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Impact of building geometry description within district energy simulations

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Abstract

To assess the feasibility of district energy systems as well as to design them in an optimal way, district energy simulations are often deployed, requiring an accurate spatial and temporal quantification of the district energy demand. Geographical information models and systems can provide input data to quantify the district energy demand, but the available levels of detail (LOD) of these data vary significantly between regions. Therefore, this work investigates the usability of LOD1 and LOD2 representations as well as the impact of building geometry within district energy simulations, by quantifying the differences in geometrical and energy characteristics between five variants of LOD1 or LOD2 representations. The most detailed LOD2 representation is thereby used as a reference. The results show that the significantly decreasing accuracy using LOD1 models may be compensated by assuming the roof shape from regional statistics. Also, aggregation of wall and roof components into a limited number of orientations significantly reduces simulation time, while maintaining the accuracy. It is concluded that geographical information models contain a significant amount of useful data, but the error that results from the deployed level of detail must be kept in mind when assessing the simulation results.

Keywords: district energy simulation; district energy demand; CityGML; GIS; LOD1; LOD2

Abbreviations: GIS – geographical information systems, LOD – level of detail, KPI – key performance indicator, RSF – roof shape factor, MPE – mean percentage error, PE – percentage error, MAPE – mean absolute percentage error

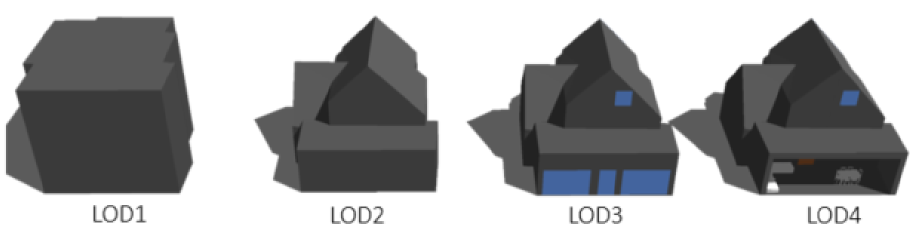
1 Introduction

The assumed and desired operation of a district energy system is determined by the thermal and electrical demand of all the buildings within the district. Hence, an accurate quantification of the energy demand of a district in dimensions of time and space serves as an important boundary condition for a correct assessment of the feasibility of district energy systems. The optimal planning of an integrated energy system also requires insight into the spatial distribution of the energy demand, since the spatial distribution determines not only the most favourable balance between heat savings and sustainable supply options [1], but also the optimal location of production and storage units. Including the spatial distribution of the energy demand is enabled through the rising popularity of geospatial data and geographical information systems (GIS) [2].

GIS are not only deployed to map the spatial distribution of the energy demand, but also to quantify the energy demand, since they are able to contain information on building geometry. Although multiple research initiatives deploy GIS as data sources for district energy simulations to quantify the annual district energy demand [3], only few include geospatial data of a GIS to calculate hourly or sub-hourly energy demand profiles (e.g. [4]). Due to the lack of an automated method to process geospatial data, most of the dynamic district energy simulations are still often carried out using an archetype approach (e.g. [5]), in which only a limited set of representative buildings is used to model the building stock of the district. However, these archetype approaches usually neglect the variability in building geometry that is characteristic for the existing building stock [6]. Especially, on a smaller scale (~100 dwellings) the use of archetypes may therefore no longer be representative, resulting in a less accurate spatial and temporal characterisation of the district energy demand. The lack of an efficient methodology to process geospatial data has been addressed by multiple initiatives, such as TEASER [7]. The results of these initiatives allow to include the variability in geometry more accurately in dynamic district energy simulations.

Geospatial data are available in all the EU countries thanks to the EU's INSPIRE directive, which aims to create a EU spatial data infrastructure for sharing environmental spatial information [8]. Their level of detail (LOD), however, varies significantly from one country to another. A definition of these LODs is provided by the CityGML standard [9], which is an open standardised data model and exchange format to store 3D city models. The data model allows for semantic modelling, which is a key requirement for geographical information data models, as not only the geometry and its appearance needs to be included, but also its properties and interrelations to other city objects. In Flanders, the available geospatial data contain the building footprint as well as its ridge height, corresponding to LOD1 representations (Figure 1), in which each building is represented by its extruded volume. Although not yet common, more detailed geometry descriptions are available for some Flemish cities, corresponding to LOD2 representations (Figure 1). Within these LOD2 representations, each building is characterised by its particular shape and defined in terms of surfaces that represent roof, ground floor or façade or parts of these. Even more detailed representations are defined (Figure 1) – LOD3 and LOD4, including respectively windows and interior – but these are even less widespread.

Figure 1. Graphical representation of the defined LODs within CityGML.

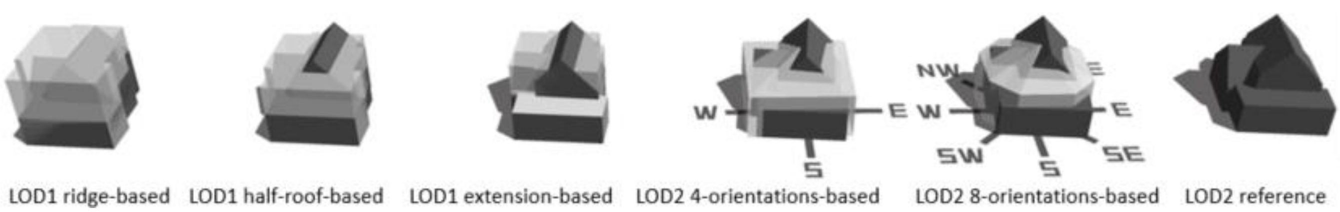


Both LOD1 and LOD2 representations are suitable for generating building energy models, but LOD1 representations are generally used due to the lack of LOD2 representations (e.g. [4]). The influence of LOD1 versus LOD2 on urban heat demand modelling has been addressed by Nouvel et al. [10]. They compared an LOD1 representation – with the height set to the average between ridge and eaves height – to an LOD2 representation for 8 600 buildings of which the representation in LOD1 differed from LOD2. The mean percentage error (MPE) on the annual heat demand – using monthly heat balances – was discovered to be less than 10% on district level [10]. Therefore, the acquisition of LOD2 representations was considered to be 'nice-to-have' rather than 'must-have', although Nouvel et al. conclude that LOD2 is preferred to LOD1 in order to estimate the heat demand at building instead of district level. A similar study, conducted by Strzalka et al. [11], also concludes that the heat demand calculation – based on monthly heat balances – deviated less than 10% between LOD1 and LOD2, but only six buildings were studied, mostly apartment buildings.

