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Automated reconstruction of 3D input data for noise simulation

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ABSTRACT

Noise is one of the main problems in urban areas. To monitor and manage noise problems, governmental organisations at all levels are obliged to regularly carry out noise studies. The simulation of noise is an important part of these studies. Currently, different organisations collect their own 3D input data as required in noise simulation in a semi-automated way, even if areas overlap. This is not efficient, but also differences in input data may lead to differences in the results of noise simulation which has a negative impact on the reliability of noise studies. To address this problem, this paper presents a methodology to automatically generate 3D input data as required in noise simulations (i.e. buildings, terrain, land coverage, bridges and noise barriers) from current 2D topographic data and point clouds. The generated data can directly be used in existing noise simulation software. A test with the generated data shows that the results of noise simulation obtained from our generated data are comparable to results obtained in a current noise study from practice. Automatically generated input data for noise simulation, as achieved in this paper, can be considered as a major step in noise studies. It does not only significantly improve the efficiency of noise studies, thus reducing their costs, but also assures consistency between different studies and therefore it improves the reliability and reproducibility. In addition, the availability of countrywide, standardised input data can help to advance noise simulation methods since the calculation method can be adopted to improved ways of 3D data acquisition and reconstruction.

1. Introduction

Noise is one of the main problems in urban areas. Long-term exposure to high noise levels causes health problems as insomnia, stress or higher risk of cardiovascular diseases. Particularly in cities, noise is considered as a serious public health problem which has been studied extensively around the world (Schutz, 1978; Zannin, 2016).

Noise mapping is needed as a tool to assess noise exposure, to communicate information to citizens, and to define action plans for protecting citizens from noise pollution in (urban) environments (Licitra, 2012). To manage noise problems, many governments at different levels (local, regional, national) are obliged to monitor noise levels through noise mapping and based on these results they have to implement solutions for noise reduction. The decision-making process of these mitigation actions are based on noise mapping studies that simulate noise levels at certain locations and predict the noise impact of the proposed actions. Apart from studies supporting the obliged noise monitoring and mitigation, further noise studies are required if a new building or infrastructure is planned, or the existing infrastructure is changed.

Also at the European level, noise studies are imposed on governmental organisations. In order to have a common management plan for reducing urban noise, the European Union formulated the 2002/49/EC Environmental Noise Directive (END) (Directive, 2002). The main objective of the directive is to determine the exposure of an individual to environmental noise through the mapping of the impact of noise. The directive also mandates that the information on environmental noise and its effects is made available to the public (Directive, 2002).

The noise maps recommended by the END are 2D maps which represent noise levels at a certain height (i.e. 4 m above the ground). However, as the sound propagates in all directions, a 2D map is insufficient to depict the changes in height. For example, the difference in noise levels at the first floor and at the top floor of a high-rise building could be significant. Showing noise levels at varying height is possible by using 2.5D and 3D city models for mapping noise.

The core of noise impact studies is the simulation of noise propagation in computer models. These models calculate noise levels on observation points that are distributed in 3D space. The noise levels are calculated based on the emission and location of the noise source and a 3D model of the environment (i.e. buildings, roads, noise barriers) that is used to determine the noise propagation.

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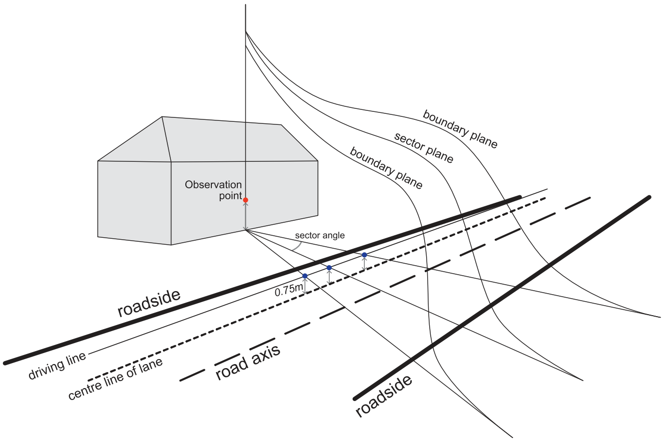

Fig. 1. Details of the Dutch regulation that prescribes how noise from traffic on observation points should be calculated. This prescribed method is further explained in Section 3.2. Adapted from http://wetten.overheid.nl/BWBR0031722/2014-05-20.

1.1. Motivation and objectives

The method for simulating noise levels is often prescribed in regulations like the “calculation and measure regulations” for roads and railways in the Netherlands (*Standaard Rekenmethode II van de RMG 2012*) (Ministerie van Infrastructuur en Milieu, 2012) see Fig. 1. These regulations apply to noise studies in the Netherlands, such as in the case of planning new – or extending existing – infrastructure and are implemented in commercial software like GeoMileu (DGMR, 2014) and Winhavik (DirActivity, 2019).

Data collection and preparation for these noise simulations is at present usually done semi-automatically (and sometimes even manually) by different companies in different ways. This causes several problems. The first problem of a lack of a uniform and centralized approach for generating input data, is that for each study it requires money and time to reconstruct the required 3D input data. Once collected, these 3D data are usually not updated nor used in other studies. Therefore, it often occurs that different organisations prepare their own 3D data for their own studies (or outsource this task), while there is overlap in area. This is highly inefficient. In addition, although the calculation method is standardised, differences in the input data (i.e. noise studies carried out by different companies) cause differences in the simulation results. Therefore noise studies for the same area based on the same method are often not comparable. This is a problem for the reliability of noise studies, while major decisions are based on the results. A final problem in the current preparation of data required for noise simulation, is that the creation of input data still requires interactive work. The human interaction complicates standardisation. Furthermore it is time consuming, prone to errors and hinders innovation in the area of noise simulation such as improving the implemented noise calculation method.

A solution to all these problems is a standardised, uniform and automated method to reconstruct 3D data describing the environment from current data sources that can directly be used in noise studies.

The aim of the research presented in this paper is to automatically reconstruct such standardised and uniform input data for noise simulation as prescribed in for example SRM II based on available data in order to improve the efficiency, reliability and consistency of noise studies.

The reconstructed data will be published as open data and can directly be used in software that implements the noise calculation method. The research is a collaboration of Rijkswaterstaat (Dutch Ministry for infrastructure), Kadaster, RIVM (National Institute for Public Health and the Environment), IPO (collaborations of all provinces in the Netherland) and Delft University of Technology.

Although the focus of our research is the Dutch calculation method for noise, it has a wider impact. We have made an inventory of noise calculation methods and guidelines in other countries in Europe which indeed show differences such as the noise source type (e.g. a single point or a line source of emission), the height of the source, approach used to calculate the noise from a source and spectral bands used. However, the requirements for the input data to calculate the noise propagation from noise source to observation point also show fundamental similarities. Therefore our results can be used to automate the reconstruction of required 3D input data for noise studies in other countries.

In addition, the findings of our research can be used in further implementation of CNOSSOS-EU. This Common framework for NOise aSSessment methOdS (CNOSSOS) was developed by the European Commission to enable a consistent, harmonised and accurate calculation and reporting of the noise levels from the main sources of urban noise (road traffic, railway traffic, aircraft and industries) for the strategic noise mapping, and thus to fulfil member states' obligations under the END (Kephalopoulos, Paviotti, & Anfosso-Lédée, 2012). Apart from the software implementations for CNOSSOS, very little has been done for the practical guidelines outlining the specifications for the input data and few experiences are available. This study can contribute to fill this gap.

1.2. Overview of the paper

In this paper, we start with an overview of previous research and current frameworks for mapping urban noise using 3D data (Section 2) and then introduce the research context and approach in Section 3. Section 4 presents the methodology we have developed for reconstructing 3D input data for noise simulation and for evaluating the (intermediate) results. We tested our methodology with real world data sets to automatically reconstruct input data for noise simulation and report the results achieved in Section 5. We close the paper with the conclusion and future work in Section 6.

