Development and evaluation of digital twins for district-level heating energy demand simulation

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Abstract. To achieve the aim of a CO_2 neutral built environment in 2050, a large part of the existing housing stock will have to be energetically retrofitted. It has been noted that a neighbourhood-oriented approach will be necessary for the feasibility, affordability and timeliness of this aim. Considering that many different stakeholders are involved in renovations at the neighbourhood level, and that multiple neighbourhoods will have to be retrofitted at the same time, efficient working methods are imperative. To facilitate the design, construction and operation of the new energy infrastructure, a prototype for a digital environment (digital twin) is developed for four Dutch pilot neighbourhoods. In this contribution, the authors will describe a procedure to convert publicly available geo-information to a CityGML model, which is used to simulate the monthly and annual space heating energy demand using SimStadt. To assess model fidelity, the simulation results are compared with publicly available aggregated energy use data. A procedure will be described to split the measured natural gas use into gas usage for space heating, domestic hot water and cooking. It is found that the simulation tends to overestimate the energy demand for space heating by 4 - 125%. This difference is largely explained by the manner in which the thermal properties of the buildings are estimated. In addition, the homogeneity of the neighbourhood in terms of the different building functions present has an impact on the accuracy of the simulation. Finally, possible invalid assumptions concerning setpoint temperatures and internal heating loads are of interest. It is concluded that more accurate simulation results will be obtained through the use of current input data. Most importantly: (i) reliable information on the buildings' current thermal properties through e.g. energy audits, and (ii) reliable information on the buildings' setpoint temperatures and internal heating loads through on-board monitoring systems.

Keywords. Energy transition, digital twin, SimStadt, neighbourhood-oriented approach
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1. Introduction

To achieve the aim of a CO_2 neutral built environment in 2050, a large part of the existing housing stock will have to be energetically retrofitted. It has been noted that a neighbourhood-oriented approach will be necessary for the feasibility, affordability and timeliness of this aim [1].

Considering that many different stakeholders are involved in renovations at the neighbourhood level, and that multiple neighbourhoods will have to be retrofitted at the same time, efficient working methods are imperative. To support the process, a Fieldlab Digitalization of the Energy Transition Twente (FiDETT) has been established, in which local and regional authorities, companies and educations and research institutions participate. Its focus is on collectively developing the necessary knowledge and skills to facilitate the neighbourhood-oriented approach and to disseminate the knowledge into practice through educational programmes.

To facilitate the design, construction and operation of the new energy infrastructure, a prototype for a digital environment (digital twin) is developed for four Dutch pilot neighbourhoods. The idea is that different stakeholders involved in the energy transition of a neighbourhood could access such a digital environment, and extract relevant information for their activities.

In this contribution, the authors will focus on a specific aspect of the digital twin, namely heating energy demand simulation using the SimStadt [2] software.

2. Research Method

2.1 Description of model construction

To create a model which can be used for simulations in SimStadt, it is necessary to collect information on the geometry of the buildings within a neighbourhood, as well as their year of construction and function. In this project, this information has been retrieved from the BAG 3D dataset [3].

The geometrical information in the BAG 3D dataset is based on a point cloud. As a result, the dataset contains ground levels and roof heights at different percentiles. As a standard, the building height is estimated as the 75th percentile of the roof height, minus the zeroth percentile of the ground level.

The ArcGIS Pro software was then used to construct three-dimensional LOD1 models of the relevant neighbourhoods. It was found that post-processing of some building geometries is necessary, as some building heights are strongly overestimated (see Fig. 1). In addition, the building functions in the dataset are replaced by the relevant Alkis codes [4], which can be read by SimStadt.

The resulting model is exported as an ESRI Shapefile, and converted to a .gml file format through editing using the FME software. The CityGML file can be read by SimStadt.

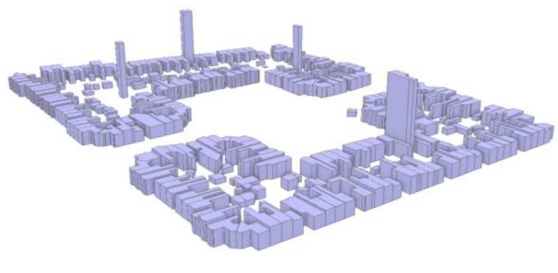

Fig. 1 – Overestimation of some building heights

2.2 Simulation using SimStadt

The SimStadt software (version 0.10.0) is used to simulate the monthly average heat demand of all buildings in the neighbourhood. This is done through the application of a monthly energy balance to each building in the neighbourhood, in which the relevant heat gains (i.e. internal and solar gains) and losses (i.e. transmission, infiltration and ventilation) are determined. When the total heat loss exceeds the total heat gains, this results in a monthly heating demand. In addition to the building geometry described in Section 2.1, the year of construction, building function and climate (year) are of importance.

