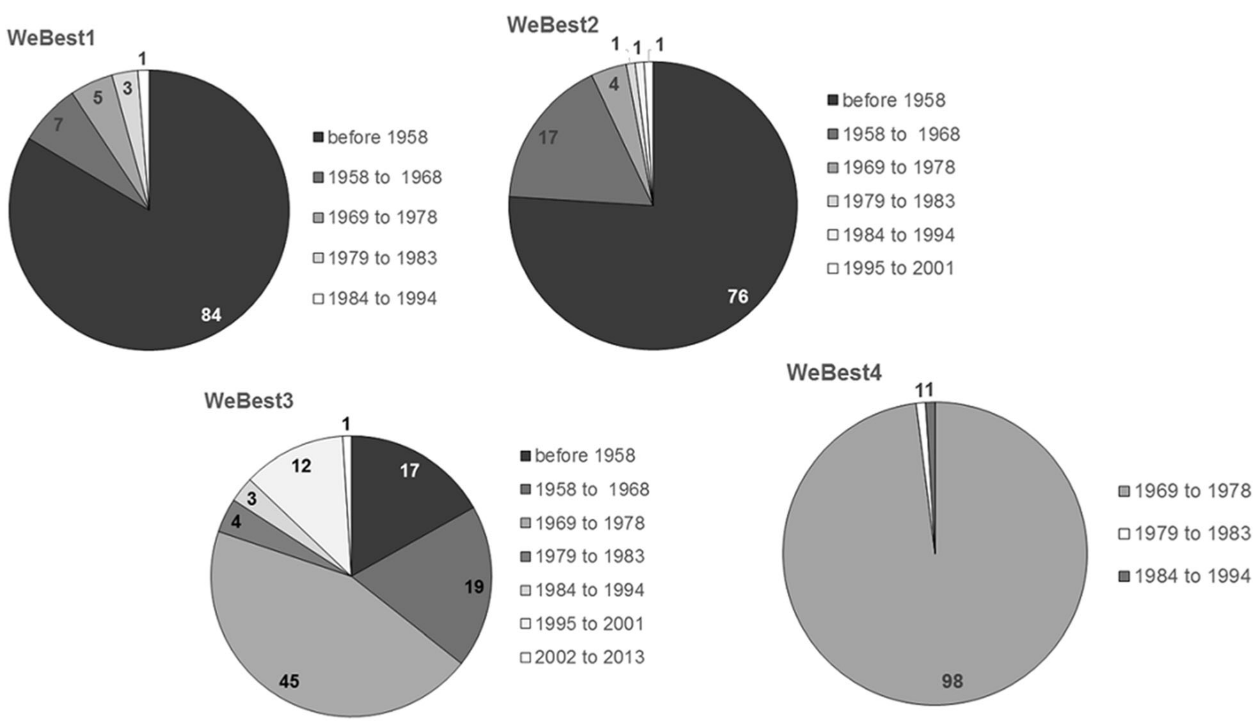

Fig. 9 Year of construction

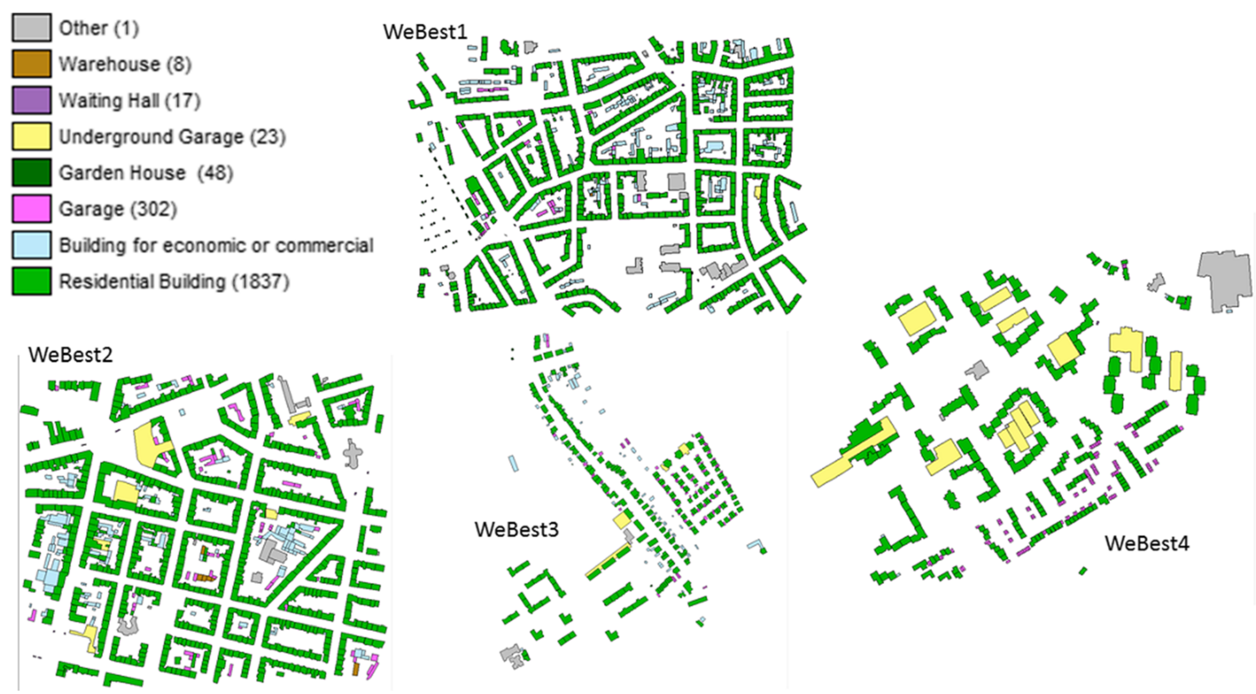

Fig. 10 Thematic maps for the building usage/typology

order to see the structural differences between all districts.

Year of construction

As shown in Fig. 9, the year of construction of the buildings differs. In the districts WeBest1 and WeBest2 most buildings (more than 70%) were built before 1958. Most buildings in the districts WeBest3 and WeBest4 were built between 1966 and 1978.

Building usage/Typology

In all districts, the majority of the buildings is in residential use (see green buildings in Fig. 10).

As shown in Table 3, there is also a quite high amount of commercial buildings, especially in the districts WeBest1 and WeBest3 (about 19%). In the districts WeBest3 and WeBest4 there are many adjoining buildings such as garages, which haven't been taken into consideration by the calculation of heat demand.

Table 3 Classification of the building usage for each district

District	WeBest1	WeBest2	WeBest3	WeBest4
Building Usage	Number of buildings [%]			
Residential	69	73	54	60
Commercial	19	14	19	2
Garages/Public parking	3	6	24	36