2. Related research

In recent years, various noise mapping software has been developed to simulate and visualise noise levels in 3D, e.g. CadnaA (Datakustik GmbH, 2014), Geomilieu (DGMR, 2014), SoundPlan (SoundPLAN GmbH, 2014), etc. The customised LIMA software (SoftNoise GmbH, 2011) was used in the 3D noise mapping for Hong Kong (Law, Lee, Lui, Yeung, & Lam, 2011). These noise mapping tools are commercial products and often support a limited number of input data formats. In addition, their implemented methodology is usually a ‘black box’ to the users and cannot be easily modified. These tools are mainly developed to simulate outdoors situations. Several open source efforts from the academic community, on the use of 3D city models to analyse how urban citizens are harmed by noise pollution, have also been reported (Kurakula & Kuffer, 2008; Law et al., 2011; Lu, Becker, & Löwner, 2017; Pamanikabud & Tansatcha, 2009; Stoter, De Kluijver, & Kurakula, 2008; Wing, Kwan, & Kwong, 2006). Stoter et al. (2008) and de Kluijver and Stoter (2003) discussed at length the importance of using 3D noise maps for noise impact studies and produced a 3D noise map using 3D city models for obstacles in the noise propagation. Ranjbar, Gharagozlou, and Nejad (2012) used 3D city models to investigate the impact of traffic noise on high rise buildings in Tehran. They tested the model with noise barriers of different heights at different distances from the edge of the highways to determine an effective approach to reduce the traffic noise in the area. Zhao et al. (2017) developed a methodology for 3D road traffic noise mapping for the city of Singapore utilising unstructured surface meshes for buildings and roads. Their work follows the UK standard CRTN (Calculation Road Traffic Noise) for noise assessment. Cai, Yao, and Wang (2018) proposed a methodology to compute large scale noise maps in 3D on a supercomputer to reduce the computation time for large urban areas. Their methodology covered the noise prediction modes together with the parallel programming algorithm implemented on a supercomputer.

Another recent attempt in using the 3D city models for mapping noise is the work of Bocher, Guillaume, Picaut, Petit, and Fortin (2019), which describes an open source implementation of a 3D noise mapping tool in a GIS software OrbisGIS[1] as a plugin: *NoiseModelling*. Their method is based on a profile of the French national method 'NMPB-08'. The work suggests that a similar approach can be used for other national or international noise mapping standards. At present, cities like Hong Kong (Law et al., 2011) and Paris (Butler, 2004) are using 3D city models for noise mapping. Efforts are also made in the BIM-GIS domain to integrate BIM and 3D GIS data to combine traffic noise calculations for outdoor and indoor environments (Deng, Cheng, & Anumba, 2016).

Apart from creating a 3D city model usable as input for noise mapping, structuring of these input data in a standardised format as required for noise simulation is another challenging task in noise simulation. To comply with the END (see above), a CityGML noise ADE (Application Domain Extension) was developed (OGC, 2012). CityGML is an international 3D standard established by the international standardisation organisation for geoinformation: Open Geospatial Consortium (OGC, 2012). The CityGML Noise ADE, extends the existing CityGML schema by adding new classes and objects relevant to noise mapping. Many cities in the state of North-Rhine Westphalia, Germany have implemented their 3D noise models based on the CityGML Noise ADE (Czerwinski, Kolbe, Plümer, & Stöcker-Meier, 2006a, 2006b; Czerwinski, Sandmann, Stöcker-Meier, & Plümer, 2007). The current Noise ADE has some limitations. For instance, it only represents noise data arising from road traffic and railways and does not support industrial noise. Kumar, Ledoux, Commandeur, and Stoter (2017) addressed these limitations by extending the ADE with new classes and attributes.

Although input data required for noise simulation has been standardised in the CityGML Noise ADE, and other researchers have created 3D data for noise simulation (de Kluijver & van Tilburg, 2018), the automated reconstruction and standardisation of 3D input data required for simulation has received little attention until now. This will improve both the effectiveness and reliability of noise simulation and is the topic of this paper.

3. Research context and approach

3.1. Research approach

In the presented research on the automated reconstruction of 3D input data for noise simulation, we focus on data that is required for representing the physical environment in order to determine the propagation of noise produced by road and railway traffic. Information on noise sources (such as traffic intensities) and their exact location are also required for noise simulation. But this information is not considered in this research, since this information is often best known at the organisation which does the study, specifically in the case of new infrastructure. In addition, this information is consistent in different noise studies (since they use the same source).

The input data is supposed to be reconstructed in such a way that it can directly be used in simulation software that implements the prescribed noise simulation method used to calculate noise levels for road and railway traffic in the Netherlands, i.e. *Wegverkeerslawaai RMW-2012* (Ministerie van Infrastructuur en Milieu, 2012). This noise simulation method is comparable to the noise simulation method for industrial noise (*Industrielawaai IL-HR-13-10/HMRI* (VROM, 1981)). Therefore, our developed methodology can also be used to reconstruct the 3D input data for that purpose. And, as mentioned in the introduction, it can serve as example for other, similar noise calculation methods in other countries.

The noise simulation method requires the following input data for describing the noise-relevant aspects of the physical environment:

- Building models
- Noise absorption and reflection factors of the land coverage
- Height of the terrain
- Height information on bridges and multi-level crossings
- Noise barriers

The requirements of the input data are described in detail in VROM (2015) and are summarised for each data layer in Section 4. For each input layer we have studied the specific data requirements and with iterative involvement of noise experts who evaluated intermediate results, we have developed and implemented our reconstruction method for each layer.

As all models and data about reality are simplifications, also the target data of our research is not a 1-to-1 model of reality and the challenge is to approach the real noise situation as much as possible. An example of the simplification of reality is that in our method we apply simplification techniques to reduce the data volume of the generated data sets (see also Section 3.5). Any form of simplification causes a deviation from measured reality and arguably makes the data less accurate. To minimise this loss of detail we perform simplification using methods that remove details that are geometrically least significant for noise simulation (while we keep noise relevant details). In addition we worked with noise experts to ensure that our simplifications only have a small to negligible effect on the final noise simulation results.

The best way to validate our results would be to compare the calculated noise levels with ground truth data (i.e. extensive measurements of noise levels). And the prescribed calculation method (i.e. SRM2) is based on such extensive measurements. However, the validation of calculated noise levels caused by a specific noise source using field measurements is complex. This is due to highly dynamic traffic and weather conditions and the occurrence of other noise sources which are not included in the simulation such as a passing airplane. To address these variances requires field measurements over longer periods, which was outside the scope of our study. In addition, the simulations often cover future scenarios for which real world measurements cannot be collected. Therefore we assessed the quality of our reconstructed input data from the difference between output values based on our input data and the output values as produced in the 'real-world' study and we let the differences be evaluated by noise experts.

Apart from this quantitative evaluation (Section 5.2), we performed a qualitative evaluation by interactive sessions with noise experts on (intermediate) results (Section 5.1).

The following subsections describe the noise calculation method in more details (Section 3.2) as well as the source data available for our study (Section 3.3). For the research, we extend the 3dfier software that automatically reconstructs 3D data from 2D large scale topography and point clouds (Commandeur et al., 2019). The 3dfier software is introduced in Section 3.4. Section 3.5 describes requirements regarding the detail of the input data for noise simulations.

3.2. The noise calculation method of our study

The calculation method of our study calculates noise levels on observation points that are distributed in 3D space. The noise levels are calculated based on the emission and location of the noise source and a 3D model of the environment (i.e. buildings, roads, noise barriers) that is used to determine the noise propagation. The calculation uses a ray tracing between the observation points and the noise sources. For each observation point a sector is defined to each noise source within a specified radius. A sector consists of a vertical center sector plane and

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[1] http://www.orbisgis.org/.

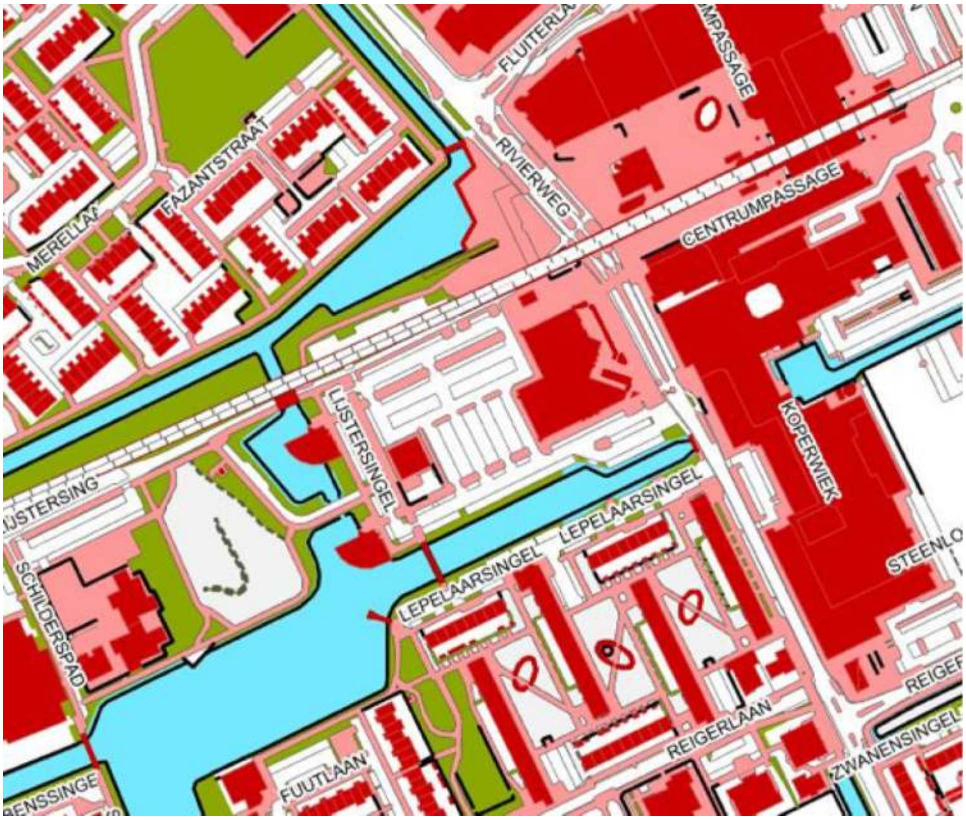


Fig. 2. Excerpt of BGT.

two vertical boundary planes at a specified 'sector angle' of the central plane (see Fig. 1). For each plane a 2D ray is traced to identify all relevant objects that are encountered between the noise source and the observation point. The noise source is represented using a driving line, which models where sound is emitted from. In a next step, this information is used to calculate the noise level at the specific point in space. This operation is performed for all observation points.

