Generating consistent triangular landscape input data optimised for noise modelling purposes

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May 28, 2021

Used acronyms

AHN	Algemeen hoogtebestand Nederland (Dutch general elevation model)	8
BAG	Basisregistratie Adressen en Gebouwen (Basic registration addresses and buildings)	19
BGT	Basisregistratie Grootschalige Topografie (basic registration large scale topography)	10
DT	Delaunay triangulation	10
DTB	Digitaal Topografisch Bestand (Digital Topographic Data)	17
END	Environmental Noise Directive	6
GIS	geographical information system	7
LoD	Level of Detail	4
LiDAR	Light Detection And Ranging	9
TIN	Triangular Irregular Network	7
RMG	Reken- en Meetvoorschrift Geluid	4
NWB	Nationaal Wegen Bestand (National Road Data)	23

1 Introduction

Noise pollution (i.e. environmental noise) is a major health problem in Europe, especially in urban areas. The majority of the environmental noise comes from roads and railways, causing continual noise in work and living environments. This exposure to noise over 55 dB affects an estimated 135 million people in Europe (European Environmental Agency, 2020). Long term exposure to noise causes psychological and physiological stress leading to several adverse health effects. It can cause annoyance, cardiovascular diseases, reduced cognitive performance (mainly among children) and sleep disturbance. These effects in term can cause displeasure, higher stress levels, reduced learning performance and reduced energy levels respectively (Basner et al., 2014). The World Health Organization and Joint Research Committee (2017) estimated that each year, between 1.0 and 1.6 million DALYs (Disability-Adjusted Life-Years) are lost in the EU due to environmental noise, in 2020 this was estimated at roughly one million, noting that this was limited by the amount of data and expected to be higher. (European Environmental Agency, 2020). The WHO Regional Office for Europe (2018) strongly advices to reduce both the emitted noise itself and on the route between the source and the affected population. In order to reduce the noise pollution, i.e. reduce number of people exposed to harmful levels of environmental noise, this noise should be monitored.

The European parliament and European Union (2002) adopted a directive which required EU member states to produce noise maps every five years. A noise map is the representation of noise indicators, either modelled or measured, in a given scenario. Measuring noise using sensors is both cost- and time-expensive, especially for larger areas. Modelling noise using prediction software is relatively cheap, fast and scalable. It is therefore most common to model noise and use measurements as verification (Murphy and King, 2014). Modelling noise consists of two steps in common noise prediction software;

1. Determine the noise sources around a point of interest and extract the environmental information between the noise sources and the point of interest (i.e. retrieve and terrain cross section with semantic data) from an environment model.

2. Compute the perceived sound level at the point of interest, given the noise source and the spatial information in between these points.

Due to the many interactions of noise with its environment, its modelling is a computationally intensive task. To keep the computation time reasonable the environment (terrain) model is a simplified model of the real world. The Environment and Planning Act (Dutch law)[1], to be active from 2022, may increase the amount of noise computations as provincial roads and industrial sites will be included in a monitoring mechanism which is now only used for state roads and major railways. Also a new monitoring mechanism for city roads will be adopted. This increase in workload could benefit from more efficient models of the terrain. During this research the generation of such an efficient terrain model is studied where a balance between accurate noise output and a reasonable amount of detail is sought.

1.1 Noise modelling

As described, modelling noise generally consists of two steps, extracting individual source - receiver propagation paths and computing the noise level for each propagation. In order to extract the propagation path several input data sets are used of which the terrain and building data sets collectively represent the environment model. Regarding this model, there is no standard or law that prescribes the characteristics of the data sets used, resulting in a variety

[1] https://www.government.nl/documents/reports/2017/02/28/environment-and-planning-act

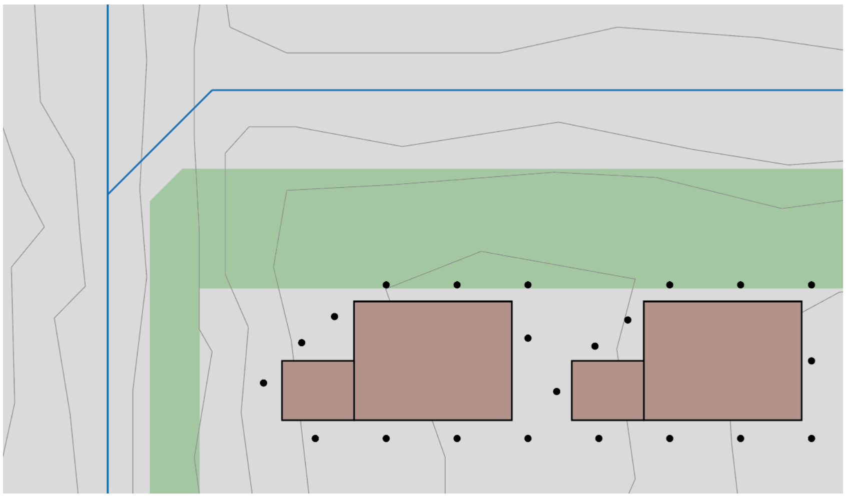


Figure 1: Schematic representation of typical noise modelling input data. Blue; roads, Grey/green; absorption factor 0/1, pink; buildings (including height), dots; immission points, grey lines; height lines.

of approaches and methods. But the following data sets are commonly included (also depicted in figure 1);

- Immission points; points where the perceived noise levels are to be determined.
- Noise sources; these are mostly roads and railways, but may include industry noise sources (aircraft noise is modelled separately). All sources either include emission levels on a dB scale directly, or it is derived from meta information like amount and type of traffic.
- Buildings; buildings with a certain Level of Detail (LoD), commonly 1.2 or 1.3 as described by Biljecki et al. (2016)).
- Elevation data; information about elevation of the natural terrain, excluding buildings and bridges.
- Noise barriers; barriers placed next to roads to reduce the noise level behind the barrier.
- Ground surface data; the ground surface has characteristics that may reflect or absorb noise.