Although the embedded height information in LOD1 and LOD2 differs, both representations include an equally detailed building footprint. Each façade part is characterised by its particular orientation, even if they differ only 1 degree in orientation. However, the computational overhead during the dynamic district energy simulations due to these detailed building footprints has never been quantified to the authors' knowledge. Additionally, different modelling possibilities from a geometrical point of view exist in 2D [12], e.g. does the building footprint represent the actual position of the walls or the projection of the roof edges to the ground? The deployed modelling approach is often not included in the metadata [12], but is required to ensure a correct assessment.

Within this context, this paper investigates the usability of both LOD1 and LOD2 representations within dynamic district energy simulations, through quantifying the differences in geometry and energy performance between five LOD1 or LOD2 representations and an LOD2 reference representation (Figure 2). Dynamic energy simulations result in (sub-)hourly energy demand profiles, useful to determine the optimal location and sizing of production and storage units as well as to study of building-network interactions and indoor climate, whereas steady-state simulations (i.e. using monthly heat balances) only result in monthly or yearly energy demands. Since dynamic simulations are more time-consuming than steady-state simulations, the difference in processing and simulation time between the five representations and the LOD2 reference representation is also quantified. Additionally, with a view to the optimal planning of district heating and cooling systems, not only the energy demand for space heating is important as key performance indicator (KPI), but also the peak power as well as the load duration curve. The focus is on the geometrical representation of 700 single-family dwellings in the Belgian city of Genk. This paper analyses how geographical information models can be deployed within dynamic district energy simulations: how can LOD1 representations be enhanced in order to obtain a more accurate geometrical representation of the considered district, and in the meantime, how can LOD1 and LOD2 representations be simplified in order to minimise computational overhead while maintaining the accuracy? By quantifying the deviations between LOD1 and LOD2, the aim of this paper is twofold: to discuss the usability of GIS as input data source to quantify the district energy demand spatially and temporally within district energy simulations and to raise awareness of the error that results from a particular geometrical representation and of the influence of this error on district energy simulation results.

Figure 2. Graphical overview of six different building geometry representations. The LOD2 reference is depicted in dark.

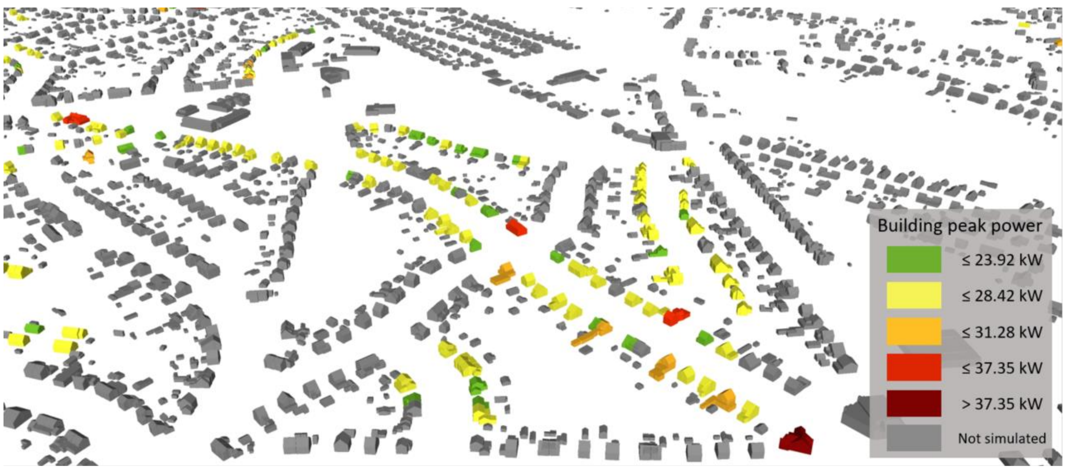


In the next Section, the methodology to quantify the district energy demand is introduced together with the six different geometrical representations. In Section 3, a detailed comparison of the resulting KPIs for the six geometrical representations is presented. In Section 4, the implications of the established analysis for future work are discussed. Finally, the main conclusions are formulated in Section 5.

2 METHODOLOGY

To investigate the potential of geographical information models to include the spatial distribution and building geometry in dynamic district energy simulations, 700 buildings located in 57 randomly selected streets of the City of Genk were modelled and simulated, using six different geometrical CityGML representations as input (Figure 2). Figure 3 depicts some of these randomly selected streets as well as the spatial distribution of the building peak power, which is enabled by using geographical information models combined with district energy simulations. FME is used to setup the CityGML models, TEASER to translate these CityGML models into IDEAS Modelica models and OpenIDEAS to run the dynamic district energy simulations in Dymola. The different geometrical representations are compared extensively to the LOD2 reference representation within Section 3, through the evaluation of heated volume, heated floor area and total loss area as geometrical KPIs as well as through the assessment of peak power, energy demand for space heating, load duration curve and overheating of both day zone and night zone as energy KPIs. The energy KPIs are selected with a view to the optimal planning of district heating and cooling systems.

Figure 3. Graphical representation of the spatial distribution of the peak power for some of the simulated buildings in the City of Genk.