The following information is used in the calculation method and partly derived from the input data of this study (see Fig. 1 for a schematic overview):

- source point: intersection of considered *sector plane* with *driving line*
- period of the day: period of the day for which the noise level is calculated
- angle of a sector: angle between the *boundary planes* of a sector and the vertical center plane
- *driving line*: line in the middle of a lane at a height of 0.75 m that represents the location of noise emission
- driving line segment: straight line between intersection points of the driving line and the boundary planes of the sector
- sector: space delineated by vertical half-surfaces of which the boundaries coincide with the vertical through the observation point
- *sector plane*: bisector-plane of two *boundary planes* of a sector
- traffic intensity: number of motor vehicles that passes by per hour averaged over 24 h (based on one year)
- traffic speed: average speed of motor vehicles representative for the concerned road segment
- observation point (W in Fig. 1): point on a facade (or in space) on which the noise level should be calculated in dB(A)
- *sector angle*: angle under which an object (facade, noise barrier, road segment) is seen from the observation point.
- noise absorption/reflection by surface, air and weather identified between emission and observation point

3.3. *Source data for the 3D data reconstruction for noise studies*

The required input data for noise simulation will be reconstructed from three countrywide data sources in the Netherlands: a 2D large-scale topographic data set, 2D building registration and point cloud data. All data sets are available as open data via the governmental web portal *PDOK* (*Publieke Dienstverlening Op de Kaart*, www.pdok.nl). The three respective data sets are described in the next three subsections, respectively, *Basisregistratie Grootschalige Topografie* (BGT, base register large-scale topography), Register for Buildings and Addresses (BAG), and Actual Height model of the Netherlands (AHN).

3.3.1. *BGT*

The *Basisregistratie Grootschalige Topografie* (Geonovum, 2013; PDOK, 2012) is a data set containing topographic objects at scale 1:500 to1:1000. The Information Model Geography (IMGeo) was established in the Netherlands in 2012 and describes the content of the BGT, covering both the geometry and semantics of objects. The mandatory core model contains object definitions for large-scale representations of roads, water, land use, land cover, bridges, tunnels, etc. The optional part of IMGeo contains an extension to 3D (Van den Brink, Stoter, & Zlatanova, 2013a, 2013b). In addition, the optional part of IMGeo allows further division of objects into parts suitable for maintenance, and contains definitions for all kinds of city furniture and other non-mandatory classes. It should be noted that the 3D geometries that we generate for buildings within this research could be the (countrywide) 3D extension of IMGeo for buildings. BGT data is acquired from aerial photos and terrestrial measurements. The data positional data accuracy varies per object type and ranges from 30 cm for railways, roads and buildings to 60 cm for water, vegetation and other land use.

Compliant with the mandatory part of IMGeo, the data is collected and maintained by municipalities, water boards, provinces, ProRail (the manager of Dutch railway network infrastructure) and Rijkswaterstaat. These data providers are required by law to provide their objects that fall under the definitions of the IMGeo core to the national 'basic registry' where they are available via a national geoportal (i.e. PDOK) for reuse. The prescribed actuality of the data in the registry depends on the type of object and is between 6 months (e.g. for buildings and roads) and 18 months (e.g. for water and vegetation). An example of BGT data is shown in Fig. 2.

3.3.2. BAG

The *Building and Address register (BAG)* contains all buildings and addresses in the Netherlands (BZK, 2018). The geometry of addresses is collected as points and those of buildings as polygons (i.e. outlines as seen from above). The BGT also contains building geometries, but they represent the footprints of buildings, which is in many cases similar as the outlines. The buildings in both data sets are linked via their unique IDs. Municipalities are responsible for collecting the BAG data and keeping the data up-to-date.

The geometry for BAG buildings is also acquired from aerial photos and terrestrial measurements and the data positional data accuracy is 30 cm. The BAG data is provided via the national geo portal PDOK both in a viewer and as a download service.

3.3.3. AHN

The national height model of the Netherlands (called AHN; see www.ahn.nl) is a point cloud acquired by airborne lidar systems. The first version of AHN (with a density of at least one point per 16 m^2, and in forests one point per 36 m^2) was completed in 2003. In the period of 2009 to 2012, the second version of the data set was acquired with an average point density of 10 points per square meter. Currently data for the third version (enriched with pulse count information) has been collected and is becoming available in chunks, after being validated and corrected. The point density of AHN3 is similar as AHN2. For the AHN2 and AHN3 point clouds it is specified that an object of 2×2 m can be mapped with an accuracy of at least 50 cm. The height accuracy is 10 cm. In addition, it contains a classification of the point cloud. Because AHN3 coverage for the complete Netherlands is only expected in 2019, we use AHN3 for the areas for which the data is available (about two third of the country). For the other areas, we use AHN2.

3.4. 3dfier

3dfier is a software that takes 2D GIS data sets (e.g. topographical data sets) and "3dfies" them (i.e. "making them three-dimensional") by lifting every polygon to 3D (Commandeur et al., 2019). The elevation is obtained from a point cloud (in LAS/LAZ format), and the semantics of every polygon is used to perform the lifting. That is, water polygons are extruded to horizontal polygons, buildings to blocks, roads as smooth surfaces, etc. Every polygon is triangulated (constrained Delaunay triangulation) and the lifted polygons are "stitched" together so that one digital surface model (DSM) is constructed. The aim is to obtain one DSM that is error-free, i.e. no intersecting triangles, no holes (the surface is watertight), where buildings are integrated in the surface, etc. This surface can then be used as input in simulation software for instance.

3.5. Requirements regarding detail of the data

Noise simulation is a computationally intensive task. Therefore, the level of detail of the input data is a trade-off between representing reality as detailed as possible and keeping the data as simple as possible in order to reduce the computational complexity. This trade-off became apparent from our initial experiments where we feed output from 3dfier without any adjustment into the noise simulation software and the software was not able to simulate even a small area. Consequently, generalisation should be applied as much as possible within the accuracy requirements of noise simulation, i.e. remove small details when they are not relevant for the accuracy level of the simulation. In the current interactive preprocessing of data for noise simulations, this is addressed by modelling more detail nearby the noise source (where noise levels quickly change over small distances) and by reducing details further away from the noise source where the variances of noise levels are lower. The reduction of acoustically non-relevant details is a principle which we have incorporated in our developed methodology based on the expertise of noise specialists (which is detailed in the next section for each data layer). This is primarily done to ensure that the data set is computationally manageable by the noise simulation software.

4. Methodology for the reconstruction of 3D input data for noise simulation

In the following subsections (Sections 4.1–4.5), we describe for each of the input layers (respectively buildings, noise reflection/absorption, terrain, bridges and noise barriers) the data requirements as described in the noise calculation method and the method we developed and implemented to reconstruct the required data. Section 5 will show the quality and usability of the reconstructed data by applying the data to simulate noise values for a selected test case.

4.1. Buildings

4.1.1. Data requirements for buildings in noise simulation

Buildings are used in noise simulation to model both the noise reflection at the facades of buildings and the noise-protecting effect (i.e. shielding) behind buildings. To simulate those effects, the simulation requires block representations of buildings, the so-called LoD1 models. The calculation rules of SRM2 only support objects with one height, i.e. the sloping roofs (the so-called LoD2 representations) are not used in noise simulation. See Biljecki, Ledoux, and Stoter (2016) for a further explanation of Levels of Details of buildings used in 3D city models.