In **step 1** all propagation paths for the receivers are extracted (see figure 2). Some EU member states prescribe methods on how to extract the paths, but this may not cover all aspects (e.g. the dutch method (Reken- en Meetvoorschrift Geluid (RMG)) provides some approaches for noise source allocation and valid reflections, but leaves room for interpretation in other situations (van Rijssel et al., 2020)). This reduces both the transparency of determination and cross comparison of noise maps produced with different methods. To account for this the ISO standard 17534[2] was developed which allows to compare results with sample data sets and methods. Peters et al. (2018) noted that the environment data is partly generated per project and thus overlapping projects result in duplicate work and may cause a different output.

In **step 2** the noise levels are computed for each source - receiver path (see figure 3). For this several methods are available, all publicly available. In the Netherlands this is the RMG 2012)[3]. More information about these standards in a European context is provided in section 1.2.

[2] https://www.iso.org/standard/59974.html

[3] https://wetten.overheid.nl/BWBR0031722/2021-04-01

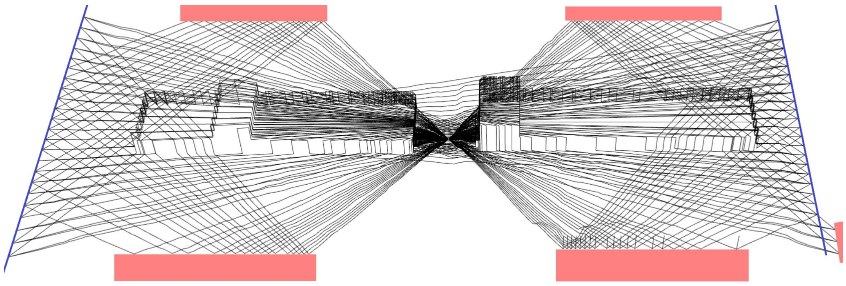


Figure 2: Schematic representation of step 1 of noise modelling; extracting propagation paths, a single receiver is located in the center with two roads on both sides. Representation includes several buildings in pink (and in the middle, which are included in the paths), direct and reflected paths (source: van Rijssel et al. (2020)).

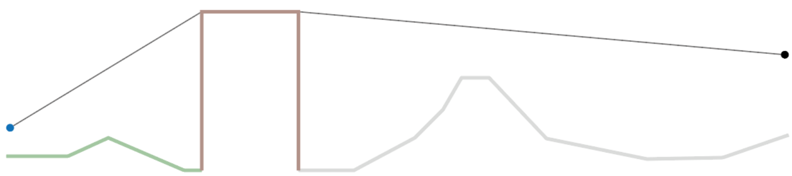


Figure 3: Schematic representation of the data in step 2 of noise modelling; a vertical cross section of the terrain to compute receiver noise level based on emission noise and terrain: blue dot; emission point, green line; absorbing ground, brown line; building, grey line; reflective ground, black line; shortest propagation path (diffracted) and black dot; receiver point.

In the Netherlands two commercial companies provide software applications to compute noise maps according to the RMG, namely DGMR (GeoMilieu)[4] and dirActivity (WinHavik)[5]. DGMR has a countrywide environment model with ground type, building and elevation data that is used in their model. To include elevation data these companies use height lines representing relevant height profiles in the terrain. In the software the elevation profile of the propagation path is extracted from the height lines and used to test for a line of sight and computation of mean height planes.

The noise levels that are predicted in the noise software are long-term yearly averaged noise indicators for specified time periods. As noise pollution during the night causes more harm, the WHO Regional Office for Europe (2018) recommended different maximum noise values for night emitted noise, namely 44 (rail) and 45 (road) dB. During the day this is 54 (rail) and 53 (road) dB. To include this difference in noise maps, separate noise level indicators are described, namely; L_{den} (day-evening-night level) (24h) and L_{night} (night level) (23.00-7.00h). Upon reading this report, the term (predicted) noise level refers to these noise indicators.

1.2 A European standard for noise modelling

When different methods are used, comparing noise maps remains troublesome. Therefore the Environmental Noise Directive (END) prescribes that a common noise assessment method is to be used by all EU member states, after it is developed (European parliament and European Union, 2002, Article 6.2). Such a method describes three main topics; Firstly, placement of immission points on the terrain for usable results. Secondly, computation of the predicted noise level given a terrain cross-section between noise source and receiver. Thirdly, prediction of generated noise levels from road, rail, industrial and aircraft sources.

In 2012 the Common NOise aSSessment methOdS (CNOSSOS-EU) was introduced (Kephalopoulos et al., 2012). The method was further developed and implemented in a new annex II of the 2002/49/EC directive (END) (European parliament and European Union, 2015). This directive states that the CNOSSOS method was to be used from December 31st 2018. In earlier mapping rounds, member states could use a method common to the other member states to produce noise maps every five years, e.g. 2007, 2012, 2017 (European parliament and European Union, 2002, Article 1.1a). Therefore, the method will be used in the mapping round of 2022. After initial implementation tests by the Netherlands it could be concluded that the CNOSSOS method provided reasonably accurate results in most scenarios, but also contained some flaws (Vergoed and van Leeuwen, 2018). This lead to an amendment for the CNOSSOS method (Kok and van Beek, 2019) that was accepted in December 2020 (European parliament and European Union, 2020).

While the incorporation of CNOSSOS will improve the comparability across noise maps from different EU member states with standardisation of noise sources and prediction of noise levels, it does not prescribe the environment model (in terms of format, quality etc.). Secondly, it does not prescribe how to extract propagation paths, i.e. what paths are valid or how to convert noise source line segments into point sources. Acknowledging the important progress CNOSSOS has brought, it still allows for variation between output noise maps when different input models are used.