Regarding only the residential buildings, the percentage ratio of each building type differs from district to district. As Table 4 shows, most buildings are multi-family houses in the districts WeBest1, WeBest2 and WeBest3. In the districts WeBest1 and WeBest4 exhibit high amounts of big multi-family houses, within WeBest 3 and especially in WeBest4 there is a significant amount of high towers.

Number of floors

Considering the number of floors (see Table 5), in the districts WeBest3 and WeBest4 most buildings are

Table 4 Classification of the residential buildings for each district

District	WeBest1	WeBest2	WeBest3	WeBest4
BuildingType	Heated area [%]			
EFH[a]	4	2	6	3
RH[b]	11	16	15	7
MFH[c]	50	51	60	14
GMH[d]	34	28	1	42
HH[e]	1	3	19	34

[a] EFH – Single family houses
[b] RH – Row-houses
[c] MFH – Multi-family houses
[d] GMH – Big multi-family houses
[e] HH – High towers

Table 5 Classification of the number of floors for each district

District	WeBest 01	WeBest 02	WeBest 03	WeBest 04
Number of Floors	Number of Buildings [%]			
1	29,9	25,8	68,0	56,9
2	7,1	15,5	21,2	15,5
3	41,7	36,4	3,4	1,2
4	20,3	17,7	5,7	3,5
5	0,3	3,0	0	1,7
6	0	0,4	0	8,7
7	0,1	0,2	0	2,9
8	0	0,1	0,7	4,1
Over 8	0	0,1	0	2,1

single-storey buildings. In the older districts WeBest1 and WeBest2, most buildings are three or four storeys high.