The calculation rules of SRM2 indicate how the impact of shielding by buildings should be calculated, but not how to determine the height of the building objects used in the calculation.

As described in Dukai, Ledoux, and Stoter (2018) and Biljecki, Heuvelink, Ledoux, and Stoter (2018), the LoD1 models automatically generated by various persons or organisations based on 2D building polygons and point clouds can differ from each other due to various reasons. The calculated reference height may differ, i.e. is the representative height of a building the highest point of a roof or the gutter height? Also, differences may occur in the underlying statistical calculations to determine the height of the blocks based on points that fall within the building polygon: does a chimney count? Or is (therefore) the average height or median of the points within a polygon a better number to represent the height of the building block?

4.1.2. Reconstructing LoD1 building models for noise simulation

Representing buildings with roof shapes (i.e. LoD2) is popular within the 3D city modelling domain and many researches have carried out studies to automatically generate LoD2 models (Jung, Jwa, & Sohn, 2017; Verdie, Lafarge, & Alliez, 2015; Xiong, Elberink, & Vosselman, 2014; Zebedin, Bauer, Karner, & Bischof, 2008). Less research has focused on the generation of LoD1 models, as they are less popular for visualisation purposes.

Block representation of buildings as required in noise simulation can be straightforwardly generated fully automatically from point clouds and 2D building polygons (i.e. footprints), which are increasingly available as open data. Therefore, LoD1 models are already frequently generated by various organisations and are used in applications such as wind flow simulations, prediction of energy consumption and loss, and noise simulations Biljecki, Stoter, Ledoux, Zlatanova, and Çöltekin (2015).

However, there are still some challenges in the reconstruction and use of LoD1 models, as mentioned above, since automatically generated

LoD1 models for the same area can differ in their reference heights for various reasons. Many users are not aware that there are a large number of options for modelling buildings as blocks based on their 2D polygon, while these options do influence the outcome of analyses for which the LoD1 models are used, see Biljecki et al. (2018). In addition, usually little is known about the quality of the automatically reconstructed LoD1 models because no metadata is generated or kept.

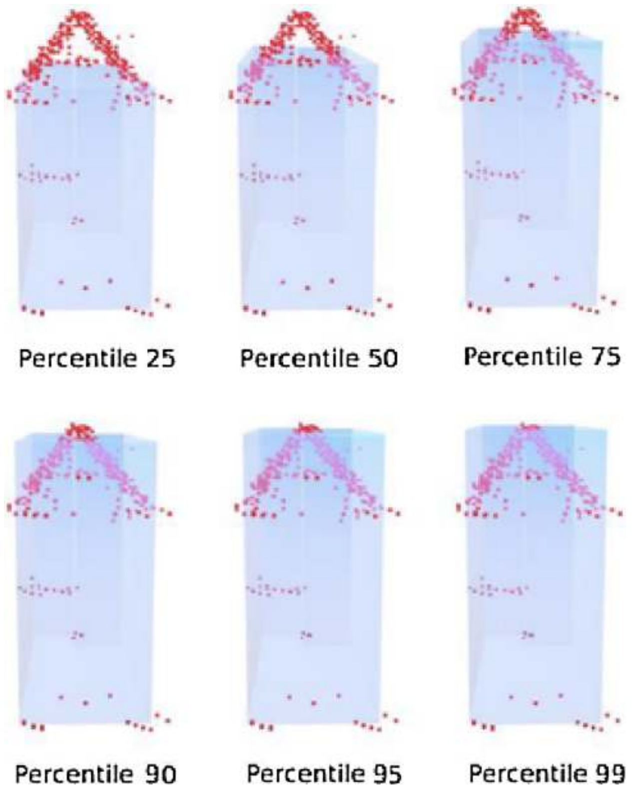
To standardise possible LoD1 variations, to let the user choose which one to use and to provide the user with insight about the generated models, we developed a 3D building service. The service generates multiple reference heights per building based on statistical calculations on height points that are inside the building footprint (i.e. 25, 50, 75, 90, 95 and 99 percentile heights), and updates the 3D models monthly for all 1̃0 million buildings in the Netherlands (3DBAG.BK.tudelft.nl) (Dukai, Stoter, & Ledoux, 2019). The service uses the BAG and AHN data sets as input.

This service is based on the 3dfier software (see Section 3.4) and generates block models from building polygons (see Section 3.3.2), based on height points (AHN) (see Section 3.3.3) that fall in the footprints of buildings.

For ground level height references (the minimum height of a 3D BAG building from which a building is extruded), i.e. 0, 10, 20, 30, 40 and 50 percentile heights, are calculated based on ground points in a 0.5 m buffer around the footprint (see Fig. 3).

The calculated ground level and reference heights are all added as attributes to the 2D BAG geometries. The user can then extrude the 2D building footprints to a height that best suits her needs. Users can view, query and download 3D BAG data via this website. The generated data set for the whole of the Netherlands is available WFS and WMS services (Dukai, 2019). The data set and the LoD1 service are described in more detail in Dukai et al. (2019).

For the generation of building models for our noise study, we use the 95 percentile height to represent the maximum height of buildings as prescribed in the noise calculation method and at the same time exclude outliers such as height points on chimneys.


Percentile 25 Percentile 50 Percentile 75

Percentile 90 Percentile 95 Percentile 99

Fig. 3. Visualization of the calculated reference heights based on percentiles and the height points that are used in the calculation for each building.

The noise reflection cannot be calculated properly if the facade segments are too detailed. Therefore, we first generalise 2D building polygons with the Douglas-Peucker line-simplification algorithm (Douglas & Peucker, 1973) before we assign heights to them with the software 3dfier. We use a threshold of 15 cm to remove unnecessary details but keep the main orientation of the facades of the buildings. Notice that this does not completely guarantee that the orientation of some facade edges is not affected, which may affect simulation results. However, in consultation with noise experts it was decided that this is an acceptable trade-off.

4.1.3. *Quality of the extruded building models*

Our developed service also generates information on the quality of the generated building models, in order to offer a user the opportunity to improve specific building objects before using it for an application, for example when a building is newer than the height data used. The quality data that we generate for each building and add as attribute are:

- when a building is newer than the used height points which makes the calculated height reference invalid
- how many height points are available for the calculation for that building
- Root Mean Square Error for each percentile. This shows to what extent a block model actually represents the building.
- whether the roof is flat or not (the generated block models mostly have higher accuracy for buildings that have flat roofs).

To obtain insight in the quality of the generated buildings covering the whole of the Netherlands, we carried out several analyses (Dukai et al., 2019). Firstly, we calculated the percentage of buildings that are newer than the point cloud used (and have therefore an invalid height). In the March 2019 version, 3.9% of the approximately 10 million were found to be newer than the height data used. Additionally, we determine the number of buildings for which no AHN height points are available. For the March 2019 version, 2% of the buildings have no roof height and 2.3% have no ground height. Missing height data can be caused by different reasons, for example when there is a new building or when a laser beam cannot reach the ground, such as the ground level at a building that is completely occluded by other buildings or buildings under bridge. The main reason for missing ground heights is an occasional, slight misalignment of the footprints and the point cloud. In these cases, the small search radius (0.5 m) is not sufficient to bridge the gaps of missing AHN points (usually due to occlusion at the foot of the building), and the buffer of building points, thus no ground points are found for the model.

To obtain further insight into the quality of the generated building data, we also investigated to what extent the geometry for the different percentiles approximates the actual building. For this, we have reviewed the RMSE for all the buildings in the Netherlands, see Fig. 4.

It shows that the median RMSE is 1.06 m for not-flat roofs and 0.31 m for flat roofs. Also, there is minimal variation in RMSE across all percentiles in buildings with flat roofs, while in case of not-flat roofs the RMSE is inversely proportional to the percentile. For buildings with not-flat roofs, the RMSE remains below 1 m for percentiles 75–99, from which we can conclude that automatically generated LoD1 buildings are indeed suitable for most GIS analyses.

4.1.4. *Reconstructing LoD1.3 building models for noise simulation*

For more detailed noise studies, we also represent height jumps that may occur within one building (represented by one polygon in 2D), for example in case of a church with a tower or a house with an attached garage. Some noise studies require such buildings to be split up to be able to represent these details, for example nearby the noise source where such details are more critical. According to the framework of Biljecki et al. (2016) these are LoD1.3 models of buildings.