1.3 Digital terrain modelling

As there are no standards on format or quality of the environment model, each country and their model suppliers can supply their models as they see fit. Data formats are reasonably

[4] https://dgmrsoftware.nl/producten/geluid-en-luchtkwaliteit/geomilieu/
[5] https://www.diractivity.nl/

predictable for noise sources (road/rail center-line or point representation), ground types (a raster or 2D tessellation with irregular polygons) and noise barriers (line segments with height attribute), but for elevation data commonly height lines are used, which may not be the most predictable. This section will shortly introduce how elevation data can be modelled and how suitable it is for noise modelling.

Elevation of a terrain can be represented in different structures and formats. In geographical information system (GIS) elevation is most often represented as a raster (pixel image), iso-contours (lines of equal altitude) or as a Triangular Irregular Network (TIN) (watertight surface mesh consisting of triangles). However, current noise modelling software in the Netherlands, and European alternatives use height lines.[4][5][6][7] These are lines in 3D Cartesian space representing relevant areas in the terrain. When considering a format for elevation data the following conditions are sought;

1. Assuring quality of the model, i.e. no relevant objects in the terrain are omitted. The quality of the model is important, as it defines the quality of the noise output, improving certainty of the outcome.
2. Represent the terrain with minimum necessary information, thus aiming to only store information with a significant impact in noise modelling. As noise modelling is a computer intense process of which the amount of elevation data highly influences the performance, minimizing this an important objective.
3. Efficient cross section extraction; extracting the terrain below the propagation path is done for each source - receiver pair, thus the data structure should allow efficient extraction.

In table 1 an overview of the methods and how they meet the conditions is provided. This is further elaborated in the text below.

Table 1: Overview of suitability elevation data structures for noise modelling.

Type	Quality assurance	Minimize data size	Cross section extraction
Raster	+	+/-	+/-
Iso-contours	+	+	- -
Height lines	-	++	- -
TIN	++	+	++

A **raster** data structure with sufficient detail where needed, will inherently provide abundant information in other areas. The quality can be assured, given a high resolution, but it exponentially decreases the performance. Extracting a cross section seems easy and straight forward, but comes with some challenges, e.g. what value should be selected if the cross section only crosses a small portion of the pixel? Does the pixel value represent the center or the average height? At last, the cross section might consist of many more or less collinear segments in flat areas, for which it might be time saving to simplify this before computing the noise level.

Using **iso-contours** allows to have a higher density of lines in steep areas and fewer in flat areas, matching with the minimal information condition. The step size provides a measure of accuracy and can provide certainty, but it does not prescribe the flow of terrain in between two lines. Finally, extracting a cross section is troublesome, as there is no information about

[6] https://www.datakustik.com/products/cadnaa/cadnaa/
[7] https://www.soundplan.eu/en/software/soundplannoise/

adjacent edges, one either requires to check all edges or use a refined structure like a KD-tree. It is also common to convert it to a TIN, which allows to walk over the triangles using neighbour relationships.

Height lines allow to only store relevant information, as it allows to place more lines at relevant areas and less in others. However, as height lines are either manually drawn or using as algorithm which follows user defined rules to define where to place height lines, and where not, is not guaranteed fail-safe. A large automatically generated data set is often manually checked and altered for specific areas, requiring human input and introducing human error. Extracting cross sections is troublesome due to no adjacency relationships, this is commonly solved the same as with iso-contours.

A **TIN** with a constant accuracy will, like iso-contours, provide more detail in steeper areas, and less in flat areas. The idea of a TIN is that it aims to represent a given terrain accurately, with as few points as possible, where the most relevant points from the point cloud are iteratively selected and added to the TIN. This continues until the difference between all points and the interpolated value in that position in the TIN is below a defined maximum deviation (see section 2.2). Therefore it guarantees the error not only at the vertices, but also within the triangles. It can therefore provide a guarantee of quality, given the accuracy of the input data. Finally, the possibility of storing adjacency (i.e. topologic relations between neighbouring triangles) allows to "walk" over the triangle and thus extract a cross section efficiently. While this adjacency requires storing more information and increasing the data size, it can increase performance. As the TIN can be generated one time, and used many times, this could result in time saving.

1.4 Collaboration on automated generation of input data

In 2017 RIVM, TU Delft and several other institutions started a collaboration to automate the generation of noise input data from country wide openly available data (Peters et al., 2018). The collaboration aimed to automatically generate noise modelling input data for existing software, which required the input elevation data to be a collection of height lines. It is likely that these lines are extracted from a TIN, as is done by Stoter et al. (2020).

Both publications mention that in noise modelling software like GeoMilieu, these height lines are converted back into a TIN when cross sections are computed. Arguably it requires duplicate work to extract lines from a TIN and then create a TIN from these lines. In addition, it first highly simplifies the terrain, followed by interpolating again and therefore adding estimated information back to it, evidently leading to loss of information and loss of certainty. For this reason Stoter et al. (2020) recommended to create a TIN and develop noise modelling software that can directly read a TIN, thus omitting the height lines.

Given the input data (point cloud) is accurate and correct, an algorithm to produce a TIN directly should allow to satisfy all conditions of the elevation model. It allows to have a variable level of detail, aiming to keep terrain details where needed, and omitting details where the impact is insignificant leading to both a model with minimal information, while allowing quality assurance and efficient cross section extraction. This recommendation was followed by publishing sample data on the TU Delft website[8] and a project to develop noise modelling software based on a TIN (van Rijssel et al., 2020). The project was a proof of concept which developed noise modelling software with results comparable with GeoMilieu. Later the sample data was expanded to a country wide model[9]. This models creates a TIN directly from the Algemeen hoogtebestand Nederland (Dutch general elevation model) (AHN) point cloud and allows for efficient and accurate terrain simplifications.