Since the LOD1 models are expected to deviate significantly from the LOD2 reference model, a preliminary analysis of the LOD2 reference representation was performed. In this Section, the setup and the results of the preliminary analysis are presented first. Then, the building simulation model and the methodology to generate these models based on the geometrical representations are introduced. Finally, all the geometrical representations are described.

2.1 PRELIMINARY ANALYSIS OF THE LOD2 REFERENCE MODEL

As LOD1 and LOD2 differ significantly in terms of geometry, a preliminary analysis of the LOD2 reference model was performed to pinpoint these differences. In LOD2, all the buildings are characterised by their particular roof shape and extensions, which influences the total loss surface area, the wall-to-roof ratio as well as the volume. In LOD1, neither roof shapes nor building extensions are included generally, although it is possible (cf. LOD1 extension-based model). Building extensions are usually not as high as the main part of the building and are often characterised by another roof shape. Therefore, additional data regarding the roofs and the extensions that is embedded within LOD2 models have been extracted, by using the commercial software Feature Manipulation Engine (FME) of Safe Software Inc. [13]. For this analysis, 12 136 single-family dwellings of the City of Genk are considered. Buildings are considered to be single-family dwellings if they are categorised as main buildings within the input file, the ridge height is less than 12.55 m and the ground floor area is less than 350 m². These thresholds are confirmed manually by visualising the resulting categorisation. The methodology to extract this data from the LOD2 model is presented first. Subsequently, the results of this preliminary analysis are presented, showing that most of the single-family dwellings are characterised by a gable roof and one building extension.

The available LOD2 model of the City of Genk consists of separate roof, wall and ground floor surfaces, which can be joined based on an object and version identifier, unique for each building and in accordance with the Flemish GIS. In order to identify the main part and the extensions, all wall surfaces are projected to the ground floor surface. All the closed polygons that can be constructed from these projections are considered to represent the ground floor of a particular building part. Finally, all the building parts are ranked based on their heights, where the main part is considered to be the highest.

Next, the roof shape of all the building parts is characterised. The roof volume is considered to be the volume that is enclosed by the particular roof surfaces, the projection of these roof surfaces to the horizontal plane at the height of the lowest point of any roof surfaces and the vertical surfaces that are needed to close this volume. Subsequently, the volume, the area of the base and the height from the base to the ridge are calculated as well as the roof shape factor (RSF). The RSF is correlated to the actual roof type and is calculated as the volume divided by the multiplication of the area and the height (Figure 4). If the height is less than 0.5 m, the roof is considered to be a flat roof. If the height is more than 0.5 m, two possible roof types are considered: a gable roof, which ideally corresponds to a RFS of 0.5, and a hip roof, which ideally corresponds to a RFS of 0.333. The threshold between both is therefore defined as 0.4167. Furthermore, to correlate the roof and extension characteristics to particular buildings, the buildings are categorised according to their type, size and number of storeys (Table 1).

Figure 4. Characterisation of roof shapes.

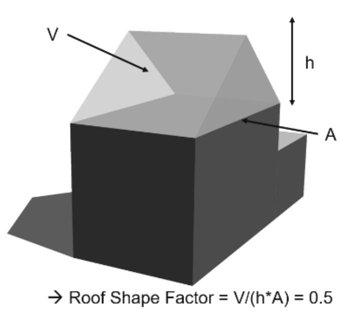


Table 1. Categorisation method and statistical analysis results, based on 12 136 single-family dwellings.

Category	Deterministic characteristic	Threshold	Total number	Roof type [%]			Number of extensions [%]					
				Gable	Hip	Flat	0	1	2	3	4	5+
All			12 136	84.2	6.7	9.1	32.1	42.5	18.7	5.0	1.2	0.5
Type	Number of neighbour buildings											
Detached		= 0	6 673	85.0	7.5	7.5	43.4	36.7	14.4	4.1	0.9	0.4
Semi-detached		= 1	4 248	84.2	5.7	10.1	19.9	48.3	23.7	5.9	1.6	0.5
Terraced		≥ 2	1 215	80.2	5.3	14.6	12.4	53.8	24.9	6.8	1.5	0.6
Size	Ground floor area											
Small		< 99.15 m²	3 034	82.0	4.6	13.4	27.9	54.6	15.5	1.8	0.2	0.0
Medium		< 123 m²	3 034	87.3	5.5	7.2	22.9	48.7	23.3	4.6	0.6	0.0
Large		< 163.81 m²	3 034	87.3	6.8	5.9	36.9	35.9	19.4	5.9	1.5	0.4

Extra-large		≥ 163.81 m²	3 034	80.1	9.8	10.1	40.7	30.7	16.7	7.7	2.7	1.5
Number of storeys	Ridge height											
1		< 6 m	1 175	44.2	3.4	52.4	46.7	37.4	12.0	3.3	0.4	0.1
2		< 9 m	4 687	85.4	6.9	7.6	41.6	38.3	15.2	3.7	0.9	0.4
3		< 12 m	6 030	90.7	7.1	2.1	22.5	46.6	22.5	6.2	1.6	0.6
4		≥ 12 m	244	92.2	5.3	2.5	17.6	43.4	24.6	10.2	2.9	1.2