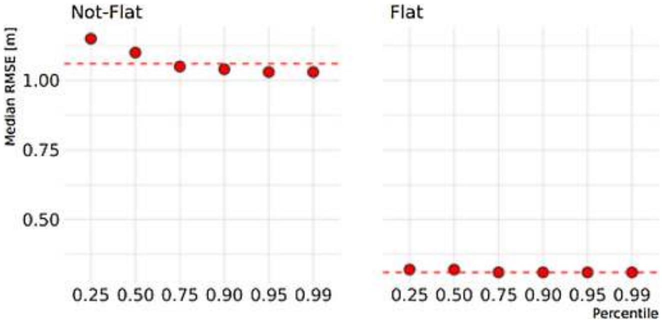


Fig. 4. The median RMSE of the geometric difference between the point cloud and extruded 3D building models, analysed for both non-flat roofs (left) and flat roofs (right). The median per roof type is indicated with the red dashed line, which is 1.06 m for non-flat roofs and 0.31 m for flat roofs. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

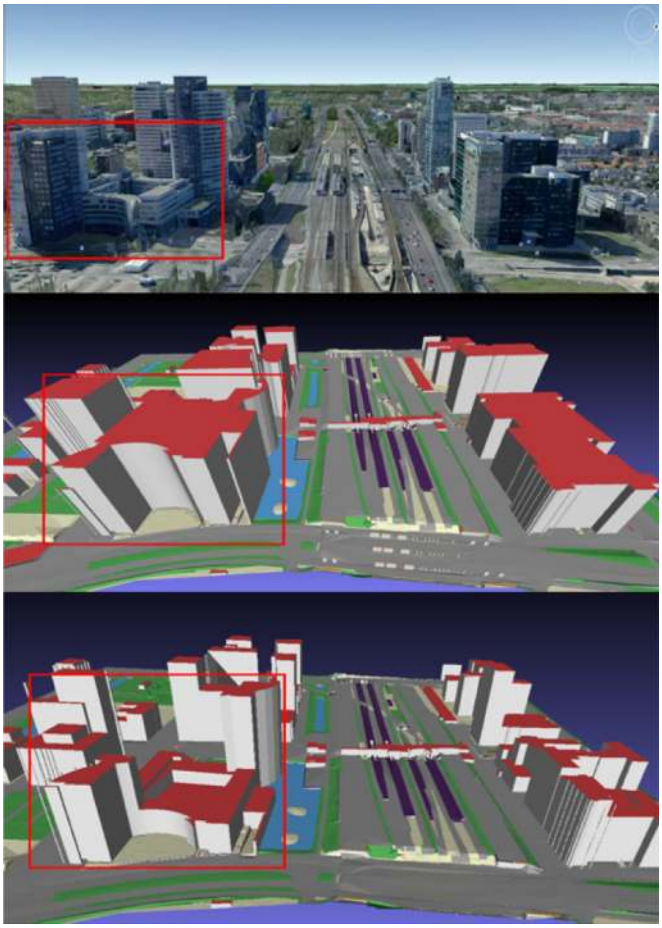


Fig. 5. (a) Single building (Google Streetview), (b) modelled as LoD1, (c) modelled as LoD1.3.

To model LoD1.3 models, we firstly detect the existence of a significant height jump within a single building and assign this information with a Boolean attribute to the building object and secondly, we model it as such (see Fig. 5). A user can then choose to use this LoD1.3 representation instead, i.e. a block representation of a building with varying extrusion heights for different parts of the building.

We first implemented the method of Commandeur (Commandeur, 2012) to automatically reconstruct LoD1.3 buildings. This method is based on the geometry of the 2D footprint: boundaries of footprints are extended inwardly until they touch the boundary at the other side of the polygon. The result is a decomposition of the footprint, see Fig. 6. The cells of the decomposition are then extruded individually and cells that share the same height are merged again.

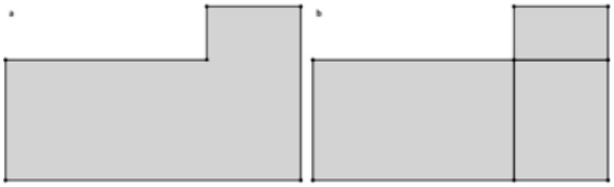


Fig. 6. (a) Original footprint, (b) decomposed footprint.

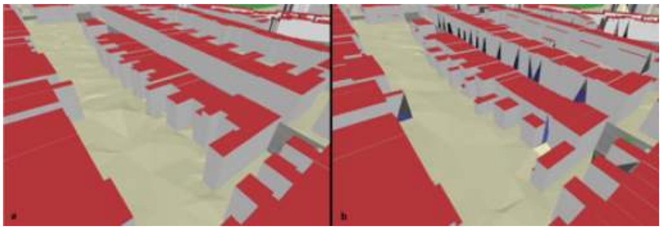


Fig. 7. Our 2D footprint segmentation method to reconstruct LoD1.3 (right) gives good results for simple buildings (left).

We have applied the decomposition algorithm to a test area in Delft and extruded the resulting polygons with 3dfier. For simple building footprints (Fig. 7) the method works well. However, with more complex buildings (Fig. 8), the resulting model consists of too many parts and is far too complex for noise simulation. Consequently, they require post-processing such as aggregation of small parts.

We therefore developed a 3D decomposition method that directly uses the point cloud to find boundary lines. The method reconstructs a LoD1.3 representation for each building in the following way:

1. Perform plane detection and identify all roof planes (Fig. 9a);
2. Detect the boundary of the roof planes using α-shapes (Edelsbrunner & Mücke, 1994) (Fig. 9b/c);
3. Perform line detection and a regularisation on the detected boundaries for each roof plane (Fig. 9d);
4. Decompose the footprint by inserting the regularised boundaries into a 2D arrangement (Fig. 9e);
5. Extrude each cell in the decomposition to its representative height (Fig. 9f).

Fig. 10 shows the results of both our 2D method and our improved 3D method for the same church. The method can account for the degree of decomposition by specifying a minimum height jump. To achieve this, adjacent cells with a height difference below a specified minimum height jump are merged in the footprint decomposition phase (step 4). Different LoD1.3 representations can thus be generated for each

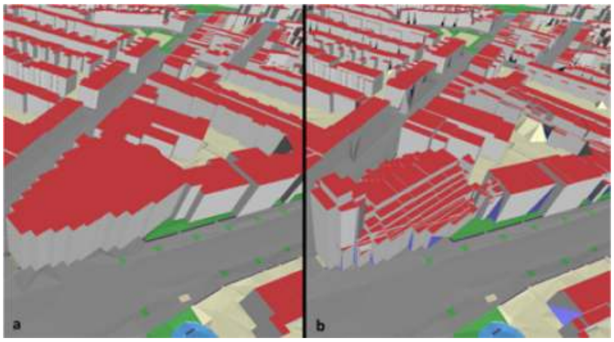


Fig. 8. Decomposing the footprint of a church with our 2D approach results in too many parts.

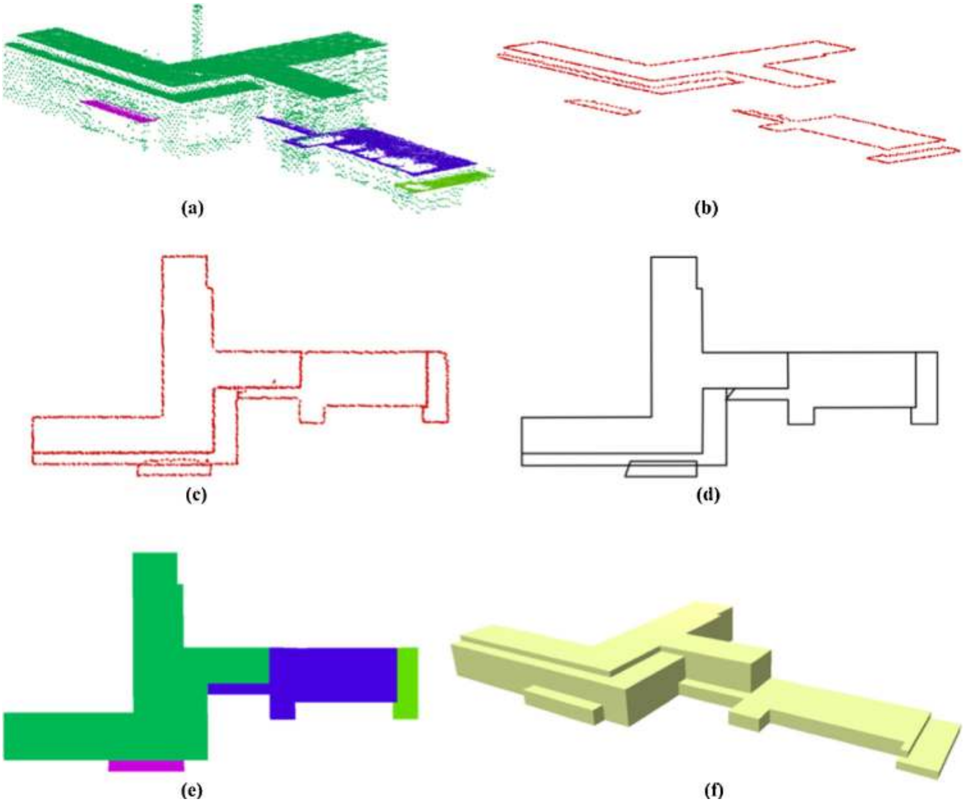


Fig. 9. The steps in our improved method to reconstruct LoD1.3 buildings.

building on the basis of different minimum height jumps. In our project we have experimented with different minimum height jumps (1, 2, 3 or 4 m) and compared these with the non-segmented LoD1 building models. The optimal values for the minimum height jump – as well as the optimal threshold value for the 2D generalisation (1, 1.5 or 2 m) – will be further fine-tuned with noise simulation practitioners.