[8] `https://3d.bk.tudelft.nl/opendata/noise3d/en.html`
[9] `https://3d.kadaster.nl/3d-geluid/`

1.5 Problem description

For several years automatic generation of noise modelling input data has been a subject of research and has been optimised over time. However, while the results are sufficient, it was also noted that a TIN could omit steps while providing more certainty over the accuracy of the result. This made the TIN promising, but more research is needed. After concept software to use a TIN was developed (van Rijssel et al., 2020), optimising the TIN can now be researched and tested.

The current country wide input data contains a TIN with a constant accuracy of 0.3 meter, i.e. the maximum error between the reality, as measured using airborne Light Detection And Ranging (LiDAR), and the TIN [9]. Noise experts mentioned the detail in the terrain is more important close to noise sources, as it highly influences the noise levels of noise propagating over this terrain. In the CNOSSOS method the noise source of road vehicles is 0.05 m above the road, where this is 0.75 m in the RMG 2012. In the case of railway noise, this is located at 0.5 and 4.0 meters in CNOSSOS and about 0.2 meter in the RMG method. This low elevation above ground is important, as a small ridge will sooner block a line of sight, causing diffraction, making the elevation accuracy close to a road important for the certainty of the noise output. Yet, further away the impact of the elevation accuracy is less significant, as further explained in section 2.3. It was also mentioned that some terrain characteristics, like ditches, are included in the TIN, as they have significant height jumps, but do not significantly influence the noise propagating over this terrain. Therefore, a TIN which adheres to these characteristics could improve both performance and quality of the output.

2 Related work

In this chapter previous research related to the topic is summarized. This includes other studies with the same or similar aim, studies that use same or similar techniques for other aims and studies that use same or similar data (modifications).

2.1 Studies on noise modelling input data

Research on optimizing elevation input data for noise modelling in the shape of a TIN has, to the best knowledge of the author, not been researched or published before. Stoter et al. (2020) mentioned the automated reconstruction of noise input data in general has received little attention up until recently. A few studies have investigated the automatic reconstruction of noise input data, namely buildings, ground types and elevation data (Peters et al., 2018; de Kluijver and van Tilburg, 2018; Stoter et al., 2020). In these studies the elevation data is provided as height lines. The research from Geodan (De Kluijver and Van Tilburg) created the data for the municipality of Lisse. This highly reduced the work load of noise experts and therefore the costs of noise analysis. The research of Peters and Stoter was more extensive on the algorithms to produce the environmental data, of which mainly the ground types and elevation data are here further explained. To extract the noise relevant data several selections were made. The height lines were selected using the polygon edges in the Basisregistratie Grootschalige Topografie (basic registration large scale topography) (BGT) and filtered on slope meta data, area of the polygon and type of the terrain. Then the lines are triangulated and the error with the elevation data from the AHN was used to add lines in high error areas to correct the model. The lines were further filtered by removing short (<0.5m) lines and removing lines that did not impact the terrain significantly (by creating a TIN and removing lines that did not cause large alterations if removed) (Stoter et al., 2020). It was mentioned that noise experts may draw more height lines close to noise sources, and less further away, however this was not implemented in the algorithm. The initial noise maps produced with this fully automatically generated input data were satisfactory, the differences between noise maps from input data prepared by DGMR[4] and noise maps with the data produced in this research were within the statistical 95% confidence interval and therefore selected as suitable for use in practice.

2.2 Construction of an elevation model

Generating an elevation model in itself is a complex process. To achieve a high quality and reliable elevation model, the input data should be accurate as well. In Europe, the surface elevation is commonly measured using airborne LiDAR. Different techniques of filtration and interpolation can be used to obtain an elevation model in raster or vector format (of which vector is most commonly a TIN for elevation data). Other formats, like iso-contours or height lines are derived from the TIN or raster format. A good interpolation method for terrains adheres to seven properties (exact, continuous, smooth, local, adaptable, computationally efficient and automatic) (Ledoux et al., 2020, section 4.1).

To obtain a TIN, different algorithms can be used. It is common to use the Delaunay triangulation (DT) criteria for a TIN as it ensures evenly spaced triangles and prevent sliver triangles (Delaunay et al., 1934). A triangulation can be made by using all vertices from the point cloud in the TIN, however, this generally results in many (small) triangles. In digital elevation modelling it is therefore common to use an algorithm which iteratively add the most suitable vertex. An example is the fast triangular approximation algorithm (Garland and Heckbert, 1997). This algorithm starts with an rough initial triangulation and per triangle iteratively adds the vertex causing the highest error until the error is below a defined threshold.

Algorithms to create such elevation maps are complex as they must be both precise and efficient to process large amounts of data within a reasonable time. Several commercial (e.g. Safe FME[10], Autodesk Recap[11], 3DReshaper[12]) and open source solutions (e.g. Cloud Compare[13], 3Dfier[14]) are available to produce a raster or mesh from a point cloud. A unique feature of 3Dfier is that it allows to create a constrained TIN based on input polygons and define different approaches for different types of terrain. For example, building polygons can be extruded with a flat roof at a specified percentile height while vegetation can be modelled with less accuracy than a road for example. Other software include automatic removal of outliers in noisy data such that the point cloud does not require pre-processing.

2.3 Noise modelling

2.3.1 CNOSSOS and the Dutch RMG method

For noise studies in the Netherlands the RMG 2012 method is used while the EU mapping rounds is done using the CNOSSOS noise calculation method. In this paragraph a short introduction is provided in how these methods compute the noise level at a receiver point, given a single noise source and the terrain in between. These methods can be used for road, railway, industry and airborne traffic. Within this research only road and railway sources are considered (further explained in 3.2), therefore this introduction mainly aims at these source types. Both RMG and CNOSSOS prescribe how the compute the source noise level based on type of source, amount of traffic, road material and other factors. From this a noise level in dB is given for eight octave bands (63, 125, 250, 500, 1000, 2000, 4000 and 8000 Hz).

To compute the total attenuation during a direct (line of sight) propagation, both methods provide several sources of energy loss, as shown in table 2. Note that the variable 'distance' is the shortest distance through air between source and receiver, which, in the case of diffraction, lays over the path like an elastic band, as the line S-O-R depicted in figure 5.