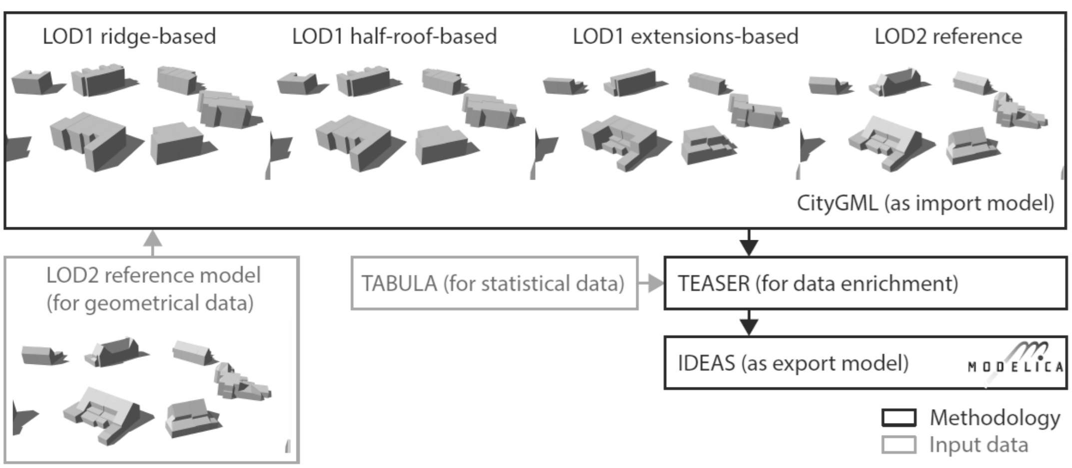
Generally, the single-family dwellings of the City of Genk are characterised by a gable roof and one building extension (Table 1). If the single-family dwellings are categorised, the one-storey houses are more likely to have a flat roof. Additionally, the detached houses, the extra-large houses as well as the one-storey houses tend to have no extensions, instead of one.

Traditional LOD1 representations include the building footprint and the ridge height, corresponding to LOD1 ridge-based models. In order to narrow the gap between these LOD1 representations and the LOD2 reference representation, two additional LOD1 representations are proposed by taking into account more characteristics of the existing building stock, more in particular: roof shape and building extensions. These representations are discussed in Section 2.3.

2.2 From geometrical representations to energy simulation models

To assess the influence of building geometry representation within district energy simulations, six different energy simulation models were generated from six different geometrical representations. TEASER – a Python package developed by RWTH Aachen [7] – translates geometrical CityGML models into Modelica models and was deployed for this purpose, although in a slightly adapted version [6]. The adapted TEASER package takes a CityGML model – either LOD1 or LOD2 – containing building geometry, building function, construction year, number of storeys and storey height as in input and exports detailed IDEAS building models (Figure 5).

Figure 5. Graphical overview of the method to translate geometrical representations into energy simulation models.



The Integrated District Energy Assessment Simulations (IDEAS) library is implemented in the Modelica language and allows simultaneous transient simulation of thermal, control and electric systems at both building and district level, as demonstrated in IEA-EBC Annex 60. The IDEAS building model, as used in this work, is elaborately described in [14]. Not only buildings, but also the district energy system can be modelled, enabling the study of building-system interactions. The IDEAS library supports detailed building energy simulations modelling transient thermal phenomena within the building using a zonal modelling approach, assuming perfect mixture of the air inside the zone. TEASER is used to generate two-zone IDEAS building models, assuming that the ground floor represents the day zone while all the upper floors belong to the night zone. As this paper intends to assess the impact of different geometrical representations, each building is implemented with an ideal radiator heating system [15] and no ventilation system. To calculate the ventilation losses, air infiltration is included, but window opening is not. Occupant behaviour is modelled following the ISO 13 790 standard with an indoor air temperature set point for day zone and night zone respectively of 21°C/18°C in the occupied period, 18°C/20°C at night and 16°C/16°C in unoccupied periods [16]. The internal gains are also set according to the standard. The simulations are conducted for the heating dominated climate of Uccle (Belgium) for a period of 1 year. An additional initialization period of 1 month is used. Dymola is used to simulate the models using the Dassl solver with an output interval of 10 min.

The IDEAS export relies on a predefined model template that is completed using the data available from TEASER, i.e. geometry and physical thermal properties. To export IDEAS building models and to perform dynamic energy simulations, additional thermal properties are required and allocated by TEASER based on construction year. All the buildings are assumed to share the same construction year – determining all the thermal properties – since the purpose of this work is to assess the influence of building geometry within district energy simulations. As a result, all the building models solely differ in geometrical properties and not in thermal properties. The thermal properties are based on statistical information and are derived from the TABULA project for Belgium [17]. The exact assumptions as well as additional features that were added to TEASER are given in [18] (Table 2).

Table 2. Overview of the used building simulation parameters.

Parameter	Units	Values
U-values	W/m^2K	
Façade		1.00
Window		3.50
Roof		0.77
Slab on ground		0.85
Window-to-wall ratio	-	0.20 (only for non-shared walls)
n50	ACH	8

2.3 Six different geometrical building representations

Six different geometrical representations are selected based on the current availability within geographical information models and the results of the preliminary analysis. FME was used not only to create the described CityGML models based on the LOD2 reference representation, but also to set certain additional attributes to the buildings as required for further processing within TEASER (Table 3). The six selected geometrical representations are presented below.

The LOD2 reference representation was generated from airborne laser scanner technology [19]. Therefore, the building footprint is assumed to represent the projection of the roof eaves to the ground, resulting in a slightly overestimated heated volume. The LOD2 reference representation was used as a basis to derive all the other representations, more in particular the LOD1 ridge-based representation, the LOD1 half-roof-based representation, the LOD1 extension-based representation, the LOD2 8-orientations-based representation and the LOD2 4-orientations-based representation (Figure 2). The LOD2 reference model – therefore all the models – represents the entire building envelope, assuming it to be heated entirely.

Most of the EU national geospatial models contain an LOD1 geometrical representation of their territory. In the Flemish GIS, as an example, buildings are represented by their footprint and their ridge height. As a first approach, the complete building footprint is extruded over its ridge height. Separate garages and garden houses are labelled as annex buildings within the geospatial data and thus excluded. This approach is referred to as the LOD1 ridge-based representation (Figure 2). The extrusion over ridge height implies that both roof shapes and building extensions are neglected.

As the statistics show that most houses have a gable roof, it is argued that an extrusion over the ridge height causes a significant overestimation of the volume. Therefore, within the second approach, the volume of the highest storey is considered to be half of its original volume, assuming it to be under a pitched and completely heated roof. This approach is referred to as the LOD1 half-roof-based representation (*Figure 2*). However, the storey heights are unknown and thus need to be estimated (Table 3). It is stressed that the "half-roof-based" height is not necessarily halfway between roof eaves and ridge, as the height is half of a storey lower than the ridge, since eave heights are often not included in LOD1 representations. Although the LOD1 half-roof-based representation intends to take the roof shape into account, it is still not able to cope with building extensions.