For buildings with only horizontal roof parts, the method works well because in these cases an LoD1.3 representation is very close to reality. In case of sloped roofs on the other hand, there can be an ambiguity in how to perform the LoD1.3 modelling, especially when there are no vertical walls to separate different roof parts. Also for noise experts it is not straightforward to decide how to best split up such buildings and to assign representative heights (see Fig. 11).

To aid noise experts in deciding which LoD to use for which buildings we provide an attribute "*roof_type*" for each building. This attribute can have the following possible values:

- 2: roof with at least one sloped roof
- 1: roof with multiple flat roofs (and no additional sloped roofs)
- 0: roof with exactly one horizontal roof, i.e. the LoD1 and LoD1.3 representations are exactly the same (and would also be the same for LoD2)
- −1: no height points found
- −2: height points found but we were not able to reconstruct the roof

In the future we plan to investigate how the LoD1.3 modelling can be improved for buildings with sloped roofs based on how the results of the noise simulation are affected.

4.2. Noise absorption and reflection

4.2.1. Data requirements for noise absorption and reflection characteristics in noise simulation

The absorbing and reflecting properties of the terrain are modeled in noise simulation as '1' (acoustically absorbing), '0' (hard, reflective) or '0.5' (half reflecting for ZOAB (*Zeer Open AsfaltBeton*, (two-layer) Offenporig Asphalt (OPA)). In current noise simulation practice, various sources are used to generate geographical data about the terrain containing these characteristics, such as the digital topographic map at 1:10 k of the Kadaster, the Land Use data of Statistics Netherlands or the BGT.

4.2.2. Reconstruction of noise absorption and reflection characteristics

To generate terrain polygons with values '1' (acoustically absorbing) and '0' (reflective), we use the BGT as a basis because it is accurate, up-to-date and available for the whole country. Together with the noise experts we have made a conversion table from the different BGT classes to 1 and 0 values, see Table 1 for examples.

Ideally, there would also be a value of 0.5 for OPA. But this pavement type is not classified in the BGT and therefore it falls outside the scope of our project. After converting the BGT objects into surfaces with the absorption/reflection noise factor, we aggregate the adjacent

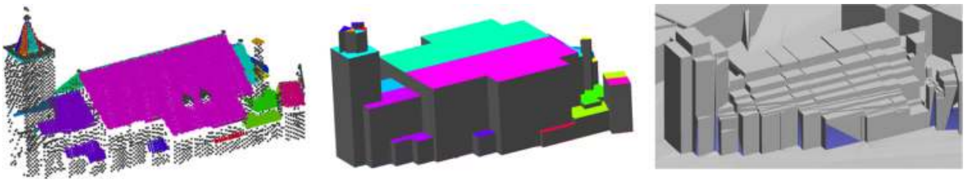


Fig. 10. Point cloud with plane segmentation (left), LoD1.3 model with our 3D approach (middle) and LoD1.3 model with our 2D approach (right).

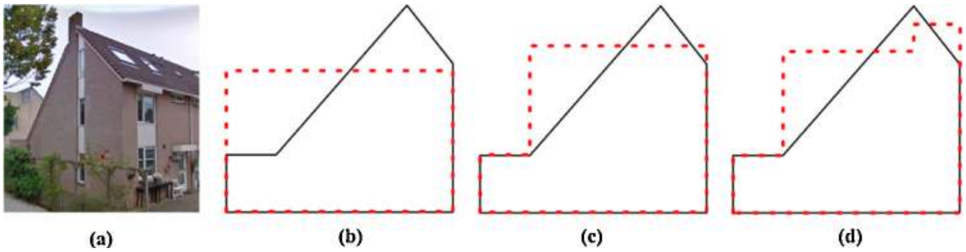


Fig. 11. Three different LoD1.3 modelling possibilities (b,c,d) for a building with an asymmetric gabled roof (a).

Table 1
BGT-class and conversion to noise-reflection value (hard and soft).

#	BGT class	Noise-reflection
1	Water	Hard
2	Paved terrain with no vegetation	Hard
3	Unpaved terrain with no vegetation (e.g. sand)	Soft
4	Vegetation	Soft
5	Building	Hard
6	Engineering construction	Hard
7	Bridge	Hard
8	Paved roads	Hard
9	Unpaved roads	Soft
10	Roads paved with Offenporig Asphalt (OPA)	0.5 absorption

surfaces with the same noise factors. The scale of the BGT is between 1:500 and 1:1000 and therefore contains a lot of details. Consequently, after the aggregation the data is still too detailed for the noise simulation in relation to the calculation time versus the required accuracy level of the data. For this reason, we eliminate small areas (i.e. smaller than 6 m^2). In addition, the boundaries are generalised using the Douglas-Peucker algorithm with a threshold of 10 cm, while keeping the topology of neighbouring polygons. The end result is shown in Fig. 12.

4.3. *Height of the terrain*

4.3.1. *Data requirements of terrain height in noise simulation*

The height of the terrain is used in noise simulation to simulate the degree of noise absorption/reflection by the surface of the terrain. In addition, height differences in the terrain can have a noise-protecting effect because it can act as a noise barrier. Finally, the terrain height in noise models often forms the height-basis to assign height information to objects such as roads and railways. The input for the height description of the terrain are 3D lines, possibly supplemented with individual height points. Using these lines as input, the simulation software generates cross-sections between the noise source and the calculation point as well as a Triangular Irregular Network (TIN) to simulate the mentioned effects.

4.3.2. *Reconstruction of terrain heights for noise simulation*

For the use of the terrain height in noise simulation, 3D polylines are needed that describe the height of the terrain with as few lines as possible, i.e. lines are only needed to represent noise-relevant changes in the terrain (local ridges and valleys). Creating a TIN from all the height points and derive isolines from the TIN would result in much too much data. In current practice, the needed height lines are usually obtained semi-interactively on the basis of available height data. To address the need for as few data as possible, the noise professional generates height lines at high detail near the noise source (where noise levels variance is higher) and height lines at low detail further away from the source. It is very hard to imitate these decisions of noise professionals and produce different levels of detail depending on the distance from the noise source. Nonetheless we have developed a method to remove non-significant height data as much as possible. For this, we use information that is available in the BGT. We assume a height difference on the boundary lines between different object types such as road-water, road-vegetation, etc. We also use the slope information in the BGT. According to the specifications of the BGT:

> *A 'slope' needs to be represented as such in the BGT if the height difference is at least 1 meter and the slope is 1: 4 or more. The feature to represent the slope is an attribute of either a road, auxiliary traffic area or terrain (all polygons) and the line at the ridge. If there is more than one object type on a slope, only the highest object contains the line representing the ridge. An object lying on a slope is always a separately bounded object with respect to an adjacent identical object that does not lie on the slope.*

We generate the 3D lines that describe the terrain for noise simulation) as follows:

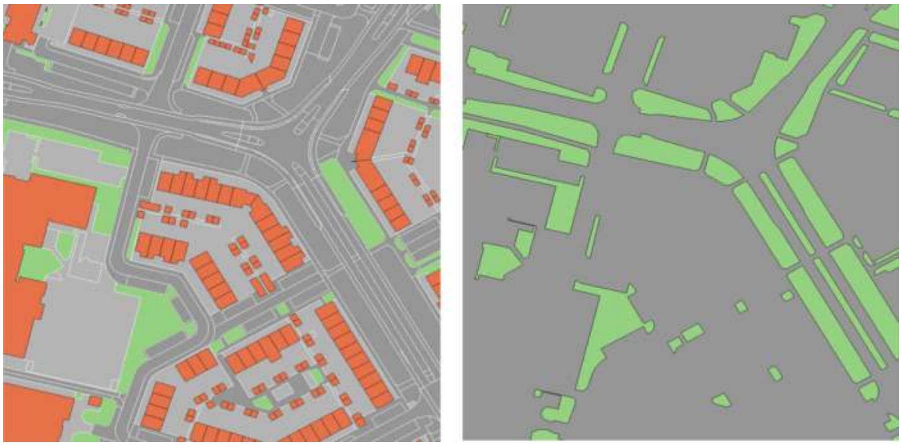


Fig. 12. Left: original BGT data; Right: after conversion into hard/soft values and aggregation.