Table 2: Overview of sound energy losses along a direct propagation path for both CNOSSOS and RMG 2012 method. Distance; shortest distance between source and receiver, Ground absorption factor; absorbent fraction of the path as value from 0 to 1.

CNOSSOS		RMG 2012	
Type of energy loss	**Dependent variables**	**Type of energy loss**	**Dependent variables**
Divergence	Distance	Divergence	Distance
Atmospheric absorption	Distance Atmospheric coefficient	Atmospheric absorption	Distance
Ground effect	Equivalent source height Equivalent receiver height Ground absorption factor Distance	Ground effect	Equivalent source height Equivalent receiver height Ground absorption factor Distance
		Meteorological effect	Distance Equivalent source height Equivalent receiver height

Note that while both methods have numerous overlaps in attenuation types and dependent variables, the formulas, and therefore the outcomes, are different. The overview aims to indicate the types of attenuation and which variables influence it. It illustrates that the elevation

[10] https://www.safe.com/fme/
[11] https://www.autodesk.com/products/recap/
[12] https://www.3dreshaper.com/en/
[13] https://cloudcompare.org/
[14] https://github.com/tudelft3d/3dfier

of the ground is only involved in the ground effect attenuation. Next to the attenuation the terrain elevation data is also used for other purposes, this is described in the next section.

2.3.2 Use of elevation data in noise modelling methods

Insufficient accuracy in the elevation profile will result in inaccurate noise level predictions. But what accuracy is sufficient? A local increase in elevation, e.g. a dyke, has a higher impact on the noise traveling over it than a local decrease in elevation, e.g. a ditch. But does this mean that removing the ditch has a negligible impact on the noise level prediction using the RMG or CNOSSOS method? As known to the author at the moment of writing, no studies have been published on the influence of elevation accuracy or terrain alterations on noise modelling. Alternatively, this section describes how the terrain elevation information is used to compute the noise level for a single source - receiver path for both the Dutch RMG and the CNOSSOS method. The RMG 2012[3]) uses the elevation data in the following ways;

1. Determine whether there is a direct (i.e. line of sight) or diffracted path and identify possible diffraction points.

2. the height points and ground types within 70 meters from emission and immission points are aggregated to obtain the mean height level and average absorption to account for the ground effects. The emission and immission sources are placed a defined distance above the local ground height. If the mean height is higher than the local height and the difference is more then the defined distance, the source / receiver height is set to 0 m in the ground effect calculation.

It is interesting that only the elevation in the first 70 meter around the source and receiver points are used to to estimate the mean height around these points. Terrain in between is only used to identify diffraction points, as paths can be considerably longer than 140 meters, the middle area can be of significant length.

The CNOSSOS method uses a different approach and uses the elevation data more extensive, as listed below;

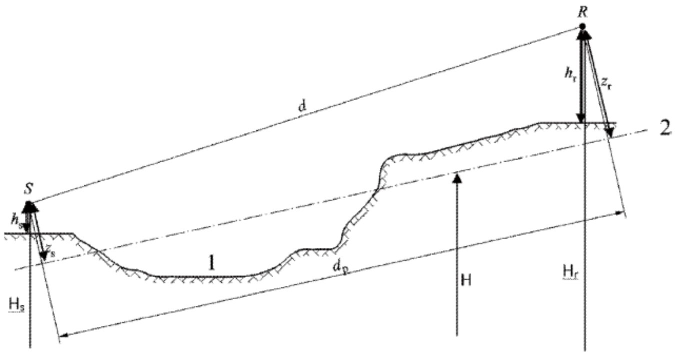
1. Determine whether there is a direct (i.e. line of sight) or diffracted (occluded) path and identify possible diffraction points.

2. Fitting of a mean height plane by means of a linear least-squares-adjustment on the elevation points. (See figures 4 and 5)

3. Relative height of source and receiver above ground is based on the orthogonal distance to the mean plane, this is treated as 0 when it is negative. (See distance z_s and z_r in figure 4)

4. In the case of vertical diffraction (figure 5) the total propagation is subdivided in sections per diffraction point, where a separate mean plane is computed.

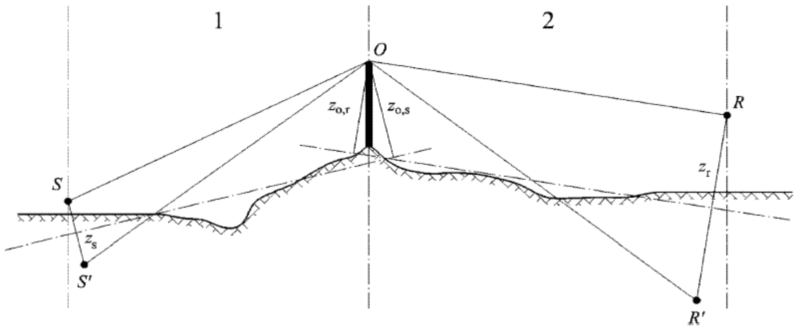
When observing the different functions of the elevation data it can be noted that for the mean plane, more accurate data will most likely not alter the mean plane significantly, as some points might be higher, others lower. The most important influence of the elevation seems to be in the detection of (natural) obstacles, i.e. to determine if there is a line-of-sight, or vertical plane diffraction. As the emission height of road sources (0.05 meter) is close to the ground, and a small ridge can already cause occlusion for many immission locations. This problem is less dominant with railway sources, which have two emission sources at 0.5 and 4.0 meters.



1: Actual relief

2: Mean plane

Figure 4: Mean elevation plane for direct path and relative height (European parliament and European Union, 2015, L 168/27)



1: Source side

2: Receiver side

Figure 5: Mean elevation plane for a diffracted path and relative height (European parliament and European Union, 2015, L 168/36)

This also plays a less significant role on the receiver side, which is at least 2 meters for accurate results.