In the PhysicsPreprocessor, thermal properties are assigned to the various buildings based on year of construction, building function and type of residential building, using a Physics Library. Four building physics libraries are available: A German one, one for New York City (NYC), a Dutch one developed by SimStadt, and a Dutch one developed by Saxion Chair of SBT. The two Dutch libraries are based on TABULA [5,6] and are used in the current project.

In the UsagePreprocessor, usage profiles are assigned to the various building functions using a Usage Library. This includes user density (persons m^{-2}), internal heat gains, setpoint temperatures (default 20 °C, night reduction to 16 °C) and use of hot tap water.

In the WeatherProcessor, weather data is used to calculate heat losses and gains, and the resulting energy consumption for heating.

2.3 Validation of simulation results

To validate the simulation results, these are compared with the actual heating energy consumption of the buildings for the districts under consideration.

The network operators in the Netherlands make data available with regard to the annual energy consumption of small-scale connections per postal code area [7]. Since most buildings in the Netherlands are currently heated with natural gas, the simulation results are compared with the natural gas consumption of the relevant postal code areas. The so-called standard annual consumption is reported, which includes the energy consumption of the buildings in the postal code area, corrected for gas quality and a normalized climate year [8].

Since natural gas is not only used for space heating, but also for domestic hot water (DHW) and cooking, the gas consumption must be split for these purposes (see Tab. 1). The gas used for space heating (SH) is then derived by subtracting the gas use for cooking and DHW from the total gas consumption.

Tab. 1 – Gas consumption for cooking and DHW

Use	Amount	Source
Cooking	37 m^3 per household	[9]
DHW	270 m^3 per household	[10]

For the conversion of m^3 of natural gas into kWh of heat, an average boiler efficiency of 104% on the net calorific value (31.65 MJ m^{-3}) is assumed.

2.4 Cases

Four Dutch neighbourhoods are simulated: Bruggenmors, Twekkelerveld, Bothoven and De Nijverheid. A sensitivity analysis (Section 3.1) is carried out on a part of Twekkelerveld, namely Bruggenmors. It consists exclusively of residential buildings. The median year of construction is 1930 (see Tab. 4).

3. Results

Firstly, a sensitivity analysis is carried out to assess the impact of varying building height, building physical properties and setpoint temperatures on the simulation results for Bruggenmors (Section 3.1). In Section 3.2, the heating energy demand is simulated for four neighbourhoods.

3.1 Sensitivity analyses

As discussed in Section 2.1, the building height is estimated as the 75th percentile of the point cloud, minus the ground level. Using this method, the building heights of several buildings are strongly overestimated (see Fig. 1). More realistic building heights are obtained through manual correction, see Tab. 2.

Tab. 2 – Building heights Bruggenmors

	Roof75	Roof75 corrected	Roof50
Min.	5.38	5.38	2.63
Mean	7.17	6.83	5.35
Median	6.84	6.82	5.51
Max.	36.81	8.20	6.98

Fig. 2 shows that the annual energy demand for space heating is overestimated for all three used building heights, compared to the data from the network operator (Enexis). The overestimation is the smallest when using the Roof50 data, as this simulates the smallest building volume to be conditioned.

As discussed in Section 2.2, several building physics libraries are available. Fig. 3 shows the simulated annual heating energy demand for two different Dutch building physics libraries (NL SimStadt and NL SBT). The energy demand for space heating is overestimated in both cases. The simulation results are almost the same, but the overestimation is slightly larger when using the NL SBT building physics library. This indicates that the NL SimStadt library uses slightly more favourable values for the physical properties of the buildings, such as thermal insulation and air permeability.

As discussed in Section 2.2, the standard usage profile in SimStadt assumes a setpoint temperature of 20 °C, with a night setback to 16 °C (hereafter referred to as 20 °C – 16 °C). Fig 4 shows the impact of using different setpoint temperatures on the simulated annual heating energy consumption. The space heating energy demand is overestimated in all cases. Naturally, the overestimation is smallest when using the lowest setpoint temperatures (18 °C – 15 °C).