Comparison between heat demand and heat consumption

The comparison between the SimStadt heat demand and the measured heat consumption was done separately for each district (see Fig. 11). As SimStadt calculates the net heat demand and the monitoring data were given as final energy consumption values, the SimStadt simulation results had to be applied with a factor for efficiency of the heating systems (88% for gas heating systems, 83% for electrical night storage heating systems) to achieve comparability.

Table 6 Considered refurbishment ratios for each district

District	Refurbishment ratio [%]
WeBest01	62,5
WeBest02	50,0
WeBest03	68,1
WeBest04	57,6

The first heat demand simulation was done using the SimStadt urban simulation platform without consideration of any refurbishment scenario. This logically led to a significant overestimation of the heat demand values in all districts. The second heat demand simulation was done by considering statistical refurbishment ratios taken from a representative survey in Essen (https://media.essen.de/media/klimawerkstadtessen/klimawerkstadtessen_dokumente/netzwerk_1/Potenziale-fuer-energieeffizientes-Modernisieren-in-Essen.pdf), which are shown in Table 6.

Refurbishment scenarios can easily be defined within the SimStadt graphical user interface and calculated automatically. As there were no detailed information about the refurbishment measures in the survey, a moderate package ("medium") was assumed considering oldest buildings first to be refurbished. This second calculation than gave heat demand results, which are very close to the measured heat consumption in all districts, except district WeBest2. The reason for these huge deviations

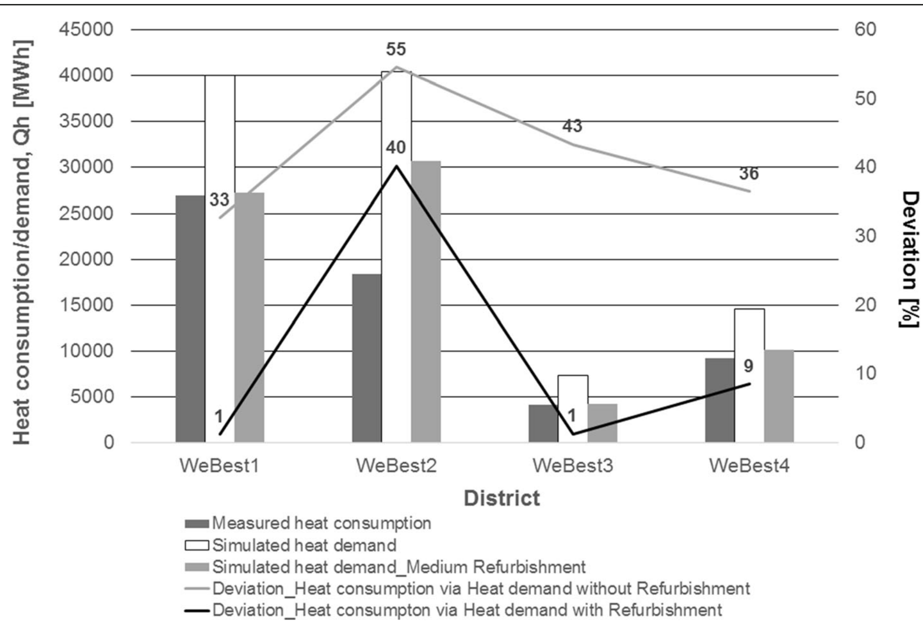

Fig. 11 Comparison between SimStadt heat demand calculation and measured heat consumption (including hot water demand and consumption)