With regard to local decreases of elevation, i.e. ditches, this will only influence the mean elevation plane.

2.4 Conclusion of related work

It is shown that the combination of terrain and noise modelling is not necessary a new terrain, the models already exist for many years, but research in the field is limited. Most knowledge lays with commercial companies as supplier of data and software. This makes the research both interesting, as much is yet to be discovered, and complex, as knowledge exists within commercial companies, but it is not publicly available. As software for individual parts of the process is available and the noise computation methods are well documented, it seems the project and the expected results are feasible.

3 Goal of this research

This research aims to automate the construction of triangular mesh based input data, specifically for noise modelling purposes. This research is not part of either step 1 or step 2 of the noise modelling process (as described in section 2.3) but it is influenced by both. Step 1 mainly influences how the information should be structured (context), while step 2 mainly influences which information should be in the model (content). Next to the research questions, also the scope is defined to determine the boundaries of the project.

3.1 Research questions

This research aims to answer the following question;

How should elevation data be included in a triangulated environment model for efficient and accurate noise modelling purposes?

Such an environment model holds information on the ground type, elevation and buildings within the terrain, of which this research will focus on the elevation data. The environment model will be used as input for noise modelling according to the RMG 2012 and CNOSSOS methods. The process of developing the environment model consists of three phases in which the following questions will be answered;

1. Which parameters influence the required elevation accuracy of the environment model, categorized on the following types;
   a) Distance to noise sources or buildings
   b) Type of surface (e.g. road, vegetation (types) and water)
   c) Local topology of the terrain (e.g. local change of elevation)
2. How can a triangular irregular network (TIN) be generated according to the local accuracy based on the parameters?
3. Which parameter settings provide a balance between quality of the output and performance?

3.2 Scope of the project

In order to maintain a focus on the research goals it is important to not only describe what will be done, but also explicitly what will not be considered during the research. This helps to keep a focus on the goal and communicate the expectations of the results. Therefore the following items are not covered in the research;

1. This research will focus on the elevation data, therefore ground type and building data sets[9] are taken as is and not further simplified.
2. The output data file format is based upon the requirements for TIN based Noise modelling software as developed during the 2020 Synthesis project "3D noise modelling", also an output file format is made for GeoMilieu software for comparison.
3. Developing triangulation software itself is not considered part of the research
4. The research is limited to the limitations of the provided software (van Rijssel et al., 2020), which are;

a) Bridges are not included in the research.
b) Only road and railway sources are recognized as a source and represented as a line segment (Industry and airborne noise are excluded)
c) Each road segment produces the same level of noise (as is hard coded in the software), therefore all road segments are treated equally in this research.
d) Noise barriers are not included in this research

Writing triangulation software is not considered as it does not directly help to answer the research questions and the amount of work. Instead the existing software 3Dfier will be used (further explained in section 4.2.3.

4 Methodology

To answer the research questions provided in the previous chapter, an approach is provided in this chapter. This research study consists of several phases, as listed below. The first phase has already been done and is described in the next section.

1. Define test areas which allow to test the programs in various environments.
2. Develop programs to execute the different steps in the method
3. Produce noise maps for the test areas using produced programs and the existing environment model.
4. Assess the quality and performance of the program and improve the program and the parameters

4.1 Test areas

In search for test areas the following criteria were used.

1. Area:
   a) Generally less than 15.000 m^2 for computation purposes, can be more when there are no buildings.
2. Terrain:
   a) One area with multiple buildings among extraordinary shaped buildings preferably with small details.
   b) At least one area with both ground types in it in both large and small shapes.
   c) Larger elevation formation (dyke or river bed)
   d) Smaller elevation formation (ditch or ridge)
   e) Small and large waters
   f) No bridges in the areas
3. Noise sources:
   a) At least one road, road type / size less relevant, preferably larger road
   b) One patch with highway for quality assessment with Digitaal Topografisch Bestand (Digital Topographic Data) (DTB)
   c) One patch with railway

Based on these criteria the following test areas have been selected (table 3). Here the color indicates the elevation (green is low, yellow is high), Red indicates the boundaries of the test area, blue lines indicate road segments, dashed lines railways, grey polygons buildings and empty / crossed areas reflective / absorbent areas respectively.

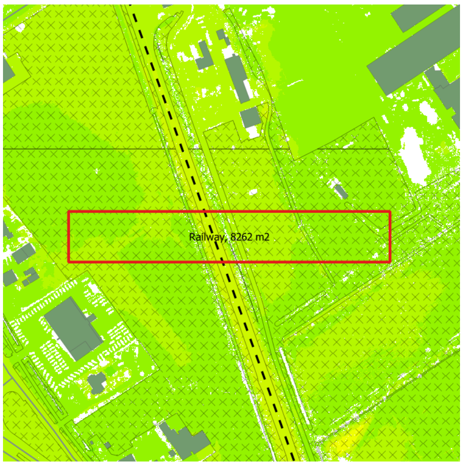
4.2 Concept of workflow

Based on the current state of research as provided in chapter 2 a workflow is deducted. This is a conceptual implementation of research question 2/ This consists of several steps which are depicted in figure 6. In the next few sections the steps in the method are further elaborated.