It is concluded that both the building height and setpoint temperatures have a significant impact on the simulated energy use for space heating. The use of the two different building physics libraries has only a very small impact on the obtained results. In the next section, the datasets/values in Tab. 3 are used for the simulations.

Tab. 3 – Used datasets/values simulation Section 3.2

Variable	Dataset/value
Weather processor	Reference climate year NEN 5060:2018
Building height	Roof75 corrected
Building Physics Library	NL SimStadt
Setpoint temperature	20 °C – 16 °C

3.2 Heating demand of case neighbourhoods

Using the inputs as listed in Tab. 3, the results in Tab. 4 are obtained. The annual heating energy demand, comprising both space heating and domestic hot water, is overestimated in all cases, ranging from 3.6% for Bothoven to as much as 124.8% for Twekkelerveld.

Bothoven is a homogenous neighbourhood, comprising only residential buildings. In addition, the median year of construction of the buildings in this neighbourhood (1982) is relatively recent. As discussed in Section 2.2, the thermal properties of the buildings are estimated based on the year of construction. For older buildings, the estimation of the thermal properties is likely to be inaccurate, as these buildings have undergone retrofits, causing an improvement of the thermal envelope. More recent buildings, such as those in Bothoven, have generally not yet undergone (major) renovations, thus the estimated thermal properties will be closer to the actual values.

For the neighbourhoods with older buildings; Bruggenmors, Twekkelerveld and De Nijverheid, the overestimation of the heating energy demand is large. When comparing the two neighbourhoods with the same median year of construction (Twekkelerveld and De Nijverheid), it seems that the homogeneity of the neighbourhood also affects the accuracy of the simulated heating energy demand.

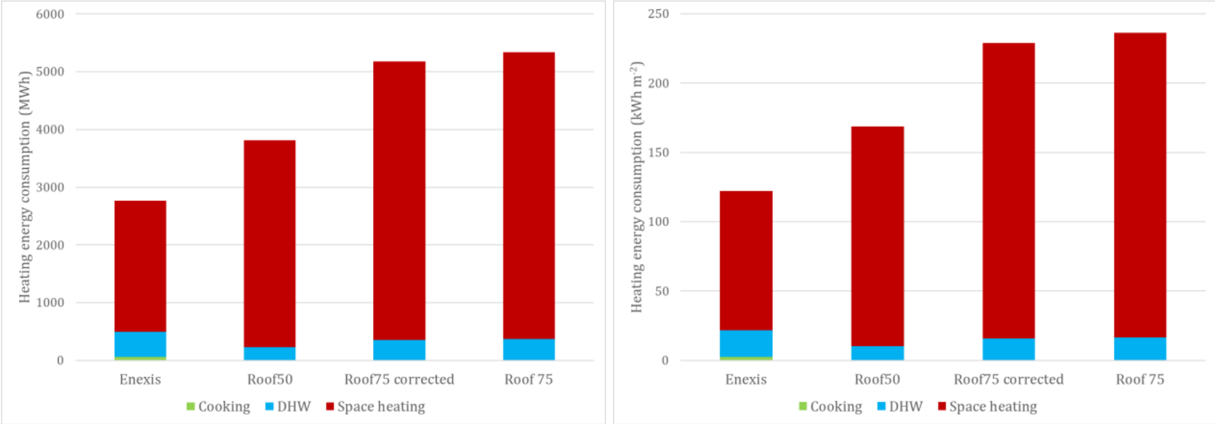

Fig. 2 –Impact of variation of building height on annual heating energy demand in MWh (left) and in kWh per m^2 heated floor area (right)