The statistics show that most houses have at least one building extension. Within the third approach, these building extensions are taken into account, assuming them to be completely heated. This approach is referred to as the LOD1 extension-based representation (Figure 2). The preliminary analysis also shows that building extensions tend to have a flat roof whereas the main volumes mostly have a pitched roof. Therefore, building extensions are represented by building blocks using the ridge-based approach, whereas the main volumes are represented using the half-roof-based approach.

The described representations can also be related to the improved LOD specification for 3D building models, as proposed by Biljecki et al. [20]. Both LOD1 ridge-based and LOD1 half-roof-based representations correspond to LOD1.2, but their height reference differs. The LOD1 extension-based representation corresponds to LOD1.3, while the LOD2 reference representation corresponds to LOD2.2.

Although the LOD2 reference representation is considered to be most accurate, it may not be the most optimal since all the building envelope parts are described separately. Processing these parts automatically implies determining their area, tilt and orientation. Building envelope parts that differ only 1 degree in orientation or tilt are thus processed separately, which may cause computational overhead during the dynamic energy simulations. Therefore, two additional representations are proposed. Within the fourth and fifth approach, all the wall and roof surfaces of the LOD2 reference representation are labelled by eight or four orientations. These are referred to as the LOD2 8-orientations-based representation and the LOD2 4-orientations-based representation respectively (Figure 2). With a view to the roof surfaces, the area-weighted average tilt of all roof surfaces are calculated first on building level and then the particular roof surfaces are labelled towards the defined orientations, using this average tilt.

Table 3. Additional attributes required for further processing within TEASER.

Attribute	Value	Explanation
Function	1 000 (= residential)	Scope of this research is single-family dwellings
Construction year	1980	Most representative for the Flemish building stock [21]
Number of storeys	Based on height	Calculated as the maximum number of storeys with a height of 3 m that fits within the ridge height (for representations that don't take building extensions into account: only 1 height per building, for representations that take building extensions into account: 1 height per building part)

Storey heights	Based on height	Estimated number of storeys is used to calculate the actual storey heights (ridge height or building part height divided by number of storeys of this building or this building part)

3 Results

In this Section, the representativeness of the LOD2 reference model is assessed first. Then, both geometrical and energy KPIs of all the models are presented as well as the differences between the models, in order to assess the capabilities of all the models with a view to the LOD2 reference model. For each building b, each KPI and each variant, the percentage error $PE^{b}_{KPI,variant}$ was calculated firstly (Equation 1). From the perspective of designing and optimising district energy systems, it is logical to focus on the behaviour of a set of buildings. Therefore, the mean PE (MPE) and the standard deviation on the PE are presented (Equation 2). However, with a view to the spatial distribution, the behaviour of a single building is important as well. Therefore, the root mean square percentage error (RMSPE) is reported as well (Equation 3).

$$PE^{b}_{KPI,variant} = \frac{KPI^{b}_{variant} - KPI^{b}_{reference}}{KPI^{b}_{reference}} \quad (1)$$

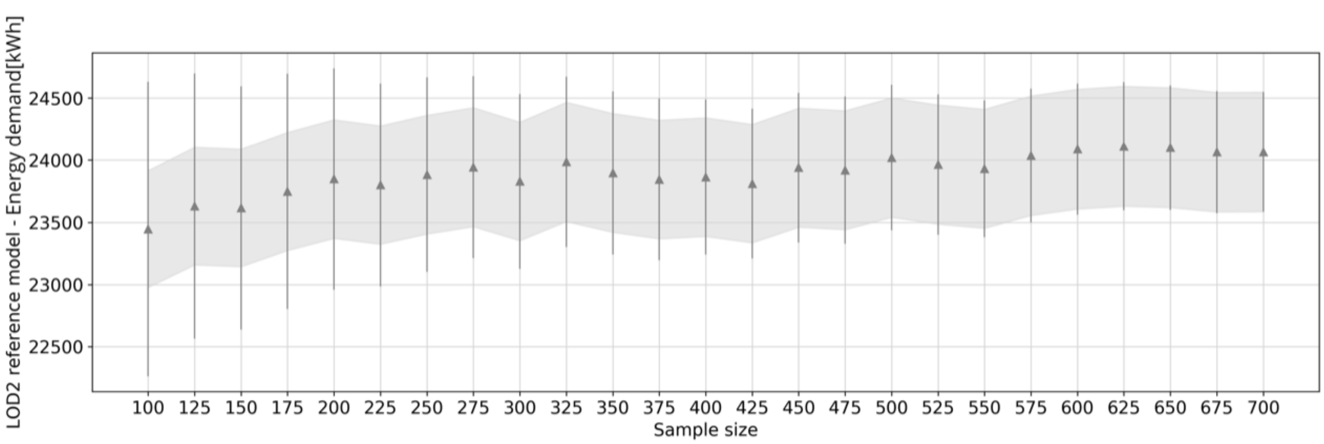
$$MPE_{KPI,variant} = \frac{\sum_{b=1}^{n} PE^{b}_{KPI,variant}}{n} \quad (2)$$

$$RMSPE_{KPI,variant} = \sqrt{\frac{\sum_{b=1}^{n} (PE^{b}_{KPI,variant})^2}{n}} \quad (3)$$

3.1 Representativeness of the LOD2 reference model

In order to ensure a representative sample of the considered LOD2 reference model for the regional building stock, the acceptable range of the 95% confidence interval for the mean was defined as 4% of the sample mean for the energy demand for space heating. Consecutively, the number of simulated buildings was increased until the acceptable range was satisfied. As can be seen in Figure 6, a sample size of 700 buildings was found to be sufficient. Figure 6 also shows that the sample mean does not vary significantly if the sample consists of more than 500 buildings. The generalisability of the performed comparison, however, cannot be proven statistically.