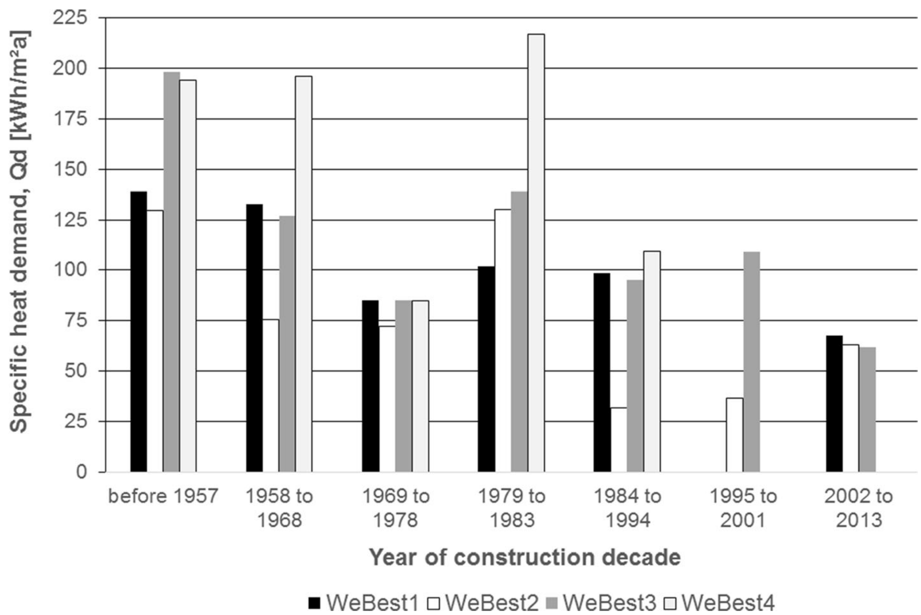

Fig. 12 Specific heat demand (space heating) as function of year of construction decade

might be due to the fact that the survey only gives refurbishment ratios for larger urban districts whereas parts within the urban district may deviate significantly. For WeBest2 the actual refurbishment rate may be higher than the adopted refurbishment rate for the entire district.

A deeper analysis of the four districts respectively building periods showed that older building classes are characterized by higher heat demand values (see Fig. 12).

Figure 13 shows that more compact building forms such as high towers and multi family houses accompany with lower heat demand values because of the beneficial ratio of surface to volume (A/V ratio).

Figure 14 is in the same direction as the bigger and more dense in terms of higher numbers of floors buildings are, the lower the specific heat demand per squaremeter and year.