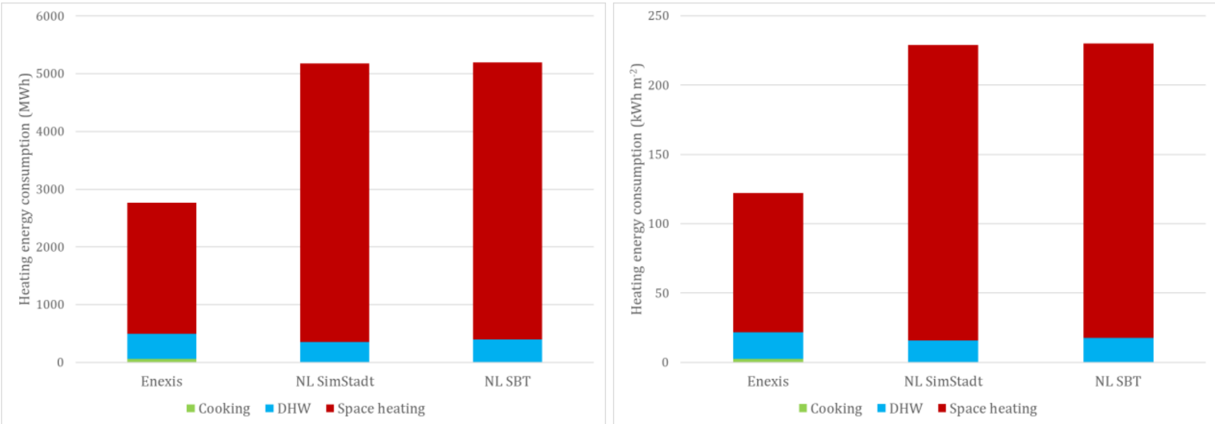

Fig. 3 – Impact of variation of building physics library on annual heating energy demand in MWh (left) and in kWh per m^2 heated floor area (right)

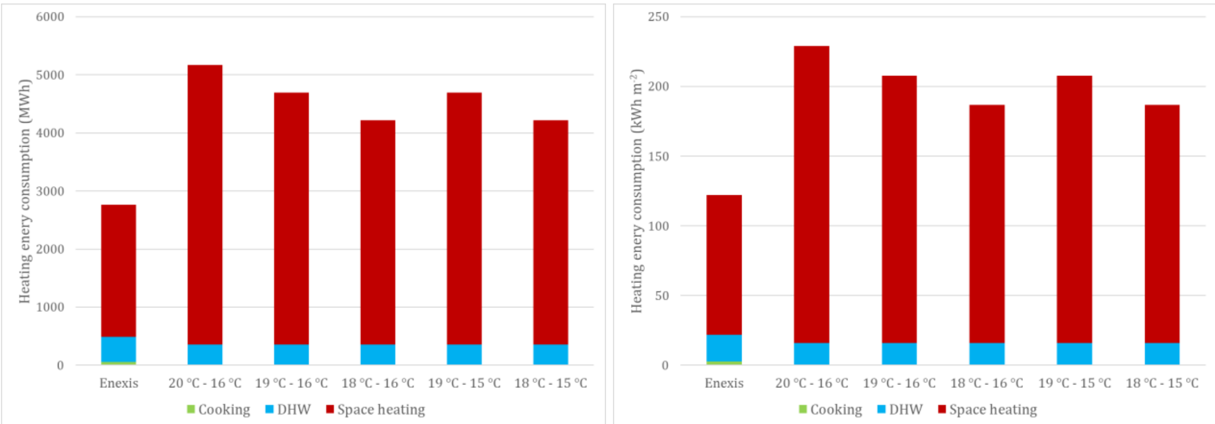

Fig. 4 – Impact of variation of setpoint temperature on annual heating energy demand in MWh (left) and in kWh per m^2 heated floor area (right)

The overestimation of the space heating energy demand (in kWh m^{-2} heated floor area) is even larger than the overestimation of the total heating energy demand (SH + DHW). It must be noted, however, that the approximate heated floor areas, which were derived from the SimStadt models, also contain inaccuracies. In particular in the case of Twekkelerverld, the heated floor area seems to be strongly overestimated, which leads to a lower space heating energy demand in kWh m^{-2} than would be expected based on the characteristics (i.e. year of construction and building functions) of the neighbourhood.

Tab. 4 – Summary of simulation results

	Bruggenmors, Enschede	Twekkelerveld, Enschede	Bothoven, Enschede	De Nijverheid, Hengelo
# simulated buildings	175	3 272 [a]	374	2 124 [a]
# gas connections	175	4 493	374	2 559
Approximate heated floor area (m^2)	22 597	921 732	35 475	374 158
Median year of construction	1930	1948	1982	1948
% residential	100.0%	95.6%	100.0%	98.4%
Measured heating demand (MWh)	2 703	59 580	3 830	36 757
Simulated heating demand (MWh)	5 175	133 922	3 969	62 240
Difference (%)	+91.5%	+124.8%	+3.6%	+69.3%
Measured space heating demand (kWh m^{-2})	100.5	52.6	81.9	81.4
Simulated space heating demand (kWh m^{-2})	213.2	123.1	96.1	149.1
Difference (%)	+112.1%	+134.0%	+17.2%	+83.3%

[a] The neighbourhoods Twekkelerveld and De Nijverheid contain fewer simulated buildings than gas connections, as these neighbourhoods contain apartment buildings. These are simulated as one building, though each apartment has its own gas connection.