Figure 6. Both the mean and the 95% confidence interval for the mean of the energy demand for space heating are depicted for an increasing sample size. The triangles represent the sample mean, the vertical bars represent the 95% confidence intervals for the sample mean and the shaded zone represents the acceptable confidence interval range of 4% of the sample mean.



3.2 THE LOD1 MODELS WITH A VIEW TO THE LOD2 REFERENCE MODEL

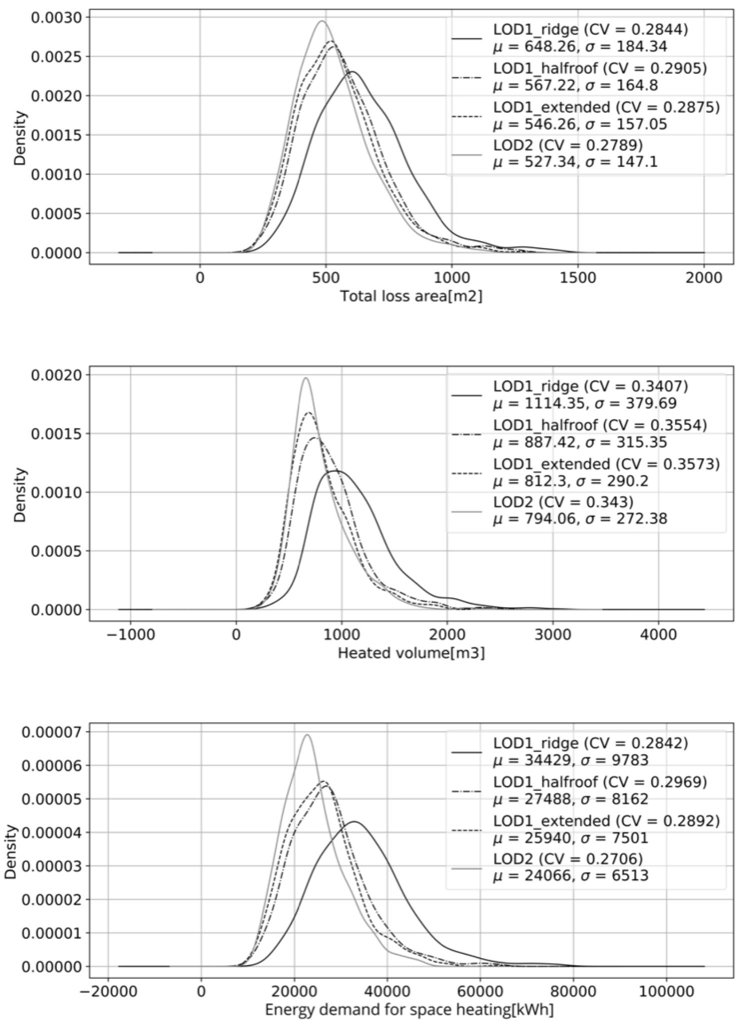
Three LOD1 models are compared to the LOD2 reference model. Their RMSPE, MPE and σ_{PE} for selected KPIs are reported in Table 4. All the LOD1 models overestimate the LOD2 model, but not to the same extent. The deviation is worst for the LOD1 ridge-based model, whereas the LOD1 half-roof-based model performs better and the deviation for the LOD1 extension-based model is the smallest. This applies not only to the geometrical KPIs (MPE for the total loss area of 23.02%, 7.55% and 3.47% respectively) but also to the energy KPIs (MPE for the energy demand for space heating of 43.44%, 14.43% and 7.77% respectively). Additionally, the MPE decreases more significantly from LOD1 ridge-based to LOD1 half-roof-based than from LOD1 half-roof-based to LOD1 extension-based. Although the total processing time of the LOD1 models is approximately 54% lower than the LOD2 reference model as a result of the simplified roof representation, the accuracy of the LOD1 models is also significantly lower compared to the LOD2 reference model.

Table 4. Overview of the RMSPE, MPE and standard deviation on the PE for all the variants and selected KPIs.

		Heated volume [-]	Heated floor area [-]	Total loss area [-]	Energy demand [-]	Overheating day zone [-]	Simulation time [-]	Total processing time [-]
LOD1 ridge-based	RMSPE	0.4616	0.2261	0.2466	0.4641	0.2545	0.4404	0.5439
	MPE	0.4152	0.1424	0.2302	0.4344	0.1868	-0.4131	-0.5224
	σ_{PE}	0.2019	0.1757	0.0885	0.1635	0.1730		
LOD1 half-roof-based	RMSPE	0.2245	0.2261	0.1141	0.2102	0.2960	0.4376	0.5406
	MPE	0.1258	0.1424	0.0755	0.1443	0.2354	-0.4059	-0.5168
	σ_{PE}	0.1861	0.1757	0.0856	0.1529	0.1796		
LOD1 extension-based	RMSPE	0.1078	0.0	0.0670	0.1367	0.1748	0.4513	0.5376
	MPE	0.0226	0.0	0.0347	0.0777	0.1031	-0.4313	-0.5215
	σ_{PE}	0.1055	0.0	0.0573	0.1126	0.1413		
LOD2 4-orientations -based	RMSPE	0.0	0.0	0.0	0.0146	0.0900	0.7422	0.5975
	MPE	0.0	0.0	0.0	-0.0037	-0.0152	-0.7368	-0.5804
	σ_{PE}	0.0	0.0	0.0	0.0141	0.0887		
LOD2 8-orientations -based	RMSPE	0.0	0.0	0.0	0.0080	0.0563	0.7398	0.5938
	MPE	0.0	0.0	0.0	-0.0029	0.0092	-0.7345	-0.5776
	σ_{PE}	0.0	0.0	0.0	0.0075	0.0556		

Figure 7 depicts the total loss area, the heated volume and the energy demand for space heating for all the LOD1 models and the LOD2 reference model. Figure 7 not only depicts the above findings, but also the ability of these models to include the geometrical variation of the existing building stock, as all the building models within the four variants are identical except for their geometry. Due to the different sizes and shapes of single-family dwellings, the existing residential building stock is characterised by a significant variation, varying from 20% to 48% for the LOD2 reference model depending on the considered KPI. Archetype approaches are often not able to take this variation into account, as they only consider a limited number of representative buildings. To consider this variation and thus achieve more accurate simulation results, geographical information models appear to be useful data sources. Figure 7 shows that all the models are characterised by similar coefficients of variation (CV). Therefore, all the variants capture the geometrical variability of the existing building stock accurately.