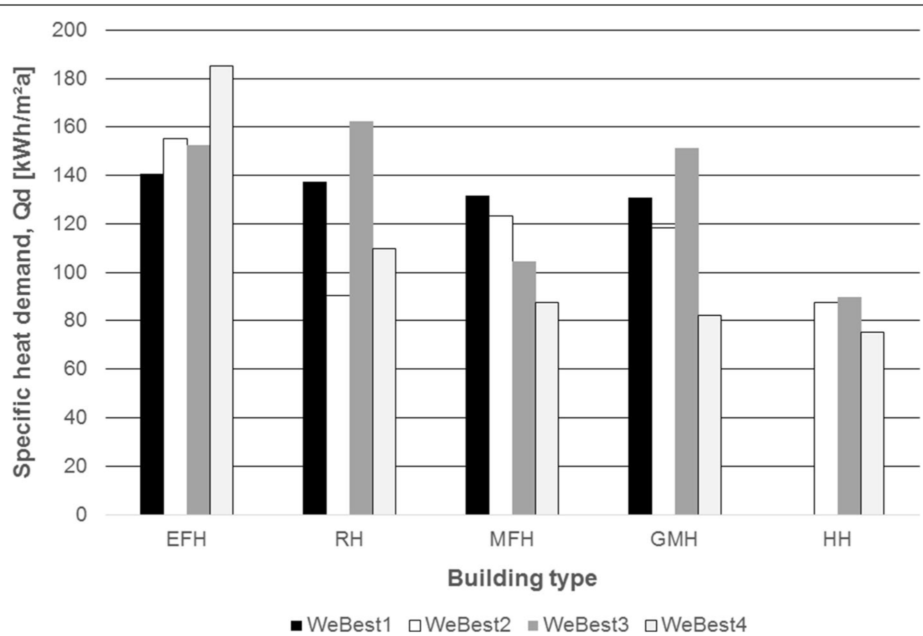

Fig. 13 Specific heat demand (space heating) as function of building type

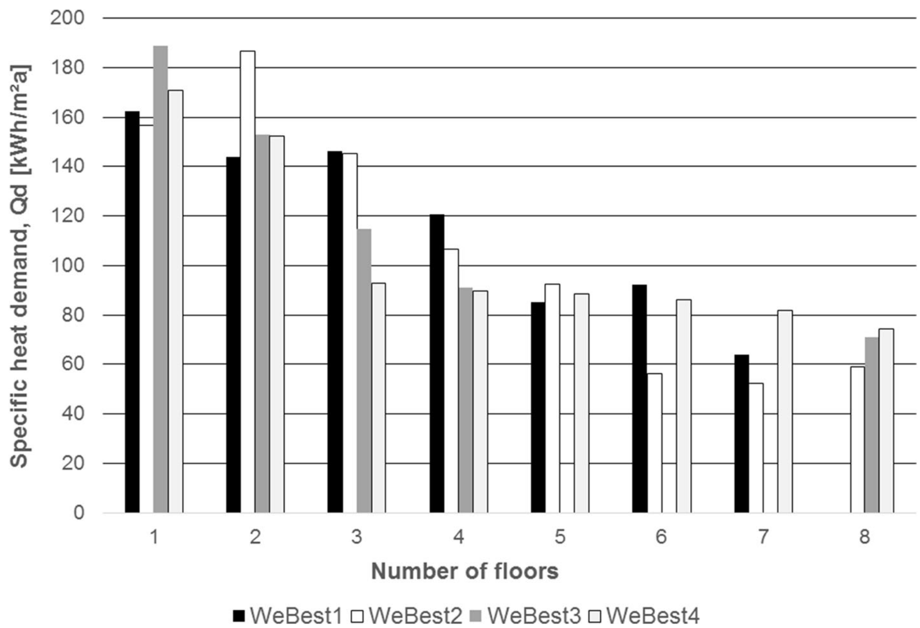

Fig. 14 Specific heat demand (space heating) as function of number of floors

Conclusions

This paper presents a method for urban scale simulation of the heat demand. To validate the monthly energy balance method used in the urban simulation platform SimStadt, the results of six different building typologies were compared with dynamic building simulations.

The simulation method comparison resulted in a reasonable agreement for four buildings out of six (deviation </= 10%) and larger deviations in two cases (17 and 24%). Preparing and transferring building models to TRNSYS proved to be timeintensive, while the SimStadt process is fully automated.

At district scale, the SimStadt results were compared with aggregated consumption values. When realistic refurbishment percentages were included in the urban simulation, the deviation was less than 9% in three districts and 40% in one of the four districts. This high deviation might due to differences in detail relating to the survey on refurbishment states per district.

The analysis showed that heat demand forecast with the urban simulation platform SimStadt based on 3D city models and building construction data bases as a function of building type and year of construction is suitable for both single buildings and city (district) scale without loss of quality by scaling up the granularity.

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Authors' contributions

HFT Stuttgart coordinated the research work and evaluated the parametric study in different scenarios by employing urban simulation platform SimStadt (www.simstadt.eu), INSEL software (www.insel.eu) and TRNSYS (www.trnsys.como) and wrote the paper. The city of Essen delivered building data (geometries, semantics) for the six case study buildings as well as the aggregated energy consumption data for the four analysed districts. All authors read and approved the final manuscript.

Competing interests

The authors declare that they have no competing interests.

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