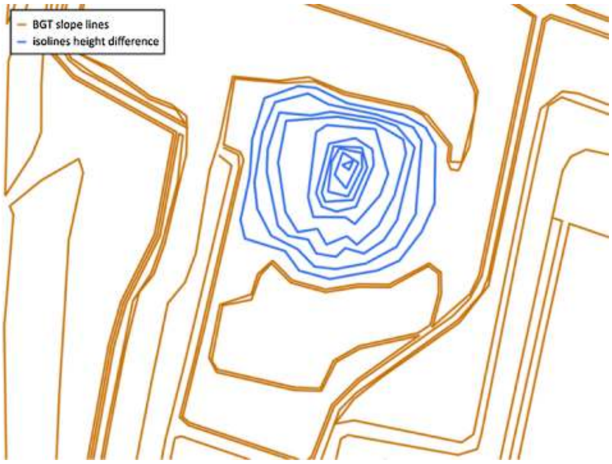


Fig. 13. Generated lines for the description of the terrain height.

- BGT objects with areas smaller than 1 m^2 are removed (because such height details are not relevant according to the noise experts).
- All neighboring objects of the same class are aggregated, taking into account BGT slope lines. We keep the latter.
- The selected BGT lines are set at height using a TIN based on the point cloud.

From an analysis of the differences between the resulting lines and the original height values within some test areas, it turned out that in the BGT at some locations the slope lines are missing where they should have been modelled according to the BGT definition. At these locations with BGT omissions we needed to make the terrain description more accurate by adding extra height information. In addition, our algorithm needed to be extended with local valleys because – in contrast to ridges – these are not modelled in the BGT. To include the missing local ridges and valleys, we improved our method in the following way (see Fig. 13):

1. A TIN is generated from the generated BGT-based height lines.
2. A TIN is generated from all points in the point cloud (without BGT lines).
3. The differences between both TINs are calculated and isolines are generated from these differences.
4. The isolines (representing the difference) of 2 m and higher are selected and based on the point clouds, these lines are converted into 3D polylines.
5. The selected and 3dfied lines are added to the BGT-based height lines.
6. Finally, unnecessary details are eliminated:
   (a) Very short lines are deleted when $<$ 0.5 m in length.
   (b) With the 3D lines a TIN is reconstructed and for each line the impact is determined after eliminating the height line. If the resulting height error in the TIN is negligible ($<$ 0.5 m), the line is permanently deleted.
   (c) The remaining lines in 3D are simplified using the Visvalingam line-simplification algorithm (Visvalingam & Whyatt, 1993) with a threshold of 10 m^2 so that the number of vertices per line are also reduced.

Fig. 13 shows the final result for both the BGT slope lines and the lines that were added using the isolines of the height difference with the point cloud.

4.4. Bridges

4.4.1. Data requirements for bridges in noise simulation.

Bridges have a separate role in the height description of physical environment in noise simulation. Firstly, because the height is difficult to reconstruct due to missing height points under bridges. Secondly, because standard noise simulation software has only limited support for bridges. After consulting with noise experts, bridges seem best to be modeled as floating surfaces that connect to adjacent road sections that are modelled as part of the terrain (see previous section).

4.4.2. Reconstructing bridge objects.

Automatically reconstructing bridges from BGT and the point cloud appeared to be a complex task because of missing height points under the bridges. In addition, bridges in the BGT are often not correctly modeled topologically (although clear guidelines are lacking). As a result, there are holes and overlap between road sections and the adjacent bridge sections. These errors are not or hardly visible, but the consequence is that automatic reconstruction of bridges and non-level crossings is an almost impossible task.

However, we have developed a method that works well for most bridges, see Fig. 14. By using an iterative 3D plane segmentation in the point clouds in the close surrounding of bridge sections, the most plausible 3D topological connection is calculated. With this connection we assign the correct height to the surrounding areas and the required floating bridges can be generated. The current method covers also the reconstruction of multi-level bridges that occur in complex road networks with multiple levels of crossings at different heights. An

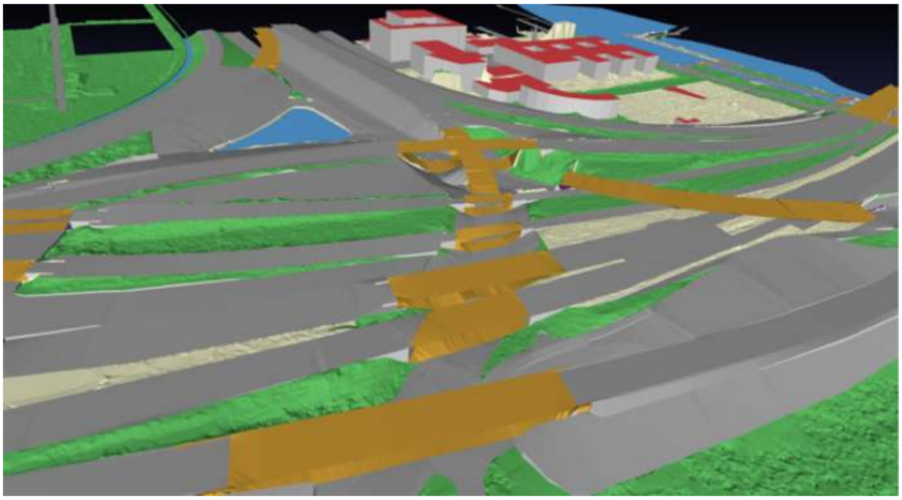


Fig. 14. Automatically generated bridge parts (brown).

improved modeling of bridges in the BGT could significantly increase the success of this method.

4.5. *Noise barriers*

4.5.1. *Data requirements of noise barriers in noise simulation*

Noise barriers protect the areas behind the barriers against the noise. These are imported in noise simulation as 3D lines with a height value per vertex. In simulation software, the lines, which represent the top of the barriers, are extruded downwards resulting in vertical “walls” (as required in the noise simulation).

4.5.2. *Reconstruction of noise barriers for noise simulation*

Information about noise barriers is available in the BGT class ‘Separation’ (*Scheiding*) with the attribute value of ‘noise barrier’ (*Geluidscherm*) for the attribute ‘physical occurrence’. For areas owned by Rijkswaterstaat (RWS), information as needed in the noise simulations is also included in RWS's *Geluidwerende Voorzieningen database (GWV)*. This is a database of RWS with all objects that protect against noise.

Due to different purposes of both data sets, the noise barriers differ in both data sources in terms of location, geometry and population (see Fig. 15). The lines in the GWV have specifically been obtained for noise simulations and represent the top of the barriers. They are therefore in principle the most suitable. The height of the lines is acquired terrestrially or is known through the design of the barriers. The lines in the BGT indicate the location where the noise barrier touches the ground level. This does not always coincide with the top of a screen as needed in noise simulation, e.g. in case of a sloping screen. Non-relevant details for noise simulation, such as underlying uprights, are also not modeled in the GWV in contrast to the BGT. For a complete picture, the noise barriers in the GWV must also be supplemented with noise barriers along regional and local roads.

To have one uniform and complete data set on noise barriers, it is preferable to manage all information about noise barriers as required for noise simulation (with noise reflection values and height) in one data set, which could be the BGT in the future.

5. Experiments, results, and discussion

In this section we assess our methodology in two ways (1) through qualitative inspection by noise experts and (2) by applying the reconstructed data to a real-world noise study and quantifying the differences of the calculated noise levels at selected observation points in both simulations.

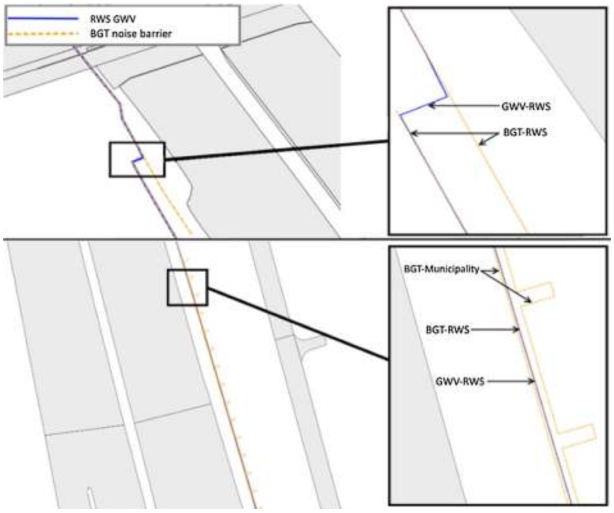


Fig. 15. Examples where noise barriers in the BGT and GWV differ.