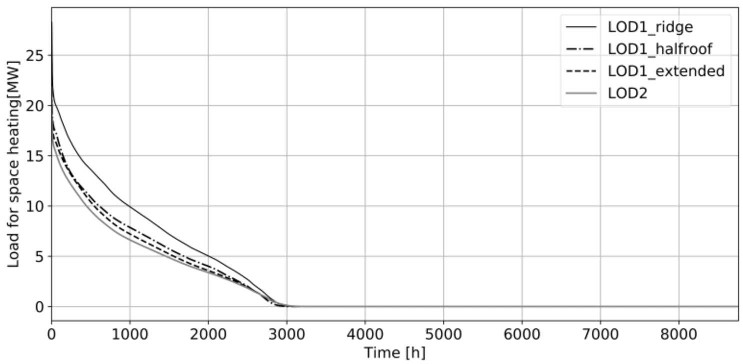
Figure 7. Kernel density plots of total loss area, heated volume and energy demand for space heating for all the LOD1 models and the LOD2 reference model.



For the optimal planning of district energy systems, a detailed temporal characterisation of the district energy demand is important, which is enabled through dynamic simulations. A load duration curve shows the required capacity of energy production to satisfy the energy demand of the 700 buildings as a function of the duration in hours. The load duration curves for the space heating demand for all the LOD1 models and the LOD2 reference model are depicted in Figure 8. Although the load duration is similar for all the models (approximately 3000 hours per year), the load differs significantly for the LOD1 ridge-based and the LOD1 half-roof-based model, which is in line with the previous findings, whereas the LOD1 extension-based model represents the LOD2 reference model best.

De Jaeger, I., Reynders, G., Ma, Y., & Saelens, D. (2018). Impact of the description of the building geometry within district energy simulations. *Energy*, 158, 1060–1069. http://doi.org/10.1016/j.energy.2018.06.098

Figure 8. Load duration curves for all the LOD1 models and the LOD2 reference model.

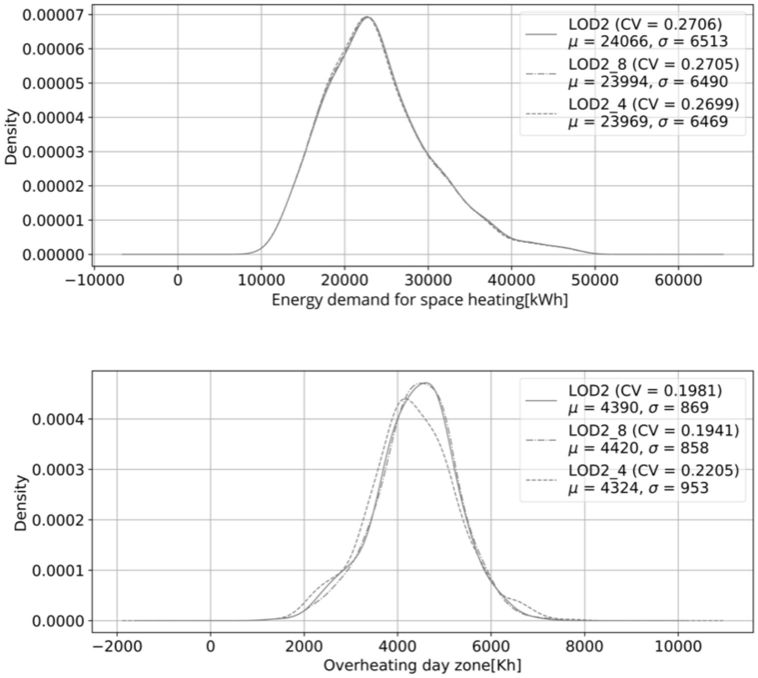


3.3 The LOD2 models with a view to the LOD2 reference model

In order to reduce the computational overhead due to the very detailed building footprints, labelling and aggregating the walls and roofs into a limited number of orientations is proposed. The resulting RMSPE, MPE as well as σ_{PE} for selected KPIs are reported in Table 4. The geometrical KPIs are identical to those of the LOD2 reference model, but the energy KPIs deviate slightly from the LOD2 reference model due to the difference in solar irradiation. The LOD2 8-orientations-based model and the LOD2 4-orientations-based model perform well compared to the LOD2 reference model regarding the energy demand for space heating (MPE of -0.29% and -0.37% respectively). As the deviation is somewhat larger for the overheating of the day zone (MPE of 0.98% and -1.52% respectively), the detailed model might be preferred for assessing the indoor climate. The reduction in simulation time, however, is substantial (73.45% and 73.68% respectively) as a result of the simplified wall and roof representation.

Figure 9 depicts the energy demand for space heating and the overheating risk of the day zone for all the LOD2 models, highlighting the above findings. Similar to the LOD1 models, Figure 9 also shows the ability of the LOD2 models to include the variation of the existing building stock, which is expected since the LOD2 orientation-based models only differ slightly from the LOD2 reference model. Since the difference in energy demand for space heating between all the LOD2 models is negligible, the load duration curves are also very similar and therefore not depicted.

Figure 9. Kernel density plots of the energy demand for space heating as well as the overheating of the day zone for all the LOD2 models.