Table 3: Overview of selected test areas located around Rhenen in province of Utrecht, Netherlands

Test area: buildings
Occluded height areas

Test area: highway
Significant elevation difference
Water bodies, no buildings



Test area: railway
Narrow ground type regions
Small elevation difference

Test area: rural area
Low elevated ridge
Narrow ground type areas

Test area: Water and terrace area
Vertical slope in terrain
Large water body

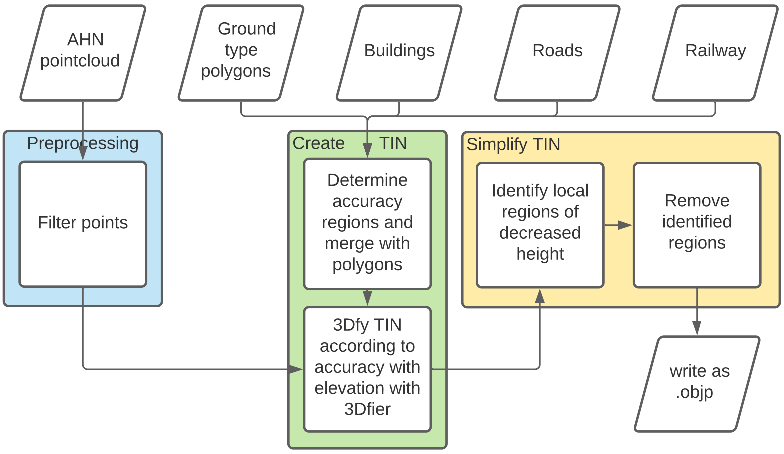


Figure 6: Flowchart of data processing, made with LucidChart

4.2.1 Input data

The different data sets are further described in chapter 6. The data is clipped to the test areas using QGIS[15] and LASTools[16]. The point cloud and ground type polygons are clipped with a buffer to ensure all possible paths are fully covered by the environment model.

4.2.2 Pre-processing

The AHN pointcloud will contain many points of objects that are not part of the terrain, a assessment will be conducted to determine if and how much it needs to be filtered before feeding it to 3Dfier (which can only filter on classification).

Ground type polygons will not be simplified, this is already done when aggregating the BGT into the ground type data set[9]. Possible further simplifications are considered out of scope, while this could increase the performance, it was decided to focus on elevation during this research.

Building polygons simplification is not part of the method, however, building parts will manually be adjusted if they are significantly different then reality (based on orthophotos). The building outline was retrieved from the Basisregistratie Adressen en Gebouwen (Basic registration addresses and buildings) (BAG) and is accurate. Simplifying the building parts (which are deducted from roof elevation differences in the point cloud) was discussed but it was decided not to include this as it should be improved in the construction of the building data set, where more information is available.

4.2.3 Create a TIN

To create a TIN, 3Dfier[14] is selected as it fits the requirements for the output TIN as described in section 4.2.5. 3Dfier allows to create a TIN using a point cloud and a set of polygons to which it will be constrained. 3Dfier also supports 7 different surface types which have different settings and options for the triangulation. In order to obtain not only different types of triangulation (e.g. flat, smooth or accurate) but also different levels of accuracy within a surface type it might be required to add new surface types to the 3Dfier software, which is possible.[14]

[15]https://www.qgis.org/en/site/index.html
[16]http://lastools.org/

In order to use 3Dfier, the ground type polygons will be subdivided in discrete accuracy regions. Another approach to have a TIN with a gradual changing accuracy level was considered, but there is no software that can handle this. Developing the triangulation software is out of scope as it is complex and not necessarily related to noise modelling.

After the input data of 3Dfier has been prepared, including the .yaml file which contains the settings, 3Dfier can be ran to produce the TIN.

4.2.4 Simplify the TIN

The second part of this research aims to further simplify the TIN and remove objects that slow down the noise modelling software without adding value to the output results. This first consists of an algorithm to identify such topologic features followed by an algorithm to efficiently remove them from the TIN.

4.2.5 Output data

To produce a noise map from an TIN based environment model, there is only one solution which was developed during a project of the MSc Geomatics at the Technical University of Delft (van Rijssel et al., 2020). This software uses requires the TIN to be in a adjusted version of the .obj file format, called the .objp (or .obj plus). This adjustment allows to store the adjacency and semantic data within the triangle. For the software to work it requires the TIN to be constrained to the ground types and the buildings. The ground type data is incorporated in the triangle and therefore each triangle can only have one ground type. The building data is used to elevate the cross section to the right building height as the TIN is not elevated to the building roof (So called LoD 2 TIN (Kumar et al., 2019)).

5 Planning and Organisation

This graduation research started April 19th 2021 and is expected to take approximately 30 weeks of which the summer period (July 3rd - August 30th) is excluded, during this time the work will be progressed parttime. The graduation is therefore expected around January 24th 2022. A Gantt chart of the time planning is provided in figure 7. It contains the different phases, hard and soft deadlines and should be interpreted as a general outline of activities. As phases and activities are not easily expressed in hours of labour, it should be interpreted as a rough guideline. The organisation of this graduation research is shortly described in section 5.1.

5.1 Project organisation

This graduation research is in collaboration with the RIVM[17]. Within RIVM the graduate is part of the department of Air quality and noise, part of the Centre for Environmental Quality[18]. The student is supervised by noise expert Arnaud Kok from the RIVM and Balázs Dukai from the TU Delft. The student has one hour bi-weekly meetings with both mentors individually and, upon request, a meeting with both mentors, possibly including the second TU Delft mentor (Jantien Stoter).

[17] https://www.rivm.nl/
[18] https://www.rivm.nl/rivm/organisatie/centrum-milieukwaliteit