4. Discussion

The previous section showed that the simulated heating energy demand of all case neighbourhoods was overestimated. Four limitations of the present study may explain some of these overestimations, both in terms of model construction (simulated heating demand) and validation (measured heating demand).

4.1 Limitations regarding the simulated heating demand

A first limitation of the current study is the use of LOD1 models. Recently, LOD2 models have become available [11]. The use thereof will result in more realistic building volumes, and therefore in more accurate simulations.

4.2 Limitations regarding the measured heating demand

For the validation of the simulation results, measured aggregated gas consumption figures from the network operator were used.

The so-called standard annual consumption is reported, which includes the energy consumption of the buildings in the postal code area, corrected for gas quality and a normalized climate year. The latter was accounted for by using the reference climate year from NEN 5060 in the simulations. However, the correction for gas quality has not been accounted for.

In addition, the total natural gas use was split into gas consumption for space heating, domestic hot water and cooking using standard figures. These do not necessarily represent the actual use in the considered neighbourhoods.

Finally, it was assumed that all buildings in the case neighbourhoods were heated by natural gas. Although this is the case for the majority of the buildings, some will be heated differently. As a result, the measured heating energy demand is actually underestimated, which means that the overestimation in the simulations is not as large.

5. Conclusions

The sensitivity analysis concluded that both the building height and the setpoint temperatures used have a significant influence on the simulated energy use for space heating. The use of the two different building physics libraries has only a very small impact on the obtained results.

By conducting simulations on four case neighbourhoods, it was found that the simulation tends to overestimate the total annual heating energy demand by 4 - 125%. This difference is largely explained by the manner in which the thermal properties of the buildings are estimated. In addition, the homogeneity of the neighbourhood in terms of the different building functions present affects the accuracy of the simulation. Finally, possible invalid assumptions with regard to setpoint temperatures and internal heating loads are of concern.

It is concluded that more accurate simulation results will be obtained through the use of current input data, with respect to: (i) the building geometry (use of LOD 2 models), (ii) reliable information on the buildings' current thermal properties through e.g. energy audits, and (iii) reliable information on the buildings' setpoint temperatures and internal heating loads through on-board monitoring systems.

6. Acknowledgement

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Onderzoek SIA.

7. References

[1] Klimaatberaad. Klimaatakkoord. 2019. www.klimaatakkoord.nl

[2] HFT Stuttgart. SimStadt2. 2021 https://simstadt.hft-stuttgart.de/en/index.jsp

[3] ArcGIS. BAG 3D - Nederland. 2020. https://www.arcgis.com/home/item.html?id=abd5e3c4b173417f8c14f1283dee33c6

[4] Fitzky, M. Vergleichende Analyse verschiedener Methoden und Datensätze zur Berechnung von Energieausweisen von Gebäuden. 2018.

[5] Loga, T., Stein, B., Diefenbach, N. TABULA building typologies in 20 European countries—Making energy-related features of residential building stocks comparable. Energy and Buildings. 2000;132, 4–12.

[6] TABULA WebTool. https://webtool.build11]ing-typology.eu/?c=se

[7] Enexis. Open data. 2021. https://www.enexis.nl/over-ons/wat-bieden-we/andere-diensten/open-data

[8] Enexis. Toelichting bij dataset Kleinverbruiksgegevens. 2018. https://www.enexis.nl/over-ons/-/media/documenten/open-data/toelichting-kleinverbruiksgegevens-open-data-enexis-netbeheer.pdf?modified=00010101000000&la=nl-nl&hash=1A66620D8DBA0D55A55767B507C535BC218B0B14

[9] Milieu Centraal. Inductie kookplaat. 2020. https://www.milieucentraal.nl/energie-besparen/apparaten-in-huis/inductie-kookplaat/

[10] Milieu Centraal. Bespaartips warm water. 2020. https://www.milieucentraal.nl/energie-besparen/duurzaam-warm-water/bespaartips-warm-water/

[11] TU Delft. 2021. https://3dbag.nl/en/viewer

Data Statement

The datasets generated and analysed during the current study are not publicly available but can be made available upon request.