5.1. *Qualitative assessment*

For the qualitative assessment, we involved noise experts in an iterative manner throughout the entire process of developing and implementing our methods to generate the data. During this process, noise experts were provided with several alternatives of the input data for critical assessment on the use of these data in noise simulation and the results were discussed in interactive sessions. Based on these assessments, the methods were improved (e.g. the reconstruction of LoD1.3 buildings and the improvements of the generated height lines, as described above) and appropriate threshold values such as for the simplification of height lines and modelling height jumps within buildings were determined. In the end, the final results have been published https://3d.bk.tudelft.nl/opendata/noise3d/en.html and discussed in a public session that was attended by more noise experts. The involved noise experts came both from four governmental organisations (municipalities, the road maintenance authority and the ministry of traffic and water) and seven companies who usually carry out noise studies for governments at all levels. They all had ample experience in working with the standardized noise calculation method implemented in commercial software as well as the preparation of the required input data for the noise calculation method. They assessed the end results as promising and emphasised the importance of making the results available to the wider public in a more sustainable way, so that the status of it can be further matured.

5.2. *Quantitative assessment*

For the quantitative study, we selected a test area near Nieuwegein, a middle large city in the centre of The Netherlands, at the crossing of several highways. In 2017, the company DGMR performed a noise study for Rijkswaterstaat in this area to determine future impact of noise caused by the surrounding highways. The input data in this study was semi-automatically generated from AHN data and manually improved. The noise absorption and reflection values were based on the 1:10k data set of the Kadaster, which is less accurate than the topographical data that we used as base (BGT). The noise simulation of this study was done with the GeoMilieu software which implements the Dutch calculations methods for noise. DGMR is the provider of this software.

To compare the two different data sets, DGMR redid the calculation for this study and replaced the data on buildings, noise absorption/reflection and height lines, with data that we automatically reconstructed for the same area. The data on the noise source (high ways) and the location of observation points were kept the same as well as were other data such as traffic intensities. Because the original study was done with LoD1 only, LoD1.3 buildings were not considered in this assessment, see Fig. 16.

It should be noted that our experiment only provided insight into the differences in results, rather than in which method is better.

Fig. 17 shows the differences between the simulation outcomes for the test area on about 1000 observation points. As can be seen from the figure, the differences range from −2.17 dB to 1.83 dB.

We calculated the following statistics for the differences:

Mean difference	0.1 dB
Standard deviation	0.7 dB
95% confidence interval	0.1 dB

According to the noise experts, these differences fall within the accuracy range of noise simulation which is 1 dB, i.e. if four different persons would create the input data for one area, the outputs would show a similar (or even a higher) variance. Therefore, we can conclude that for 95% of the observation points the automated reconstructed data does not result in a significant difference, while our data improve the efficiency and reliability of noise studies, i.e. the input data that we

Fig. 16. Screenshot from the reconstructed noise data in noise simulation software GeoMilieu.

reconstructed are generated once in an automated manner based on the most up to date source data and can be used in any noise study. Our method has therefore proved to be successful.

For 5% of the observation points, the differences were exceeding the reliability interval. By further inspection by noise experts it appeared that often these differences were caused by more detailed and up-to-date (and therefore improved) data in our methodology (e.g. use of BGT instead of 1:10k land use data), which means that the quality of our data (and therefore of the calculated noise levels) are sometimes higher. In the future we will study further improvement and simplification of the reconstructed data while keeping the acoustically relevant characteristics. We will run the simulation with different degrees of simplification to study these effects. In addition, we will test in more areas, to make our algorithms more robust, i.e. applicable for specific situations that may occur elsewhere.

6. Conclusion

This paper presents our methodology to automatically reconstruct 3D data about buildings, noise absorption/reflection, terrain height, bridges and noise barriers, from countrywide available 2D topographical data and point clouds for noise simulation. From the experiments of applying our methods to reconstruct data for a real-world noise study and from the assessment by noise experts, we can conclude that the results fall within the accuracy range for noise studies and therefore that our methodology is suitable for use in practice.

Automatically generated input data for noise simulation, as studied in this paper, can be considered as a major step in noise studies. It does not only significantly improve the efficiency of noise studies, thus reducing their costs, but also assures consistency between different studies and therefore it improves the reliability and reproducibility. In addition, the availability of countrywide, standardised input data can help to advance noise simulation methods since the calculation method can be adopted to improved ways of 3D data acquisition and reconstruction. The algorithm to reconstruct 3D geometries of buildings that we have developed within this research could be used to generate the (countrywide) 3D extension of IMGeo for buildings. This is currently further being investigated.

In future work, we plan to apply our algorithms to other test areas and evaluate also these results in sessions with expertised noise

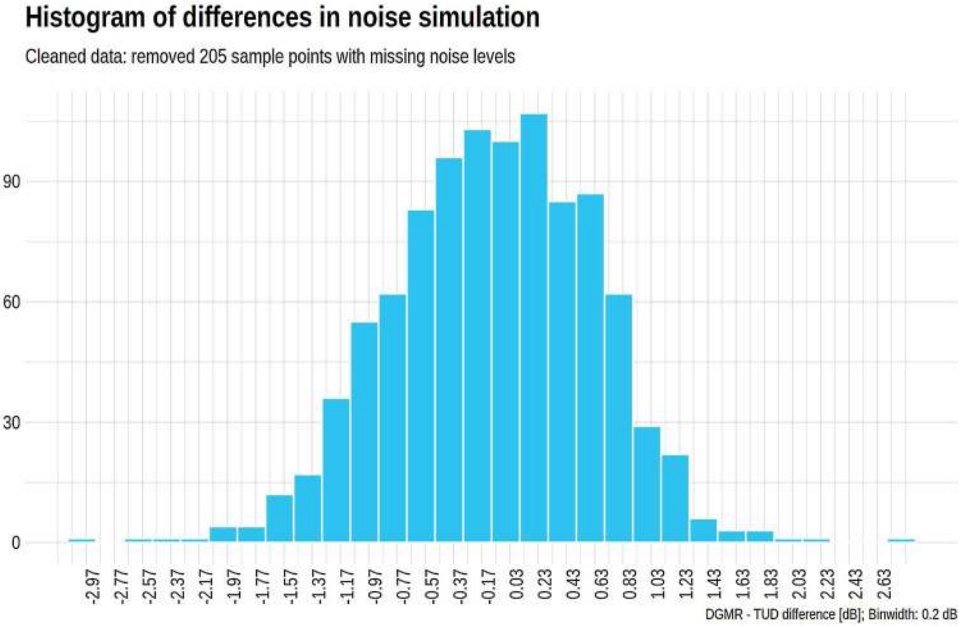


Fig. 17. Histogram of differences in results of noise simulation between the simulation based on the original input data and based on our generated input data.

modellers. This will help us to further decide on optimal ways of modelling input data also in relation to the impact the choice of parameter values has on the noise simulation results, so that we can implement these adjustments accordingly. In our iterative discussions with noise experts, we observed that even for manual data creation, it is often ambiguous what the best decision is, for example for the reconstruction of a LoD1.3 building as shown in Fig. 9. Therefore, these feedback sessions with noise modellers will help to standardise such decisions to obtain consistent input data for noise simulations.

Another topic for future work is to generate a TIN representing the height of the terrain that can directly be read by the simulation software. The current process derives height lines from a TIN, which are again transferred to a TIN in the simulation software. This evidently results in information loss. The direct use of the generated and simplified TIN will be studied in close collaboration with the simulation software developers.

Future work will also study further simplification of the reconstructed data while keeping the acoustically relevant characteristics. We will run the simulation with different degrees of simplification to study these effects. We will also see if the extent of simplification can be adjusted to the aim and area of the study: further simplification for larger study areas, like a province, for which also a lower accuracy level is required and less simplification for local studies.

Other topics for future work are scaling up to the whole country, developing a standard for the formal definition of input data for noise simulations, investigating how the data can be kept up-to-date (which is possible by using point clouds generated from aerial images which are yearly acquired)ivestigating how historical versions of input data (used for studies in the past) can be maintained and kept available, and improving the input data concerning bridges.

Finally, we are exploring the 3D data reconstrcution for other domain, This research showed how methods to automatically generate application-specific 3D data can be designed and implemented by a close collaboration with domain experts. Based on these experiences, we are currently developing and implementing similar methods with experts from other domains to generate 3D data from existing data sources to be used in other simulations, e.g. for flooding, air pollution and wind.

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Declarations of interest

None declared.

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