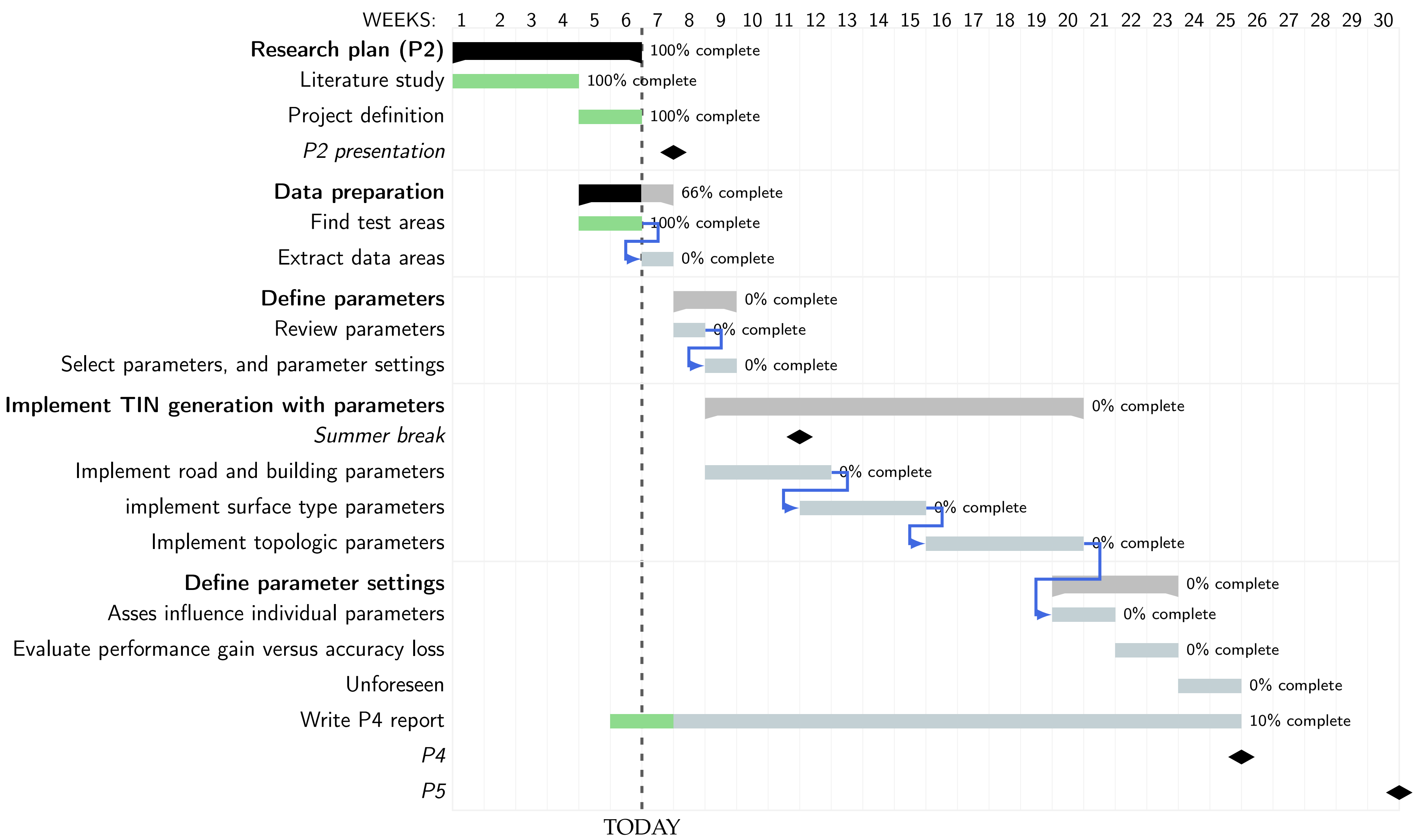


Figure 7: Gantt chart of the planning, made with pgfgantt

6 Tools and datasets used

During this research a set of input data sets will be used to produce the results. Also a selection of tools will be used to produce the product, gather and visualize input and output data. These are described in this section.

6.1 Input data sets

An overview of the used data sets is provided in table 4. To select the most suitable source for the type of data several criteria were tested; The aim is to use accurate and detailed information as well as using mostly common data types and formats to make reuse for other regions and countries accessible. A short explanation is given for each type of data;

1. The elevation data is given as a point cloud which provides the most raw and accurate information.
2. The 3D noise input data has a public LoD 1.3 building data set based upon the BAG and BGT and elevated using the AHN 3 point cloud. It is selected over the BAG (common building administration) as it is already has height elevation in LoD 1.3 and includes smaller buildings and sheds from the BGT.
3. The 3D noise ground type data is based upon the BGT where the surface classification is subdivided in reflective and absorbing materials, than adjacent polygons of the same type are merged to reduce the number of polygons (Peters et al., 2018).
4. The Nationaal Wegen Bestand (National Road Data) (NWB) contains the national road data of which the linestrings are selected which represent roads as lines (highway roads represented by two line segments for each driving direction, other roads with a single line).
5. The Prorail railway data set contains all railways of the Netherlands of which the "spooras" data is used.
6. The DTB contains information about transport routes over water and land, namely waterways and highways. From this data the line data is selected which contains accurate height information that can be used to asses the quality of the output of this research.

Table 4: Overview of used data sets

Name	Purpose	Data structure	Source	Link
AHN 3	Elevation data	pointcloud	Rijkswaterstaat	PDOK
3D geluid	Building data	polygons	TU Delft and Kadaster	Kadaster
3D geluid	Groundtype data	polygons	TU Delft and Kadaster	Kadaster
BGT	Surface type	polygons	Kadaster	PDOK
NWB	Noise source	linestring	Rijkswaterstaat	PDOK
Railways	Noise source	linestring	Prorail	PDOK
DTB	quality control	linestring	Rijkswaterstaat	PDOK

6.2 Tools

To execute the steps of this research several software tools will be used. An overview is provided in table 5. Next to tools that are used to perform specific operations, code is also developed to alter the data. This code will be written in C++ or Python depending on the task.

Table 5: Overview of used tools

Name	Purpose	Owner	Open source
QGIS 3.18	Clipping input data and visualising output noise maps	QGIS	Open source (free)
LasTools	Clip and filter point cloud	RapidLasso	Commercial (license required)
Blender 2.92	Visualisation of the TIN	Blender Foundation	Open Source (free)
3Dfier 1.3.0/1	Generation of the TIN	3Dfier	Open Source (free)
python 3.9	Running Python code	Python	Open Source (free)
Visual Studio 2019	Writing and compiling C++ code	Microsoft	Commercial (free)
Visual Studio Code	Writing Python code	Microsoft	Commercial (free)
Overleaf	Writing documentation	Overleaf	Commercial (student license)

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