4 DISCUSSION

Within this Section, the extrapolation potential of the presented results is discussed first. Subsequently, possible shortcomings of the presented methodology are described. Finally, the required data to generate the presented geometrical representations as well as the need for additional data are addressed.

The proposed improvement of LOD1 ridge-based models – assuming gable roofs and reducing the attic volume – will only be meaningful if a major part of the single-family houses has a gable roof. This assumption is meaningful for the regional building stock around the City of Genk, but may be inapplicable to other areas with different building stock characteristics. As an example, a flat roof characterises less than 10% of the single-family houses in the City of Genk in Belgium, whereas 60% of the buildings in the City of Ludwigsburg in Germany [10] have a flat roof. Since German buildings and Belgian buildings appear to have different probable roof shapes, the probable presence of building extensions might also differ. The different characteristics of the building stock are likely to explain the higher MAPE that was found in this work (16% for the LOD1 half-roof-based model) compared to the work of Nouvel et al. (7.3%, note that the definition of the LOD1 slightly differs between both works) [10].

Throughout this work, the LOD2 reference model is assumed to represent the ground truth. However, the LOD2 model accuracy is unlikely to be 100%, since it is generated through airborne laser scanning technologies (e.g. walls are projected from roof eaves). Obviously, the LOD2 model accuracy might nuance the presented results. Although multiple accuracy assessment measures and their results for given datasets are available [22], such an assessment was not performed for the deployed LOD2 model. Nonetheless, these airborne laser scanning technologies are currently best practice. Alternatively, measured energy use profiles could be used as a reference, but this was impossible within this work due to their unavailability in adequate spatial and temporal resolution for Flanders. Although the LOD2 model is used as a reference, its resulting district energy demand should be validated against measured energy use data.

The LOD2 8-orientations-based model and the LOD2 4-orientations-based model perform well compared to the LOD2 reference model regarding the energy demand for space heating, but not to the same extent regarding the overheating of the day zone due to the difference in solar irradiation. Shading effects caused by neighbour buildings or other urban objects have not been taken into account, which might nuance these results.

Both the LOD1 ridge-based representation and the LOD1 half-roof-based representation can be constructed for most EU countries. The LOD1 extension-based representation, on the other hand, is not universally applicable, since this representation requires building footprint and height information for main volume and building extensions. The proposed simplification of labelling walls and roofs towards a limited number of orientations can be applied for both LOD1 and LOD2 representations.

All the LOD1 models underestimate roof areas and overestimate wall areas consistently, which causes increased errors on the energy demand for space heating if the thermal performance of both roofs and walls differ largely. In Flanders e.g., 82% of the single-family dwelling has (partial or overall) roof insulation, whereas only 47% has (partial or overall) wall insulation [23]. This issue highlights the need for more national statistics, containing detailed information regarding the thermal performance of the existing building stock.

This work highlights the impact of building geometry description on the modelled district energy demand for space heating. Since the energy demand for domestic hot water has not been considered in this study, the impact of building geometry description on the total district energy demand is expected to be lower than the impact on the energy demand for space heating. However, it should be noted that apart from the employed building geometry description, the assumed thermal performance of the building envelope and the assumed occupant behaviour among others also cause the discrepancy between the modelled and the actual district energy demand. Their impact on the district energy demand is required to put the presented results into perspective and is therefore considered as future work.

5 Conclusion

In order to assess the usability of GIS as input data source and to raise awareness of the error that results from a particular geometrical representation and of the influence of this error on district energy simulation results, five different LOD1 and LOD2 models were studied and compared to an LOD2 reference model.

Geographical information models appear to be very useful within district energy simulations for two reasons. Firstly, they enable to include the spatial dimension of the district energy simulation results more accurately, allowing to optimise the location of production and storage units within district energy systems. Secondly, they enable to include the variability that is characteristic for the existing building stock. All the geometrical variants that were studied in this work are equally capable to include this variability, since the coefficients of variation for both geometrical and energy KPIs are similar (e.g. approximately 28% for the energy demand for space heating). Geographical information models is preferred to archetype approaches especially when the spatial and temporal scale of the simulation decreases and variability becomes more important.

Although geographical information models provide excellent input for district energy simulations, they often contain both too much and too little data. The building footprint is often too detailed (to an equal extent for both LOD1 and LOD2 models), whereas the building height is often too rough (e.g. only one value per building in LOD1 models).

A simplification of the building footprint was proposed by grouping walls and roofs in a limited number of orientations. The simulation time for both the LOD2 8-orientations-based model and the LOD2 4-orientations-based model decreased with 73% and 74% respectively compared to the LOD2 reference model, while maintaining the accuracy for the energy demand for space heating of the LOD2 reference model (underestimation of 0.29% and 0.37% respectively). Not only the energy demand, but also the load duration curves are similar. There is no substantial preference for either four or eight orientations, as they perform very similar. Considering the significant reduction in simulation time and the applicability to both LOD1 and LOD2 models, the proposed simplification is found to be very effective to quantify the district energy use in dimensions of time and space.

Depending on the available height information, LOD1 half-roof-based models are preferred to LOD1 ridge-based models regarding the energy demand for space heating (MPE of 14% and 43%), as they can be generated by combining LOD1 ridge-based models and knowledge of the existing building stock, whereas LOD1 extension-based models – which perform even better for energy demand for space heating (MPE of 7.8%) – require additional height information and cannot be estimated based of knowledge on the building stock. Therefore, in the trade-off between effort and accuracy, LOD1 half-roof-based models are favoured within the LOD1 models.

Nevertheless, LOD1 half-roof-based models underestimate roof areas and overestimate wall areas consistently, which causes increased errors on the energy demand for space heating if the thermal performance of both roofs and walls differ largely. Moreover, the LOD2 reference model – therefore all the models – represents the entire building envelopes, assuming that in-house garages and attics are heated. Excluding in-house garage and attics can only be achieved by more detailed models or by more detailed statistics on the existing building stock. The lack of input data regarding the existing building stock and of national statistics is a key issue in performing district energy simulations.

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